The effect of road roughness (and test speed) on GripTester measurements

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An important note for the reader

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Contents

Executive summary

It has been well proven that as the skid resistance of a road surfacing decreases, the number of loss-of-control crashes in wet conditions increases, causing road death and injuries. However, the management of skid resistance of road surfacing continues to be difficult due to the inherent variability involved in skid resistance measurements and the interpretation of results. This research was an investigation and analysis of just one of those variable factors; being the effect road roughness has on skid resistance measurement undertaken using the GripTester device. There are a number of other continuous skid resistance measurement devices used in New Zealand and internationally and the findings of this research do not necessarily relate to those devices. The most commonly known is the SCRIM device that the New Zealand Transport Agency (NZTA) has used to measure skid resistance annually on New Zealand state highways since the development of a skid resistance policy to reduce wet skid resistance related crashes (T/10). Some local territorial road authorities have used the SCRIM, ROAR or GripTester continuous measurement devices.

The data required for the research was collected by field testing on specially chosen sites in the Franklin and Waipa districts that had varying road roughness. The methodological steps used to collect GripTester skid resistance data from the chosen sites is outlined below:

1 Identify appropriate test sections

The identification of test sections required an initial desk study. The sites were mainly identified and chosen from the Franklin District Council road asset and maintenance management (RAMM) database although a few were undertaken in the Waipa district in the Waikato region. Test sections were selected according to five levels of predefined National Association of Australian State Roads Authority (NAASRA) roughness bands and three macrotexture levels.

2 Site validations

In order to determine whether the roughness and texture data of the selected sites obtained from the RAMM database reflected present in-field conditions, a field survey was undertaken of each of the sites using the Pavement Management Services laser profilograph. This field survey measured the actual road roughness and the macrotexture of the sites prior to skid resistance testing with the GripTester.

3 Field tests

Each section underwent a series of GripTester runs at four varying speeds. Data collected at each test section included the grip number (GN) measurements at both 1m and 10m averaged intervals. The 10m averaged surveys reflected the normal operation of the GripTester as used in network and project surveys.

A Dynamic Friction Tester (DF Tester), a stationary skid resistance measurement device, was also used in the field tests at specific locations to eliminate speed and road roughness effects that might have affected the GripTester device. The results obtained from the DF Tester were used for correlating against the GripTester results at various vehicle towing speeds.

4 Data analysis

The collected data resulted in a variety of skid resistance values in terms of GN for different speeds for each test section. The relationship between the measured coefficient of friction and the test speed for each of the test sections was then developed. Relationships between the skid resistance and the road roughness as well as the surface textures were also determined during data analysis.

5 Research summary and conclusions

The research results found that the DF Tester as a stationary device was highly repeatable with a coefficient of variation ≤2.5%. It was also shown to be a very useful calibration device for continuous friction measurement devices such as the GripTester. The GripTester can also be reasonably repeatable with a coefficient of variation of typically ≤6.0% between multiple test runs when the test device and measuring tyre have been appropriately conditioned. The coefficient of variation can increase up to approximately 11% on a relatively short road section if the tyre is not conditioned prior to a test site survey.

The research using a GripTester found some unexpected results that did not concur with accepted theory (eg that as measurement speed increases, skid resistance reduces and at a greater rate when the macrotexture is high in comparison to sections with low macrotexture). This research has raised some further questions about the behaviour of skid resistance and the various measurement devices used to determine a measured coefficient of friction. The findings are however limited to the GripTester device and some aspects do not apply to other skid resistance measurement devices (eg SCRIM and ROAR). In summary, the following conclusions have been drawn from this research:

- There is a satisfactory linear model of the relationship of GN to the explanatory variables texture, testing speed and road roughness. Test speed and texture would appear to have an impact on the measurement of the GN but surprisingly road roughness does not appear to have an influence on the GN as has been hypothesised. More needs to be done in this area to better model the factors influencing the GripTester results.
- Generally, at lower test speeds (less than 75 km/h) the GN (on individual road sections) may not be dependent on test speeds, but this depends on the nature and condition of the road surfaces being tested.
- A relationship between the GN obtained from the GripTester and the coefficient of friction obtained from the DF Tester was found to be independent of the test speed of the GripTester on the test site. A good correlation was found between the GripTester and the DF Tester on this site.
- In view of these findings, it can be safely considered that the GN is influenced by the test speed and that texture is also a minor factor (to be further investigated). However this research showed that the GN as measured by the GripTester is not significantly influenced by road roughness up to 170 NAASRA counts per km and at testing speeds lower than 75km/h.

Further research is required with a greater sample population and site matrix with various skid resistance measurement devices to determine whether some of the unexpected results found during the research were primarily due to the small population size or alternatively due to the GripTester measurement device alone.

Abstract

This research investigated the effect of road roughness, macrotexture and testing speed on GripTester measurements.

Field tests were conducted by the GripTester at various test speeds on sites with varying road roughness in South Auckland. The variables – road roughness, texture and test speeds – were measured and plotted against each other along with grip number (GN) as obtained from the GripTester. Tests with the DF Tester were also carried out at one site and directly correlated with GripTester results at various towing speeds. It was found the GN might not be dependent on test speeds while testing at speeds lower than 75km/h; however, an inverse relationship occurred at higher speeds, on a limited number of test sites. Road roughness was found to have no effect on GripTester measurements and texture appeared to be a minor factor.

In conclusion, the explanatory variables on the GN are test speed and perhaps texture. However, unaccounted factors that are specific to test sites proved to have some degree of effect. Future research recommendations include searching for better controlled test sites and larger samples to clarify the effect of texture on the GN and to expose unidentified factors that can influence GripTester output.

1 Introduction

The aim of this research project was was to develop a better understanding of the effect longitudinal road roughness has on skid resistance measurement and more specifically on the GripTester measuring device. The research also considered the effect of the GripTester testing speed on skid resistance measurements using various levels of road roughness.

1.1 Background

Crash database statistics show that each year in New Zealand there are approximately 12,000 fatal and injury reported crashes and 23% of these crashes occur in wet and/or misty weather. In wet weather conditions, the presence of water on the pavement surface increases the risk of skidding with the result that approximately 1.6 times more fatal and injury crashes occur in wet conditions than in dry conditions on New Zealand state highways (Dunlop 2003).

Friction is defined as the resistance to motion between two surfaces in contact; in this case the vehicle tyre and the road surface. Its magnitude is expressed by the coefficient of friction which is a ratio of two forces, one parallel to the road surface and tyre contact area that is opposed to vehicle motion (the friction force) and the other perpendicular to this surface of contact (the normal force generated from the vehicle load). Water on the pavement surface acts as a lubricant that significantly reduces the coefficient of friction between the tyres and the 'texture' of the aggregate surface. The term 'wet skid resistance' is used to characterise the contribution the road surface makes to the available level of surface friction in wet conditions.

To reduce the higher crash rates that occur in wet weather conditions, it is necessary to maintain differing skid resistance levels for various traffic site categories based on an understanding of the relationship between increasing crash rates (risk) and decreasing levels of skid resistance. In New Zealand, skid resistance standards on state highways (NZTA T/10 specification 2010) are set out as a guide to highway engineers for paving new road surfaces as well as to producing an efficient and effective pavement surface maintenance routine. The standard of skid resistance levels varies between different road site categories based upon equalising the crash risk across the road network. For road sections that are classified as high risk, the standard intervention level (IL) of required skid resistance will be significantly higher than for low-risk road sections. Pavement surfacing properties such as the textural wavelengths at the macro- and micro-levels bear an important role in providing adequate skid resistance.

Surface texture that contributes to skid resistance is generally divided into two categories: *microtexture* and *macrotexture*. Microtexture is defined as the harsh features of each individual aggregate chip that is not generally visible to the naked eye, or features that can only be seen by a microscope. Texture on this scale (less than or equal to 0.5mm) is provided by the crystalline structure of the aggregate particles and how it is cemented into the particle matrix in the upper layer of the surfacing aggregate material. Macrotexture refers to the wavelength features between 0.5 and 50mm and is determined by the size, grade and spacing between the aggregates. It is the surface characteristic perceived by someone standing on and looking at the road surface.

Road roughness is defined as the larger wavelength irregularities of the road surface: the sizes of irregularity are between 0.5m to 50m. These wavelengths are usually less significant for the generation of surface friction, except that the interaction between longer wavelength features and vehicle suspension (or in this case the GripTester skid testing device) influences the contact between the road surface and vehicle tyre.

1.2 Need for research

This research project sought to quantify the effect that road roughness wavelengths had on the GripTester (a device commonly used in New Zealand and internationally to measure the coefficient of friction predominantly on airport runways and road pavement surfaces). It should be noted here that the NZTA does not currently use the GripTester for network surveys on state highways although it has been used for many research projects and project level surveys on both state highways and local roads.

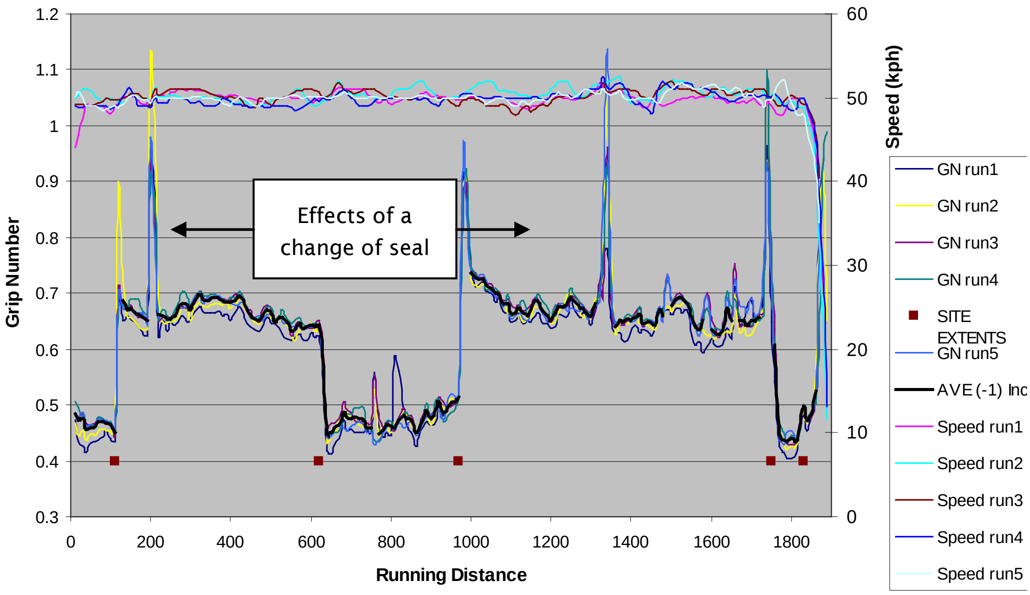
Research studies conducted by Roe and Hartshorne (1998) and Wambald et al (1995) and others have shown that vehicle speed affects the available skid resistance. The faster the vehicle is travelling the less contacting force between the vehicle tyres and the pavement surface and hence, the measured coefficient of friction will reduce significantly. The rate of reduction is dependent upon the macrotexture of the pavement surface and the relationship between skid resistance levels and travelling speeds is typically a negative exponential relationship with increasing speed.

A variety of measuring devices have been designed and are available to measure the friction of the road surface. The ones most familiar in New Zealand include: the SCRIM machine (sideway-force coefficient routine investigation machine), GripTester, RoAR, British Pendulum Tester and the Dynamic Friction Tester (DF Tester) – refer to appendices A and B for descriptions of the GripTester and DF Tester used in this research. Most of the devices have quite different design methodologies and measurement characteristics and therefore the calculated output coefficient of friction will differ from one device to another. All the test devices are similar in that they use rubber compound sliding to some degree either in-line or at an angle to the vehicle direction to calculate the coefficient of friction. Therefore, all test devices provide an indication of the level of skid resistance and in theory the output from one device can be correlated to another device or to an International Friction Index (IFI) (Wambald et al 1995). However, the correlation relationships have been proven to be largely unreliable for road surfaces in New Zealand and in many other countries.

The GripTester is widely used around the world to obtain surface friction measurements on airport runways, road pavements, pedestrian walkways and for research purposes. It is a three-wheeled trailer (one test wheel and two bogey wheels) that can be towed behind a vehicle with a water delivery system. The GripTester is a braked wheel method that measures the drag force and load force on a single treadless American Society for Testing and Materials (ASTM)-specified rubber test tyre of 254mm diameter during braked skidding at approximately 15% of the survey speed.

A previous research study in New Zealand conducted by Cenek et al in 2004, although limited in data, reported on the sensitivity of the GripTester to various road texture wavelengths (microtexture and macrotexture). This research extended those findings to consider the effect of increasing longitudinal road roughness and testing speed on GripTester measurements. Furthermore, skid resistance measurement testing with the GripTester appears to show that road surfaces with significant road roughness or 'bumps' adversely affect the measured coefficient of friction (refer to figure 1.1 which clearly shows the bumps from a change of seal). This research investigated whether these effects on skid resistance measurement are due to the speed and suspension system of the GripTester device rather than actual skid resistance changes.

Figure 1.1 Effects of road roughness on GripTester measurements



1.3 Research objectives

The primary goal of this research was to understand whether skid resistance measurements obtained from the GripTester device testing at various speeds were affected by increasing road roughness. The GripTester is a relatively light device (85kg total weight) in comparison with the commonly known SCRIM truck measurement device that hydraulically controls a 200kg load on each testing tyre.

The specific objectives of the research programme were to:

- quantify the effect of longitudinal road roughness on the GripTester device
- measure the effects of surface texture on the results produced by the GripTester in comparison with the DF Tester
- measure the effects of travelling speeds on the results obtained by the GripTester, on various road surfaces with various levels of road roughness.

The research outcomes would allow road controlling authorities (RCAs) and consultants to specify skid resistance testing protocols to ensure measurements undertaken by the GripTester are least affected by external variables (eg speed and road roughness). This in turn will provide RCAs with greater confidence in the GripTester test measurements when the testing protocols have been followed.

1.4 Scope of the report

This report presents the results of research on the effect of road roughness and testing speed on GripTester measurements. Chapter 2 discusses the relationship between crash risk and skid resistance, the factors that affect skid resistance measurement and the textural wavelengths associated with skid resistance including a summary of road roughness. Chapter 3 describes the equipment and chapter 4 describes the experimental design methodology used in the field testing. Chapter 5 describes the data processing methods used to summarise the raw data results from field testing and chapter 6 discusses the results of the analysis. Chapter 7 provides conclusions and recommendations from the research.

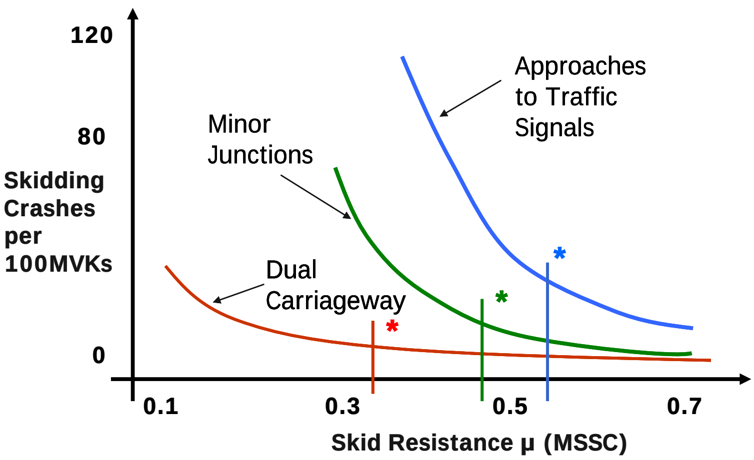
2 Skid resistance literature

2.1 Road safety, risk and policy

There is no doubt that as the skid resistance of a road surface decreases, the crash rate increases. This significant road safety issue is amplified when the pavement is wet because the contact between the tyres and the road is reduced and water acts as a lubricant. The resistance to skidding of a road surface is therefore one of the fundamental requirements that highway engineers must consider in pavement design to provide a safe travelled surface. Whether the surfacing is the wearing course of an asphalt mix or a chipsealed surfacing, the skid resistance is governed by the properties of the aggregate.

Different sites present different risks, and consequently, in an attempt to obtain a relatively constant risk of a wet skidding crash across a road network, road agencies (initially in the UK) attempted to align the skid resistance of the site with the risk or need for heavy braking. From this, a number of site categories describing the situations found on a road network and the minimum specified level of skid resistance for each category, have been developed. Figure 2.1 demonstrates in an idealised form how the minimum desirable standards of skid resistance for various road site categories have been established based upon the risk of a skidding crash. A high minimum standard of skid resistance at 'high-risk' areas (eg the approaches to traffic signals) is specified which is then progressively reduced to relatively low levels on straight and event free locations (eg on a dual carriageway).

Figure 2.1 Crash risk, road site category and standard of skid resistance – idealised from Rogers and Gargett (1991)



Note: * denotes the desirable minimum level of skid resistance standard for each road site category before the crash risk significantly increases.

The state highway standard is specified in NZTA T/10 (2010) and was first implemented in earlier versions in 1995. New Zealand has a high percentage of hilly to mountainous terrain and is geologically young. Therefore, the roads are characterised by curvilinear geometrical alignments, poor local aggregates and variable environmental/climatic conditions compared with many other countries. Consequently, loss-of-control crashes are over represented.

Transportation engineering professionals must do better as current rates of road crashes and specifically loss-of-control crashes that result in road fatalities in New Zealand (while comparable to other OECD countries), are at levels that are politically and socially unacceptable. The Ministry of Transport road safety targets to 2020 and 2040 are understandably challenging and will not be realised without significant improvements/changes to current practices. The management of skid resistance sits within one of the four pillars of the recently adopted 'safe system' approach. To do better in this one pillar, the factors that vary the measured skid resistance over time must be better understood to enable appropriate risk management practices to be incorporated into current policies. Road asset managers need to be able to have confidence in the results from measurement devices so they can better predict when the skid resistance of an existing surfacing is likely to fail and plan accordingly for future treatments.

2.2 The variability of skid resistance

The skid resistance available at any particular time, either to the road user or as tested dynamically by a friction tester, depends upon many variables. It is not constant nor is it easily predictable over time. The variables that can affect the level of skid resistance and their inter-relationships are many and complex. They can be grouped under four main categories:

1. **Surface aggregate factors** (eg geological properties of the aggregate, surface microtexture and macrotexture, chip size and shape and type of surfacing)
2. **Load factors** (eg surface age, traffic intensity, composition and flow conditions, and road geometry)
3. **Environmental factors** (eg water film thickness, surface contamination, temperature, seasonal and short-term rainfall effects)
4. **Vehicle or skid resistance measurement device factors** (eg vehicle or test device measurement speed, angle of tyres, wheel slip ratio, tyre characteristics, tread depth and patterns).

This research targeted a better understanding of the fourth category, the dynamics of a measurement device (the GripTester) on its associated skid resistance output measurement data. The research considered the GripTester measurement device as a 'vehicle' to determine whether the 'vehicle' device itself (eg the device weight and suspension system) is affected by increasing road roughness and test operating speed. Other effects are discussed in detail in Wilson (2006).

2.3 Terminology

Skid resistance refers to the extent that a surface contributes to friction and usually refers to wet skid resistance. Skid resistance can be predicted by sliding some rubbery material over a section of wet surface and measuring the force developed against the movement (O'Flaherty 2002).

Road 'surface friction' and 'skid resistance' are often used interchangeably by those involved with the management and maintenance of road networks. Cenek et al (2003) state there is a subtle difference between the two variables.

Road surface friction refers to the resistive force that is developed between a specific road surface under particular conditions. As the frictional force provided by the tyre/road combination is proportional to the load applied, it is normalised by the load to give a coefficient of friction (CoF).

The CoF is affected by a large number of variables as outlined above. In general terms, when a surface is dry, the CoF is normally high and adequate for most normal vehicle manoeuvres. However, when the road surface is wet, the CoF decreases significantly and becomes more dependent on the condition of the tyre and the road surface.

'Skid resistance' is the term used to describe the contribution the road makes to the development of tyre/road friction. It is essentially a measurement of the CoF obtained under standardised conditions in which various variables are controlled so that the effects of the road surface characteristics can be isolated. Skid resistance, as with surface friction, is high in dry conditions and so the term skid resistance is almost always used in the context of wet road surfaces.

'Drag factor' is a term that is often used in accident reconstruction work and exists when two surfaces are in contact and move relative to each other. When gravity supplies the normal force, the term is synonymous with the CoF if the two surfaces are horizontal. The drag factor will differ from the CoF when measured on inclines as the drag factor alone measures the combined influence of the CoF and the slope of the incline. By measuring on an incline, the results will reflect the effect of the incline in overcoming the friction forces between the two surfaces. This could be important in crash reconstruction because it will provide a direct measure of the actual drag factor at work, a slope compensated static or 'dynamic drag factor'. It is common practice in crash reconstructions for a CoF to be used in conjunction with a 'correction grade drag factor' in order to estimate the true drag factor (Pazzaglia and Nelson 1993).

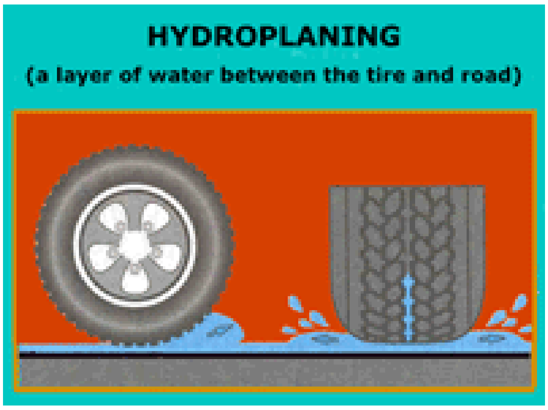
2.4 Wet skid resistance

Wet skid resistance will increase the risk of skidding between the tyres and road surface. This is due to the fact that water acts as a lubricant and will decrease contact between the tyre and the road surface, therefore it is important for the tyre to break through the film layer of water to increase the contact between the tyre and the road surface – even very thin water films can greatly reduce friction.

There are two components of rubber tyre friction; *adhesion* and *hysteresis. Adhesion friction* is when the tyre rubber is locally bonded to the surface whereas *hysteresis friction* is caused from the surface projections deforming the tyre. Normally in dry situations, adhesion friction is greater than hysteresis and vice versa in wet situations (Wilson 2006).

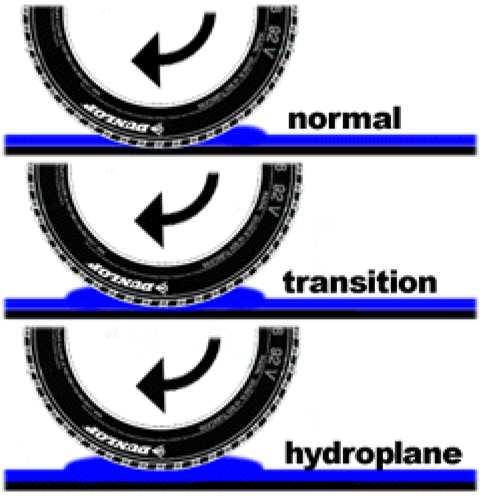
Hydroplaning results when a vehicle travels across a wet surface at a speed which does not give the tyre sufficient time to channel the moisture away from the centre. Consequently, the tyre loses contact and therefore traction to the pavement surface (Davis 2006) (refer to figure 2.2).

Figure 2.2 Hydroplaning condition (Davis 2006)



As speed increases, the amount of water built up in the centre of the tyre increases also. Viscous conditions can also be referred to as partial hydroplaning; this condition can also occur at low speeds when the tyre begins to lose contact with the pavement surface. During dynamic conditions (full hydroplaning), the vehicle is usually travelling at higher speeds and causes the tyre to lift off from the pavement (refer to figure 2.3), leaving no contact with the surface. At this stage braking and cornering have very limited control (Wilson 2006).

Figure 2.3 Illustration of normal, partial and full hydroplaning (Davis 2006)



2.5 Measuring skid resistance

The measurement of skid resistance on the pavement surface enables highway engineers to predict safety-related issues on wet pavements and helps in the setting of maintenance priorities for road systems. This data is helpful for the effective management of road system budgets and the gathering of condition information on the pavement properties for preparing appropriate standards. The primary purpose is to reduce crash rates especially in wet conditions (Elsenaar et al 1977).

Each year, there are approximately 300–350 highway fatalities and more than 10,000 injury crashes in New Zealand (MoT 2012) with approximately 20% – 25% of these due to wet weather loss-of-control crashes. It is important to remember that incidents on the highway rarely have a single contributory factor and are defined as being 'rare, random and multifactor events where the driver has failed to cope with their environment' (Land Transport NZ 2004). Human, vehicle and other road environment factors and their interactions need to be considered, meaning that no simple method exists for defining, in terms of skid resistance, a 'safe' or a 'hazardous' surface, or a skid resistance value at which a site automatically transforms from 'safe' to 'hazardous' (Austroads 2005).

The casual factors are therefore most commonly multi-factored and include not only road environment factors such as skid resistance, but also the driver and to a lesser extent the vehicle. From previous research studies, it is evident that the geological and material performance properties, the road geometry, design speed and how this relates to the approach operating speeds, the pavement surfacing type, construction quality, maintenance treatments, practices and strategies used, and the traffic volumes, especially heavy commercial vehicle (HCV) volumes, all affect the rates of polishing (deterioration) of measured skid resistance and are therefore key factors that need careful monitoring to prevent increasing loss-of-control crash rates. For this reason, most countries now have risk-based skid resistance standards for various sections of the highway environment for national or trunk roads. These standards focus mainly on the choice of aggregates, HCV volumes and the geometric characteristics of the road section.

Regular maintenance, high-quality treatments and strict standards can offer the basis to maintain certain levels of skid resistance. However, to achieve sufficient and affordable skid resistance, it is necessary to make good use of local materials, the workmanship of contractors and the experience of the highway engineers (Elsenaar et al 1977). Many researchers (eg Hosking 1976 and 1992; Roe and Hartshorne 1998; Rogers and Gargett 1991; Henry 2000) reported that the reduction of skid resistance on a highway would lead to a significant increase in crash rates. Future research must consider how what is termed ‘marginal’ aggregate can be modified to perform adequately in-field to resist aggregate ‘polishing’. Setting and maintaining appropriate levels of skid resistance based on crash risk on the road network will allow the appropriate prioritisation and optimisation of road funds and the management of maintenance treatments and activities to enable a safer and more efficient and effective transport system. To effectively manage this system requires a good understanding of the factors that cause change in skid resistance and regular continuous skid resistance condition testing of road sections. These tasks require professional experience and expertise to routinely monitor the condition of the roads, identify the deficient elements of the network, prioritise and programme the deficient elements for treatment and select appropriate warning or interim measures when deficiencies cannot be corrected immediately.

2.6 Skid resistance standards

A relationship has consistently been found between skid resistance and wet road condition crash rates and this is clearly demonstrated by crash rates falling following treatments to improve skid resistance. This established relationship can create a desire to provide a uniformly high level of skid resistance across an entire road network. However, this would prove to be prohibitively expensive, unsustainable in terms of resource usage, largely unnecessary and would not generate the cost benefits associated with a better and more targeted strategy. Accordingly, Austroads (2005) states:

> *A common theme of historical, and many current, strategies for managing skid resistance is the equalisation of crash risk across a road network by maintaining appropriate levels of skid resistance at all locations, based on site characteristics. These can be grouped into nominal site categories. This approach assists in ensuring that the provision of high friction surface treatments can be targeted to where they are most needed, such as at intersections, the approaches to traffic signals and on tight curves.*

Giles (1957) from the UK proposed the first comprehensive standards on skid resistance suggesting four site categories based on requirements for wet skid resistance and a minimum coefficient of friction as measured by the sideways force coefficient (SFC) device at 30m/h (SFC_{30}). The requirements were based upon comparisons between SFC data at ‘crash blackspots’ and SFC taken at random on similar sites.

This early standard led to the UK Highways Agency’s (2004) HD 28/94 standard, which has recently been further revised to incorporate the findings of the crash risk study undertaken by Viner et al (2005). The main concepts of the earlier standard were confirmed and they remain features of the revised standard published as HD 28/04 and reported in Sinhal (2005). New developments in the SCRIM device, updated survey procedures and a rationalisation of the site categories have also been incorporated in the revised standard and a range of investigatory levels for each site category has been introduced.

Importantly, the revised standard highlights the importance of engineering judgement in setting appropriate investigatory levels (ILs) for each site and in conducting site investigations to determine those sites most likely to deliver improvements in crash risk as a result of providing better skid resistance. The flexibility to undertake these assessments was contained within the previous standard; however, experience from implementation had indicated that this part of the policy was not being applied robustly in practice. Sinhal (2005) reports that:

> *A major feature of the new standard is the greater range and detail of the advice included to guide those responsible for providing adequate skid resistance in the application of the standard. Clear advice and guidance is provided in setting investigatory levels and carrying out investigations to determine if treatment is required.*

A higher or lower IL than indicated in the standard may be assigned if justified by the observed crash records and local risk assessment. New Zealand's skid resistance standards are based on those adopted by the UK, with some adjustments made after a 1997 analysis of wet-road skidding injury crashes in New Zealand during the period 1990–1994 (Transit NZ and Roading NZ 2005).

The current *Specification for state highway skid resistance management* (T10 specification) (NZTA 2010) specifies threshold levels (TLs) for each site category; these are set 0.10 below the level of the IL. The IL is set at a level that should trigger an onsite data investigation, and if required, treatment should be undertaken within the next financial year. The TL is set at a level that is intended to trigger an immediate response and some form of action at the site starting with a minimum treatment of advisory signing (slippery when wet signs).

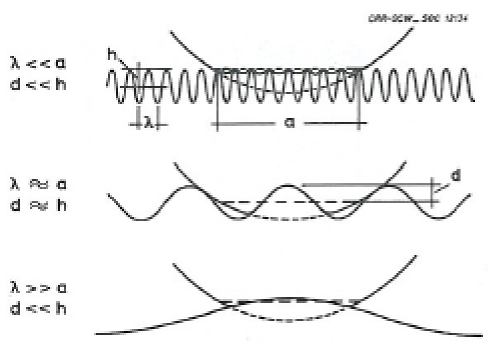
The T/10 specification incorporates the latest revisions of the UK Highways Agency's HD 28/04 standard in that it allows the IL to be modified (lower or higher) based upon other factors such as historical crash rates. The 2010 version still relies heavily on the polished stone value (PSV) equation to predict a required skid resistance level and an aggregate chip that will meet this requirement throughout the surfacing life, although, it does allow alternative predictive methods for the selection of aggregates where in-field performance can be demonstrated. The NZTA policy defines skid resistance for five main site categories of IL and TL, using equilibrium SCRIM coefficient (ESC) that is the SCRIM coefficient (SC) adjusted within and between year variations to standardise wet-road skidding crash risk across the network (Cook et al 2004).

2.7 Pavement surface texture

Each feature of the pavement surface performance is primarily or partially determined by the surface irregularities on different wavelength scales. Traditionally, surface irregularities can be classified into three main categories: *microtexture, macrotexture* and *longitudinal road roughness.* There has been recent research relating performance and pavement characteristics which has created another category for an unchecked range or irregularities. The new category is called megatexture with the wavelengths between 50mm and 500mm (Descornet 1989).

Figure 2.4 shows the deformation of a tyre travelling over various road profiles with irregularities of the same amplitude but different wavelengths. As surface irregularities increase it may bind to cause dynamic effects that generate vibrations inside the vehicle, noise due to contact between the tyres and pavement surface, and higher fuel consumption due to additional rolling resistance (Descornet 1989).

Figure 2.4 Deformation of tyre when rolling on a profile with a = length of tyre footprint, h = mean profile depth, λ = profile wavelength (Descornet 1989)



Micro-texture: λ < 0.5mm
Macro-texture: 0.5mm < λ < 50mm
Mega-texture: 50mm < λ < 500mm
Roughness: 0.5m < λ < 50 m

Figure 2.5 Performance features of road pavements against wavelength ranges of surface irregularities that influence them (Descornet 1989)

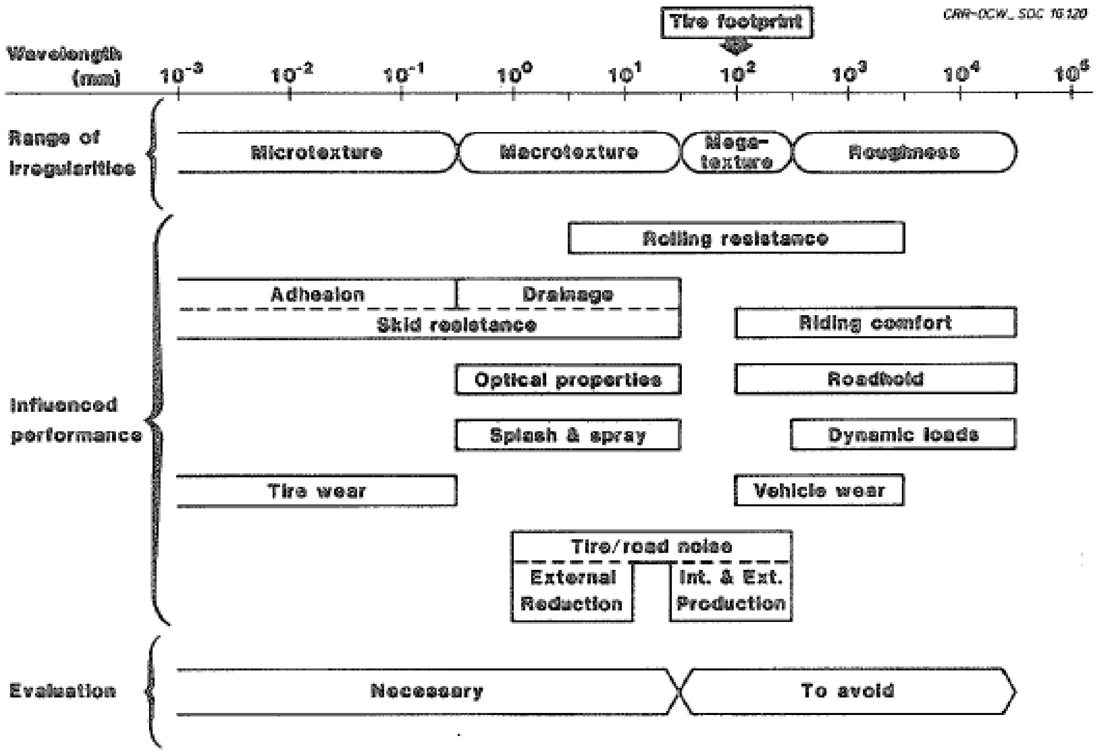


Figure 2.5 shows another wavelength diagram illustrating the range of wavelength of surface irregularities and the parameters that will be affected.

The irregularities of the pavement surface will subject the sprung and unsprung masses of the vehicle to vertical oscillations that cause the loads exerting onto the pavement to vary by 10% – 20%. The relationships between loads exerted and the damaging effect is non-linear and the damaging effect caused by the variation could be up to a 30% – 40% increase in the number of equivalent standard axles. This effect will lead to an accelerated deterioration of the pavement (Descornet 1989; de Pont and Pidwerbesky 2000).

2.7.1 Microtexture

Microtexture can be defined as any feature on a road stone that is smaller than the stone itself and ranges from roughness or harshness that can be seen by the naked eye down to roughness that can only be seen by an electronic microscope (Stevenson 1997). Microtexture determines the level of skid resistance by providing sliding contact resistance; this is the dominant factor in skid resistance in dry and low speed conditions (Wilson 2006). It also helps in wet conditions as microtexture breaks the film of water allowing some adhesion to the surface.

Aggregate without any harshness is considered to be undesirable and can easily cause loss-of-vehicle control leading to road crashes. The skid resistance on a chipseal road depends mainly on the microtexture of the aggregate. Microtexture can be worn away by high proportions of heavy commercial vehicles in the traffic mix, by vehicle tyres polishing the aggregate surface (Stevenson 1997).

Recent research in New Zealand has focused on understanding the mechanisms for the polishing of aggregates as this is important for road safety as well as for economics. Research studies have shown that skid resistance restoration and maintenance programmes can significantly reduce crashes each year in New Zealand. Therefore, reducing the rate of microtexture deterioration will result in significant road user social cost savings for roading authorities (Stevenson 1997).

The resistance to aggregate polishing has traditionally been measured in the laboratory in terms of the PSV test although more recently (both in New Zealand and the UK) the PSV test method has been shown to be a poor indicator of in-field skid resistance performance. Other methods have been developed including the Auckland Pavement Polishing Device and Wehner Schulze device which show promise in predicting the aggregate's ability to resist polishing (Wilson 2006; Wilson and Black 2008; Dunford 2008). The microtexture can be measured indirectly or directly by methods such as: 'the indirect friction measurements at low slip speeds' (eg side force routine investigation coefficient (SCRIM), the GripTester, RoAR and the DF Tester), 'subjective assessment using pictures' and 'directly by measurement using optic devices' (Do et al 2000).

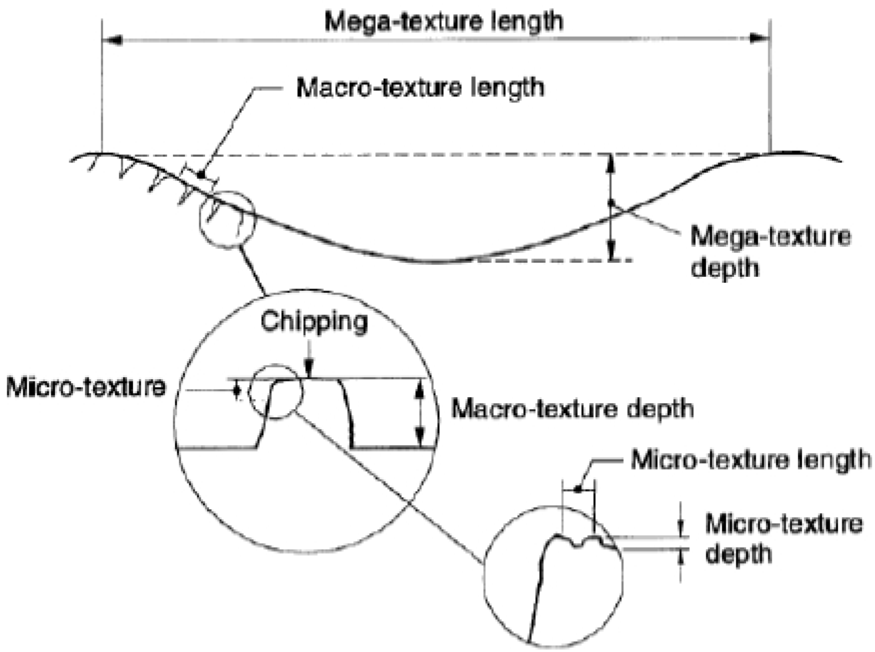
Previous research studies on measuring microtexture parameters are defined from the contact mechanisms between wet roads and vehicle tyres. The parameters defined are size, density and shape of the aggregate chips. The ability to resist polishing over time is more complex as it depends not only on the harshness of the aggregate (initial microtexture) but on the geological source properties, the grain sizes and the toughness of the aggregate minerals and the degree of cementation of the clastic matrix between minerals and grains (Wilson and Black 2009).

2.7.2 Macrotexture

The range of size for macrotexture is between 0.5mm and 10mm and macrotexture provides escape paths for the water and for hysteretic friction to develop, therefore a minimum macrotexture around 0.8mm is preferable at high speeds. Minimum macrotexture levels are appropriately specified in NZTA T/10 (2010).

Figure 2.6 shows the relationship between megatexture, macrotexture and microtexture. It also shows that macrotexture is determined by size, grade and spacing between the aggregate chips for asphalt layers and chipseal surfaces.

Figure 2.6 Relationship between megatexture, macrotexture and microtexture



2.7.3 Megatexture

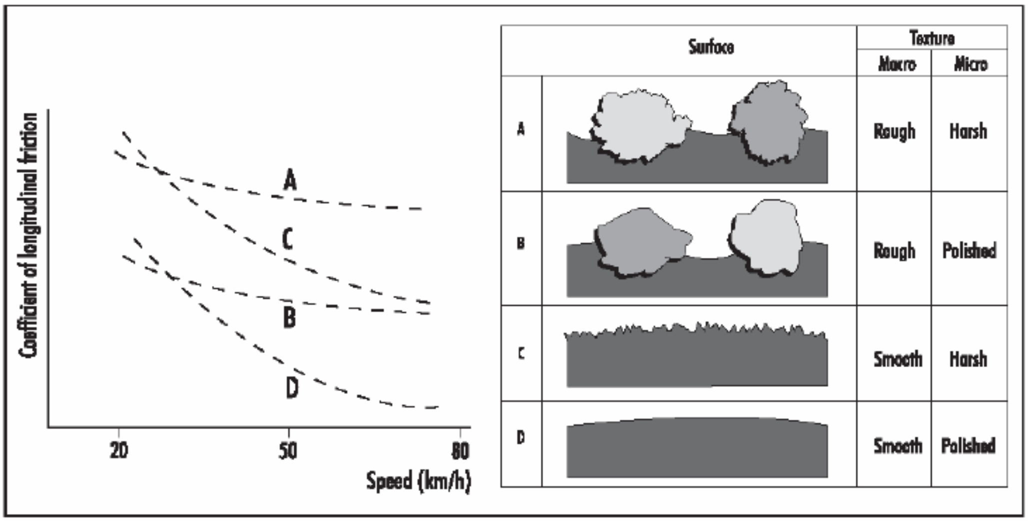
Previously methods and devices for measuring the various wavelength textures were limited. Megatexture is out of the normal measuring range and therefore could not be easily measured. However, with the new generation of contactless profilometers such as laser profilometers, megatexture is now easily measured (Descornet 1989). Thus, it is possible to optimise road pavement performance while meeting most of the requirements. Some surface wavelength variations must be present and yet others are undesirable.

Megatexture can be caused by deterioration of the road, examples of such deterioration are alligator cracks and spalling, small potholes, plucking and scabbling. However, it can also exist in newly built roads, as it can be a byproduct of the way macrotexture is achieved: ‘a pavement surface with two chip sizes, a chip bituminous’ [chip seal or surfacing dressing] ‘or cement concrete’ or ‘a stripping concrete’ (Descornet 1989). This megatexture can be a result of tyres contacting irregular areas of the surface due to a lack of homogeneity in the macrotexture.

2.7.4 Relationship between texture and speed

Microtexture determines the maximum skid resistance achievable at low speed and is the dominant factor in dry and low speed conditions. Macrotexture on the other hand establishes the rate of reduction in skid resistance as speed increases. As shown in figure 2.7, as the vehicle speed increases, the skid resistance the vehicle experiences will decrease in a negative exponential manner. If the macrotexture is rough, the rate of reduction in skid resistance due to speed will not be as rapid (Wilson 2006). It is therefore necessary to have harsh microtexture and rough macrotexture in high-speed areas whereas in low-speed areas it was previously thought that the road’s microtexture harshness was sufficient and macrotexture less important. This was especially so as high macrotexture also causes an increase in noise propagation and is therefore less desirable in urban residential areas (a significant adverse environmental factor).

Figure 2.7 Relationship between textures and speeds (PIARC World Road Association 2003)



However, Roe and Hartshorne (1998) conducted research with a locked-wheel skid tester over a range of speeds between 20 and 130km/h that concluded macrotexture still has an impact on skid resistance levels at speeds as low as 50km/h, which is similar to the situation shown in figure 2.7 (ie the difference between A and C or B and D at a speed of 50km/h respectively).

2.7.5 Macrotexture measurement

Continuous macrotexture measurements are now predominantly undertaken by laser texture measurements usually described as the mean profile depth (MPD). Alternatively the volumetric sand patch test method can be used to determine macrotexture at a specific location.

2.7.6 Road roughness

After the development of the International Roughness Index (IRI) the term 'roughness' has been typically used to refer to measuring the riding qualities of the surface itself as well as the IRI roughness measurement (Prozzi 2001). However, the riding quality is defined here as pavement performance as perceived by the user, while the roughness will be referred to as the longitudinal unevenness of the road surface as measured in terms of IRI or NAASRA counts/km.

The roughness of the pavement is one of the indicators of pavement structural performance as it directly affects the way in which pavements serve the road user. The pavement roughness may also affect the driving comfort (riding qualities), vehicle operating costs and safety (Hajek et al 1998). However, this should not be confused with the *harshness* or roughness relating to other texture ranges previously discussed.

2.7.7 International Roughness Index

According to ASTM E867-82A, roughness is defined as 'The deviations of the surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads and drainage.'

The IRI is an indicator and a measuring scale for pavement roughness based on the response of a standard motor vehicle to a single longitudinal profile of the road surface (Hajek et al 1998). IRI was originally developed in 1986 using the results collected from the International Road Roughness Experiment held in Brazil in 1982 (Sayers 1995).

The IRI has now become a well-recognised standard for measurement of pavement roughness globally. However, there is a wide variety of alternative devices used for measuring road profiles; these vary from hand-held dipsticks to high-speed profilers (Perera et al 1996), with each of the devices having their own measuring units. Hajek et al (1998) evaluated the consequences of switching unique device measurements to the universal IRI roughness measurements and this has since become an international standard and a commonly used pavement condition index as it offers many advantages to highway agencies.

The IRI is a geographically transferable and time-stable standard of measurement of road roughness, because it is directly measurable as the vertical accumulating displacement of a vehicle in m/km. The IRI is now used by most worldwide agencies and this has encouraged local transportation agencies to use it as well. The general use of the IRI has led to more equitable allocation of pavement maintenance funding as the pavement serviceability can now be directly compared between different areas within or between countries (Hajek et al 1998).

The use of the IRI requires the measurement of actual pavement profiles and is now most usually measured by laser profilographs. Knowledge of the pavement profile can also be used to help determine the source of pavement roughness as well as designing an effective maintenance and rehabilitation treatment programme (Hajek et al 1998).

2.7.8 Roughness measuring devices

Since the late 1950s, many road profiling devices and roughness indices have been developed and used to measure and quantify pavement performance. Yet, most of the systems fall into the category of response-type road roughness measuring systems (RTRRMS) meaning they measure the response of a specific mechanical device to pavement roughness (Hajek et al 1998). These systems usually required some conversion by developing transformation equations to the IRI. More recently, many transportation agencies have changed from using the response-type measurements to laser-based pavement profile measurements (laser profilographs) which form the basis of the IRI (Hajek et al 1998). In New Zealand, the RTRRMS were typically the National Association of Australian State Roading Authorities (NAASRA) roughness meter system prior to laser-based IRI methods. Most road agencies in New Zealand still report road roughness in terms of both NAASRA counts/km as well as the IRI.

2.8 Skid resistance measurement devices

There is a variety of skid testing equipment/methods available for skid resistance measurement that have been developed by different countries over the last 50 or more years. However, all of the commercially available test equipment essentially uses the same principle, that is, to measure the resistance of a rubber slider or tyre being forced to slide across a wetted road surface, under an applied load (Austroads 2005). The horizontal friction, traction or force resisting the sliding of the tyre or slider is measured, and the vertical load is either measured or assumed to be constant.

The frictional force measured depends upon the load that is applied, and therefore the coefficient of surface friction (*sfc*, *f* or μ) is the ratio of the frictional force resisting motion divided by the applied vertical load.

The range of wet skid resistance measuring techniques available is usually categorised into either:

- in-situ field road surface based devices, or
- laboratory-based measurement devices.

The in-situ road surface (on-site) devices can be further divided into two basic categories: those capable of measuring continuously over a long stretch of pavement surfacing (continuous friction measurement equipment devices) and those which measure skid resistance at specific sites (stationary devices). The continuous techniques can also be categorised as either 'angled test wheel methods' or the 'braked wheel method'. The braked wheel method can be further subdivided into locked-wheel, variable slip and fixed slip methods. The most common static devices can either be used at a specific point on a road surface or in the laboratory. These techniques all measure friction, although with different weightings on the variables that surface friction depends upon. Figure 2.8 shows a classification of the different skid resistance measurement methods and subsequent examples of commonly used measurement devices that all use some form of contact between rubber and the road surface.

Due to their significant differences, a direct comparison between the different device results is not generally possible. Measured friction is dependent on variable parameters such as slip ratio, testing speed, vertical load, tyre-rubber composition, tyre tread and inflation pressure and the amount of surface water present. Some of the systems detect the peak friction and some vary the slip in an attempt to operate around the peak friction level. Henry (2000) states that each method of measuring friction has advantages. The direct use of the values produced by one type of measurement relates to a different testing scenario. The locked wheel method simulates emergency braking without anti-lock brakes (ABS), the sideway-force method measures the ability to maintain control in curves, and the fixed slip and variable slip methods relate to braking with ABS. The variation of friction with slip speed is shown in figure 2.9.

Figure 2.8 Classification of skid resistance measuring contact methods with common examples

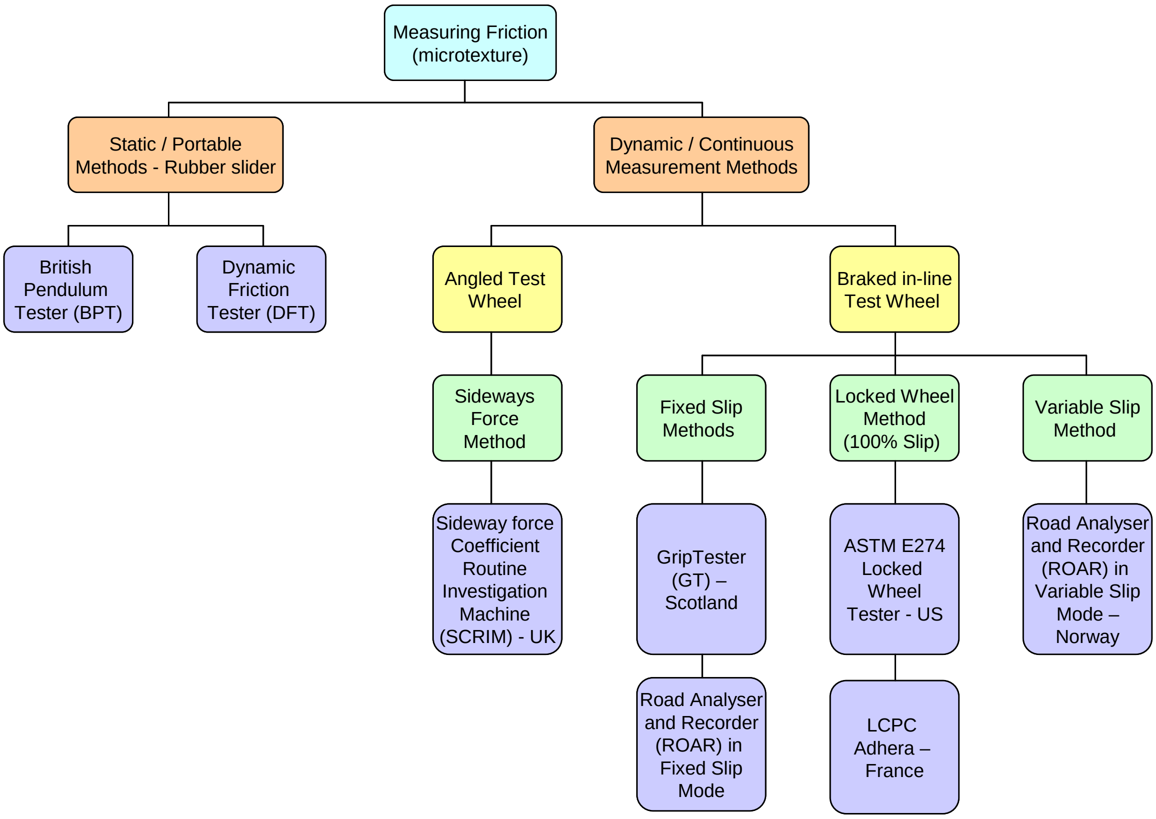
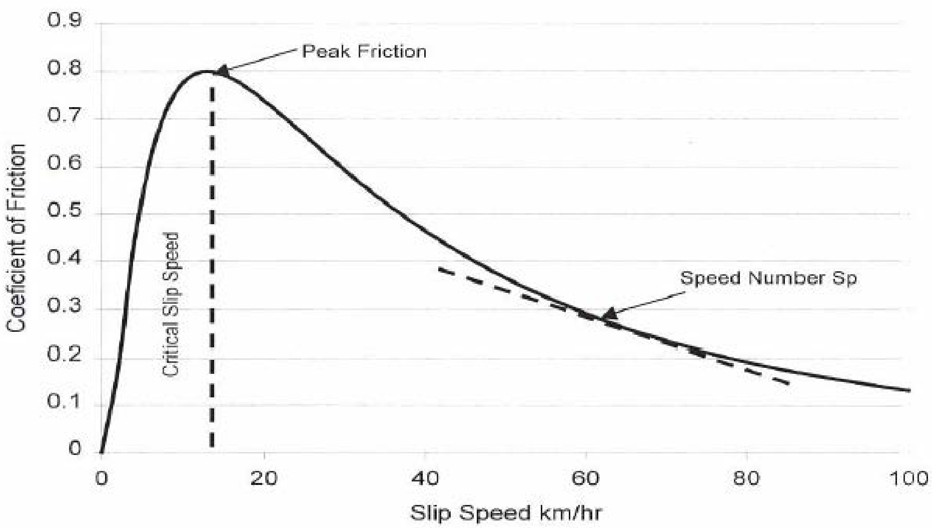


Figure 2.9 Relationship of slip speed to friction on a road surface (Austroads 2005)



The PIARC World Road Association International Harmonisation study (Wambold et al 1995) tested 51 various skid testing and texture devices (37 friction measurement and 14 texture measurement devices).

Commonly known devices used in New Zealand and Australia for measuring surface friction that can be correlated to microtexture measurements are SCRIM, GripTester, RoAR, DF Tester and the British Pendulum Tester. These devices, the methods and the harmonisation models are described in various publications, including Wilson (2006), and will therefore not be discussed in detail in this report. However, as the testing devices vary considerably by the factors listed above, combined with the variation in environmental factors that affect skid resistance (such as rainfall history, contaminants and seasonal factors), the harmonisation attempts have yet to produce reliable correlation equations from one device to another.

The objective of this research project was to determine the effect of road roughness on the GripTester device and this was therefore the skid testing device primarily used. The DF Tester was also used for field correlation exercises as this is a stationary device and independent of the effects of longitudinal road roughness. A laser profilograph from Pavement Management Services (PMS) was also used to measure actual site road roughness and macrotexture (MPD) measurements. The GripTester and DF Tester are described in more detail in appendices A and B.

2.8.1 GripTester device

The GripTester is categorised as a fixed slip braked in-line measuring device which is achieved by the means of a chain and sprocket transmission (Wilson 2006). The GripTester is shown in figure 2.10 and was developed by Findlay Irvine Limited in Scotland initially for skid resistance measurement of airport runways, but has since been used extensively internationally for road pavement skid resistance testing (Findlay Irvine 2005). The GripTester has one test wheel that is braked and two bogey driving wheels and weighs approximately 85kg.

Figure 2.10 GripTester

The GripTester operates using a single treadless rubber measuring test tyre of 254mm in diameter as specified in the ASTM (2008) to simulate the drag force and load force during skidding at approximately 15% of the survey speed (Wilson 2006). The results obtained from the GripTester are the ratio between the fraction of tractive drag force (F_d) and the load force (Q) and this coefficient of friction ratio is known as the grip number (GN) and can be defined as follows:

$$GN = \frac{F_d}{Q}$$

Skid resistance measuring devices usually simulate a CoF in wet conditions and therefore require water spraying onto the road surface in front of the measuring tyre (eg lowest skid resistance for road users). The GripTester measuring device is installed with a water delivery system that can be operated automatically or manually to provide a 0.25mm water film beneath the testing tyre relative to the test operating speed. The GripTester is portable and is handy for transportation; and it can be towed by any towing vehicle. The GripTester is described in more detail in appendix A.

2.8.2 DF Tester

The Dynamic Friction Tester (DF Tester), as shown in figures 2.11 and 2.12, is a static or stationary tester for measuring skid resistance. The device was designed in Japan by Nippo Sangyo Co and is used to measure the CoF on pavement surfaces.

Figure 2.11 DF Tester – front view

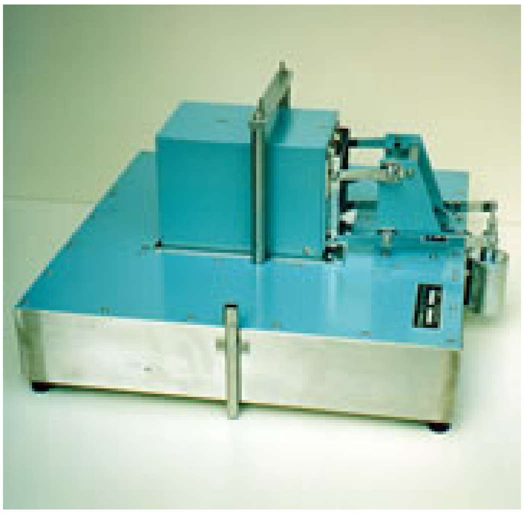


Figure 2.12 DF Tester – bottom view

The device has been recognised to be very stable and is used as a measuring reference in the recently published IFI ASTM International Standard (Wilson 2006). The DF Tester can be used in laboratory experiments as well as in the field. The output produced by the DF Tester is known as the coefficient of friction (μ). This can be represented as:

$$\mu = \frac{F}{Q}$$

Where μ is the coefficient of friction, F is the horizontal torque force and Q is the weight force on the rubber sliders that are attached to the DF tester. The DF Tester is described in more detail in appendix B.

2.8.3 Laser profilograph

The laser profilograph system used in this research is manufactured by Greenwood Engineering of Denmark and is a device that obtains up to three dimensional condition information of the pavement surface (Greenwood Engineering 2012). The laser profilograph system shown in figure 3.2 is attached to the PMS testing vehicle used in this research.

The profilograph system has up to 15 laser profile sensors used in conjunction with the advanced data acquisition and an inertial reference system. The laser profilograph can analyse the pavement in the longitudinal and transverse direction (cross-sectional shape) as well as recording and analysing the unevenness of pavement, pavement crossfall and grades, rutting and produce output in terms of the IRI and other indices such as NAASRA roughness indices. In addition, the laser profilograph system is capable of recording macrotexture of the pavement at normal driving speeds. The laser profilograph system is relatively lightweight and transferable and therefore can be mounted onto most vehicles with reasonably little effort (Greenwood Engineering 2012).

2.8.4 Summary of previous research

Little previous research was found on the effects of longitudinal road roughness on specific continuous skid resistance measurement device outputs such as the GripTester. A summary of applicable research is:

- Cenek et al (2003) and Wilson (2006) found skid testers (including the GripTester) have differing sensitivities to microtexture and macrotexture properties of road surfaces. The extension of this work implies road roughness may also affect skid resistance measurement, especially at higher test speeds.
- Cenek et al (2003) also found that the contribution of macrotexture to overall skid resistance is comparable to that of aggregate microtexture, suggesting that the components of hysteresis and adhesion on chip seal surfaces are similar in magnitude.

3 Experimental equipment

3.1 Introduction

The key equipment used to undertake this research was the GripTester, DF Tester, Sensotec accelerometer and the laser profilograph[1]. Each piece of equipment had its unique and important role in the study.

The GripTester was used to measure the continuous CoF of the pavement surfaces in order to quantify the effects of road roughness, surface textures and travelling speeds on skid resistance measurement. The DF Tester was employed in this study for the purpose of correlating the continuous skid resistance measurement obtained with the GripTester irrespective of speed and longitudinal road roughness effects. The Sensotec Accelerometers were mounted on the GripTester to monitor the vertical movements (due to road roughness) experienced by the GripTester device while travelling across the test sections at various testing speeds. The laser profilograph was used to measure the longitudinal profile (road roughness), and macrotexture, crossfall and the geometric curvature of each site prior to undertaking actual field experiments.

3.2 GripTester data collection

The GripTester shown in figure 2.10 is an instrument that measures surface friction using the fixed slip principle. The GripTester consists of three wheels assembled like that of a tricycle. The surface friction is measured by the front wheel (also known as the braked wheel). The measuring wheel is fitted with a smooth tyre made to ASTM specification and is mounted on an axle mechanism aimed to measure both horizontal drag and vertical load.

The GripTester has dimensions of 1010mm X 790mm X 510mm and weighs 85kg and therefore it is relatively convenient and portable for towing in a trailer compared with other continuous surface friction testers. The horizontal drag and vertical load experienced by the measuring tyre is transmitted to the axle through a transmission chain, the total up and down movement of the transmission chain must not be less than 17mm or greater than 22mm (refer to appendix A for more details).

3.2.1 Standard test procedures

When travelling over the test surface, the horizontal drag and vertical load measurements are continuously calculated and transmitted to a data collection computer usually situated in the towing vehicle. The survey speed is also calculated and stored in the computer for each 1m or 10m averaged friction reading (depending upon operating mode chosen).

Proprietary GripTester software, Airbase was installed on a PC computer with the Windows operating system and a USB port. During a testing survey, the computer displays the average friction reading in 10m length intervals. The data is transmitted from the measuring wheel and axle through the data cable to the PC computer. Data is stored directly into a Microsoft Access database for convenient data processing.

The Airbase Windows software allows users to perform all the functions associated with collecting and reporting runway friction data. It also allows collection and reporting of friction data on taxiways, aprons and roads and is useful for short research sections but not for road network surveys where it is better to use the Roadbase software.

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[1] Acknowledgement is given to Pavement Management Services who undertook the macrotexture surveys using their laser profilograph

The GripTester can perform two types of friction testing:

1 Operational friction testing

2 Maintenance friction testing.

Operational friction testing enables surface friction testing in all kinds of conditions: wet, misty and even in snow conditions and does not deliver a water film depth as part of the testing procedure. Previous research has shown that many road accidents occur during wet and misty conditions, especially when snow and water have accumulated on the road surface decreasing the skid resistance of the pavement surface and also when hydroplaning conditions prevail. Operational friction testing enables researchers to carry out skid testing during winter seasons, when surfaces are entirely or partially accumulated with ice, water snow or slush. However, when considering such tests, operators should take into consideration that friction surveys carried out on adjacent dry surfaces do not give useful information. Friction surveys carried out on surfaces that are heavily accumulated with standing water or slush will also not give reliable information as a constant water depth is not ensured. Similarly data collected from standing water deeper than 1mm or slush deeper than 3mm will not give accurate skid resistance results for the road surface-vehicle interface due to the dynamic drag of the wedge of water in front of the tyre and the separation from the road surface.

Maintenance friction testing measures the surface friction of the road surface in standard conditions. Water is distributed to the measuring wheel-road interface with a specified thickness of water film (usually 0.25mm) to simulate wet skid resistance conditions and a standard test speed of 50km/h towing speed. Maintenance friction testing is a necessary procedure for any advanced pavement management system and the information it provides allows traffic and transportation engineers to schedule an effective and efficient maintenance programme. This research was based on this type of survey which is most commonly used for measuring the surface friction under standard wet road surface conditions. This is undertaken in order for traffic and highway engineers to manage and design the most appropriate maintenance treatments and practices for the particular road section as well as giving guidance on establishing the appropriate design objectives of new road surfaces, maintenance planning and minimum friction levels for the pavement surfaces. Airport testing commonly uses water depths of up to 1.0mm and standard test speeds of 65 to 90km/h towing speeds.

In congested road conditions and low road speed environments (especially in urban areas) lower towing speeds are often required as it is difficult to maintain a constant 50km/h speed. Higher speed surveys are usually only undertaken on roads for research purposes, ie to determine the effect of other variables (including macrotexture).

3.2.2 Calibration procedures

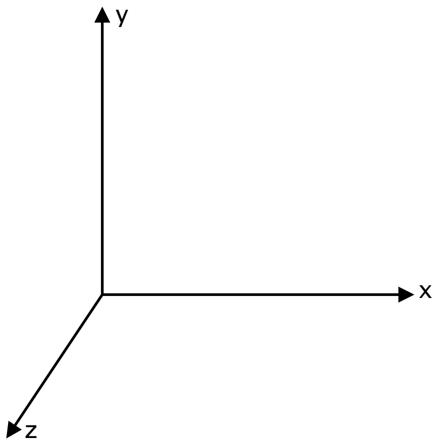
The GripTester has standard calibration procedures and daily/monthly maintenance checks to help ensure data quality integrity is obtained from the testing device. These procedures developed by Findlay Irvine Ltd were followed as standard research operating practices that included checking the charge of the two 12 volt batteries, the operation of running wheels, the measuring wheel surface and depth of rubber, the alignment of the axle, the transmission and chain sprocket system including chain tension and lubrication, the suspension system, the horizontal drag and vertical load cell calibration (load zero, load gain, drag zero, drag gain).

The GripTester also calculates the distance travelled according to the rotation of its drive wheels. As the distance per rotation varies slightly with the wearing of the tyre rubber it is important to calibrate the distance per rotation (DPR) with a known straight distance. The DPR calibration was undertaken at the beginning of the research project by calibrating the distance with a known 1km section.

3.3 Sensotec accelerometer

An axial accelerometer was used in this research in order to measure the vertical acceleration experienced by the GripTester during testing due to the longitudinal unevenness (road roughness) of the road surface. An axial accelerometer is a measuring device, which is able to measure the amplitude of the movement in up to three-dimensions (x, y and z) (refer to figure 3.1).

Figure 3.1 Three-dimensional axis



3.3.1 Basic accelerometer theory

Accelerometers are measured in terms of accelerations; this is calculated based on the combination of Newton's third law and Hooke's law of spring action. Newton's third law states that if a force is exerted on a mass, then the mass will experience acceleration. This can be represented by the following equation:

$$F = ma$$

Where

F is the force exerted on the mass (measured in Newton N)

m is the mass (measured in kilograms kg)

a is the acceleration due to the force (measured in metres per second squared ms^{-2}).

Likewise, Hooke's law states that if a force is applied on a spring with a certain spring constant, the spring is extended from its equilibrium position for a certain distance. This can be represented by the following equation: -

$$F = k\Delta x$$

Where

F is the force applied to the spring (measured in Newton N)

k is the spring constant (measured in force per unit length Nm^{-1})

Δx is the distance extended due to the force applied.

By substitution, then:

$$ma = k\Delta x$$

$$a = \frac{k}{m}\Delta x$$

3.3.2 Sensotec low frequency accelerometer

The accelerometer used in this research was designed by *Honeywell Sensotec* and is a low frequency accelerometer. The low frequency accelerometer is designed with low impedance strain gauges. This is an important feature of the experiment, as the impedance of the cables will be affected by the impedance of the accelerometer, thus, lowering the impedance level will increase the accuracy of the accelerometer output. Furthermore, a low frequency accelerometer will minimise the sensitivity to external 'noise'. Results of the accelerometer calibration are shown in appendix B.

3.4 Dynamic Friction Tester

The results obtained from the DF Tester in this research were used to correlate with the GripTester measurements and to identify if the GripTester measurements were affected by higher roughness in comparison with the DF Tester results which are independent of longitudinal unevenness or texture ranges. The DF Tester was recently selected as a standard reference for the correlation of skid resistance devices by ASTM International as they recognised its consistency and ability to produce repeatable measurements for time and temperature. The precision of the DF Tester has demonstrated a range of standard deviation of 0.044 (at 30km/h) to 0.038 (at 60km/h) for eight measurements on the same testing surface.

3.5 Laser profilograph

The laser profilograph as shown in figure 3.2 was designed and developed by Greenwood Engineering in Denmark. At present, there is one laser profilograph in New Zealand which is owned and operated by PMS in Hamilton. There is also the SCRIM+ device that comes out to New Zealand annually from WDM UK Ltd to survey the New Zealand state highway network and some local territorial road networks.

Figure 3.2 Laser profilograph owned by Pavement Management Services

The front laser beam shown in figure 3.2 can configure up to 25 lasers (the PMS laser profilograph has 13). Each laser beam collects measurements from the pavement to the beam at a sample rate of 16kHz and the travelled distance is measured with a resolution rate of 20,000 samples per wheel revolution. The recorded signals from each laser sensor are stored separately for the convenience of further analysis. The power supply for the laser profilograph, signal controller and the computer systems is located in the vehicle cabin.

The profilograph can collect both longitudinal and transverse profiles, evenness, roughness (both in terms of the IRI and NAASRA counts), pavement crossfall and rutting, macrotexture (in terms of mean profile depth), geometrical grading and differential global processing system (GPS) locations. High accuracy of results can be generated by the laser profilograph as its laser sensors allow three-dimensional measurements.

Most pavement measurement devices have limited operating speeds, but the laser profilograph enables testing to be operated from 20 to 150km/h and results generated can also be stored at a maximum rate of 5mm distance intervals. Each research test section was surveyed by the PMS laser profilograph for the determination of road roughness (IRI and NAASRA and macrotexture (MPD)).

4 Experimental methodology

4.1 Introduction

This section presents the procedures and descriptions for determining the test sites and the methodology adopted in the research. The three main pieces of equipment used were the GripTester, the DF Tester and a vertical accelerometer discussed previously. The first section concentrates on the explanation of the methodologies and criteria for site locations and selection. The last two sections describe the procedures for testing with the skid resistance measuring device and include the operation of the software programme.

4.2 Objectives of the research

The main objectives of this research study were to investigate the output errors (or variants) produced by the GripTester due to different road roughness and surface texture properties as well as to assign the most suitable test speed for testing with the GripTester device.

4.3 Test site selection procedures

A test site selection matrix with five different NAASRA roughness bands (<69.1, 69.1–85.0, 85.0–103.2, 103.2–116.0 and >116.0 counts/km) and three surface macrotexture ranges (<1.09mm, 1.10–1.69mm, and >1.7mm) was developed (refer to table 4.1) with sites that populated each matrix cell. The road roughness was measured in NAASRA counts per kilometre as this is the traditional roughness measurement technique used in Australia and New Zealand and is still the most commonly understood roughness measure. Some agencies use the International IRI rather than NAASRA, and an approximate equivalent value of IRI from the NAASRA roughness value can be derived by the following equation: -

$$IRI = \frac{NAASRA + 1.3}{26.5}$$

Table 4.1 Site selection matrix

Roughness level (NAASRA counts/km)	Texture level (mm)		
	<1.09	1.10–1.69	>1.7
<69.1			
69.1–85.0			
85.0–103.2			
103.2–116.0			
>116.0			

The NAASRA roughness is determined by a mathematical model of two longitudinal profiles measured simultaneously. The model is referred to as a half-car model having a dynamic response equivalent to a standard vehicle.

As noted previously, texture wavelengths are classified as microtexture (texture <0.5mm), macrotexture (texture from 0.5mm–50mm), megatexture (texture from 50–500mm) and longitudinal unevenness or road roughness (from 0.50m–50m). This research attempted to determine whether there was any significant relationship between skid resistance measurements obtained from the GripTester and road roughness and to a lesser extent macrotexture. Macrotexture used in this study is characterised by the MPD, which is a measuring technique to determine the average texture depth (measured in terms of millimetres) based on the readings from high-speed laser driven data collection equipment such as the laser profilograph.

Most of the selected road sites were chosen in the Franklin District, south of Auckland city as it was more likely roads with the range of roughness required to populate the site matrix could be located close together; traffic congestion was less and the roads would allow higher than typical urban operating speeds (>50km/h). Roads in the Franklin District area are managed and monitored under the supervision of Opus Consultants who maintain the area's road assessment and maintenance management (RAMM) road inventory and condition database. Most road controlling authorities (RCAs) in New Zealand use the RAMM database to record all new, maintenance, repair and replacement activities for each road type within their geographic area. This database assists in the preparation of maintenance schedules for each particular road. The RAMM database was used to help determine possible road test sections for more detailed study. The RAMM database supplied the following information as required by this study (refer to table 4.2):

- road name
- start and end linear referencing of the sections
- directions
- roughness
- texture
- surface types
- age of pavement.

4.3.1 Data capture setup

Nineteen sites were initially selected from the RAMM database. The site features are shown in table 4.2 (sections A – E). However, during the testing period, Franklin District Council resealed test sections E1 – E3 and therefore the road roughness and surface textures for those sites were no longer applicable (as shown in table 4.2). Hence, three more sites were selected within the Waipa District Council area with similar properties to sections E1 – E3.

Sites selected were approximately 150m to 300m in length, geometrically level and straight. The sites were also selected on the basis of relatively homogenous roughness and texture ranges throughout the sections to eliminate other possible effects that could alter the results produced by the GripTester. The age of the pavement sections was also taken into consideration, as pavements newer than two years can still be experiencing initial aggregate polishing (in a typically negative exponential manner) and could therefore be less stable over time and after multiple test runs. Previous research (Oliver et al 1988; Henry 2000; and Cenek et al 1999) indicated that skid resistance of road surfaces would reach an equilibrium level state from six months to approximately seven years after construction of the surface, depending on aggregate type, annual average daily traffic volume (AADT) and traffic composition levels. Thereafter, depending on climatic conditions, the skid resistance measurements would vary by seasonal and short-term effects. From experience, an equilibrium level is commonly reached within the first two years on chip sealed surfaces in New Zealand that have at least 2000 AADT.

The final 19 sites (after three had been eliminated) were chosen according to the criteria mentioned above and their road roughness and texture properties. The selection of sites provided at least two similar sites for each roughness/texture range. The sites selected are summarised in table 4.2.

4.3.2 Site locations

The Franklin District Area consists of primarily rural roads with a wide variety of roughness and texture ranges and it is also reasonably close to the University of Auckland. There was a preference to test roads in rural areas because of lower AADT flows. The testing speed for the GripTester on this research project ranged from 30km/h to 90km/h. Low-speed testing tends to hold up traffic whereas a clear road is required for testing at higher speeds to obtain results that are more consistent. Four GripTester testing speeds: 30km/h, 50km/h, 70km/h and 90km/h were chosen for the test runs.

The sites were finalised and located in the suburbs of Glenbrook, Waiuku, Pukekohe and Buckland being mostly ‘rural’ in nature, whereas the sites located in the Pukekohe area are categorised as ‘urban’.

Table 4.2 Finalised site matrix

Section ID	Roughness (counts/km)	MPD texture (mm)	Road name	Carriageway start	Carriageway end	Total distance (m)	Direction	Surface type	Age (yr)	Speed (km/h)
A1	50–70	>1.7	Glenbrook Rd	13,200	13,400	200	Left	2CHIP	2	100
A2	90–110	>1.7	Glenbrook Rd	14,100	14,306	206	Left	2CHIP	2	100
A3	90–110	1.1 to 1.7	Glenbrook-Waiuku Rd	1700	1900	200	Left	2CHIP	1	100
A4	90–110	1.1 to 1.7	Glenbrook-Waiuku Rd	3100	3300	200	Left	1CHIP (CHIPSEAL 1COAT)	10	100
B1	70–90	>1.7	Waiuku Rd	8400	8600	200	Right	2CHIP	1	100
B2	90–110	>1.7	Waiuku Rd	8500	8700	200	Left	2CHIP	1	100
B3	70–90	>1.7	Waiuku Rd	7100	7300	200	Left	1CHIP (CHIPSEAL 1COAT)	14	100
C1	50–70	<1.1	Manukau Rd	500	700	200	Left	AC	4	70
C2	50–70	<1.1	Manukau Rd	1300	1560	260	Right	AC	6	70
C3	70–90	<1.1	Massey Ave	200	380	180	Right	AC	2	50
D1	50–70	>1.7	Buckland Rd	6700	6900	200	Left	1CHIP (CHIPSEAL 1COAT)	9	100
D2	50–70	1.1 to 1.7	George St	1400	1600	200	Left	1CHIP (CHIPSEAL 1COAT)	9	50
D3	70–90	1.1 to 1.7	River Rd	100	300	200	Left	2CHIP (CHIPSEAL 2COAT), 1CHIP(CHIPSEAL 1COAT)	4–7 years	100
D4	50–70	1.1 to 1.7	River Rd	500	700	200	Right	2CHIP	5	100
D5	70–90	1.1 to 1.7	George St	1600	1800	200	Right	1CHIP (CHIPSEAL 1COAT)	9	70
D6	70–90	<1.1	Buckland Rd	7800	8000	200	Right	2CHIP (CHIPSEAL 2COAT)	1	50
E1	110–130		George St	500	700	200	Right	500-700 SLURRY	10	50
E2	>130		George St	500	700	200	Left	SLURRY	10	50
E3	110–130		George St	1100	1300	200	Left	SLURRY	10	50
F1	110–130	>1.7	Rukuhia Rd	3250	3450	200	Right	1CHIP (CHIPSEAL 1COAT)		100
F2	>130	>1.7	Rukuhia Rd	6350	6560	200	Right	1CHIP (CHIPSEAL 1COAT)		100
F3	>130	>1.7	Rukuhia Rd	6650	6870	200	Right	1CHIP (CHIPSEAL 1COAT)		100

4.3.3 Site visit

After selecting suitable sites from the RAMM database, site visits were undertaken to confirm locations, pavement condition and testing criteria. For each potential site, pavement condition distresses such as potholes, large cracks and flushing were noted as these could possibly affect the output produced by the GripTester.

Start and end points for each test section were then determined. The testing start point was located approximately 50m before the actual start of the selected section; likewise, the end point was located around 50m after the actual end of the section. Temporary spray paint markings were used to mark out the test start and end points on the road surface and/or on clearly marked nearby features.

Testing with the GripTester was mostly carried out with at least three test runs for each site. It was therefore important to locate wide and safe turning areas for the towing vehicle to undertake a safe U-turn vehicle manoeuvre. Furthermore, the GripTester, although reasonably robust, needs careful handling and should not be run up onto kerbs etc.

4.4 Procedures for testing with the GripTester

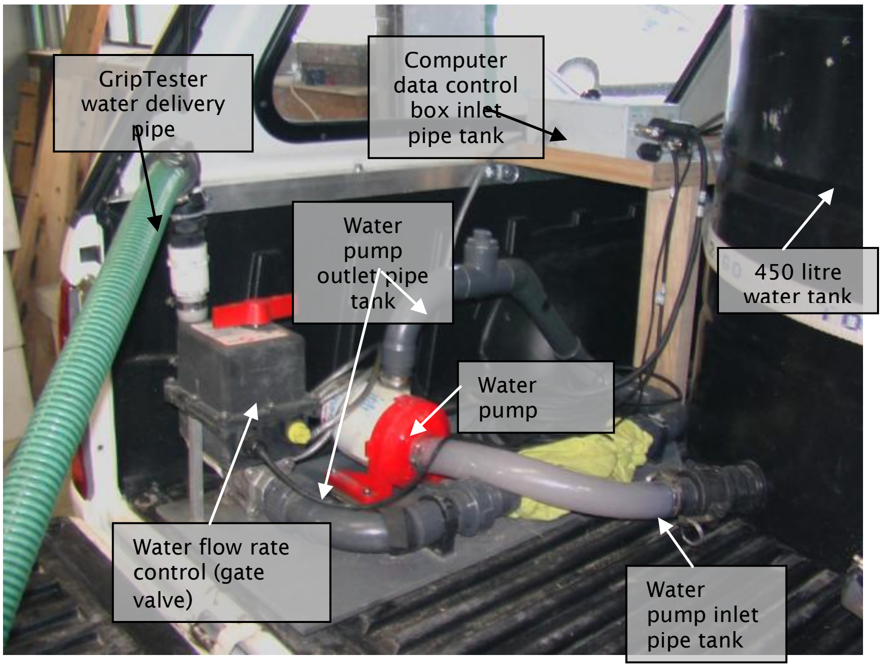
4.4.1 GripTester setup

The procedures for setting up the GripTester on site and after equipment calibration are relatively simple. Additional equipment required to be fitted onto the GripTester prior to testing are the water distribution system, tow bar, safety chains, data transmission cables and computer setup.

Since skid resistance is lowest in wet road conditions the coefficient of friction obtained by the GripTester is normally tested in controlled wet road surface conditions. The University of Auckland GripTester (GT281) utilises an automatic watering system and software that automatically modifies the water pump flow rate based on the testing speed to keep a constant water depth at the tyre–road surface interface. As the GripTester uses relatively large amounts of water during testing, a 450 litre water tank has been installed at the back of the tow vehicle. The GripTester is towed behind the test vehicle that houses a water bag/container and associated automatic pump control equipment (see figure 4.1).

The GripTester software commonly used is Airbase; however, in this research a modified version of the software was used in conjunction with the software Roadbase. In both cases, the user can either manually select the flow of water measured in terms of litres per second, or pre-select the depth of water film (measured in terms of millimetres) and the software automatically modifies the water pump flow rate to keep a constant water depth at the tyre–road surface interface. In this research project, a standard water film depth of 0.25mm was selected.

Figure 4.1 GripTester automatic watering system and water storage tank in back of testing vehicle



The GripTester has an internal computerised programme, which continuously records the resisting force experienced by the measuring wheel during testing and the vertical load. It also monitors/records the testing velocity, the amount of water introduced to the axle and the running distance of the test section. The GripTester computerised control module is shown in figure 4.2.

During testing, all data is constantly transmitted to the laptop computer via the data transmission cable. The cable is connected from the front of the GripTester to the laptop computer located in the testing vehicle.

Figure 4.2 GripTester control panel

4.4.2 Data output

Two files are produced from each testing run with the Roadbase software. Results collected from the GripTester are stored in a database spreadsheet (.dat) file. The surface friction related results are then extracted from the database spreadsheet and combined with header files to provide a complete database for the test results.

The Airport software stores all testing results for each testing section in one data format spreadsheet and only the database spreadsheet file is created. The Airport software continually stores multiple data runs to one database spreadsheet until the testing is terminated.

4.4.3 Testing procedures with the GripTester

Prior to testing, several data checks are required. These include:

- water checks including both the amount of water in the tank and that the pump system is operating correctly
- ambient and surface temperatures prior to (and after) test runs.

After the GripTester has been setup and the Airport or Roadbase software has been launched, testing commences by selecting 'GripTester survey' in the software program and a minimum manual water flow rate of at least 1 litre/second to activate the pump system.

Pressing the Start button of the software program when the vehicle passes the assigned starting point for the section activates the recording of the skid resistance survey data. Triggering the Marker button (which can be triggered more than once in each test run) allows the software program to record a particular location by linear distance recording while testing continues. This enables a log of additional survey information (eg the beginning and/or end of a flushed bitumen road surface section) to track back to the exact position of interest when analysing the results. This function is used to locate potholes, cracks, change of seals and other factors that might affect the homogenous properties of the road surfaces. When the testing vehicle travels past the assigned ending point of the testing section, an End button is activated to terminate the GripTester's data collection test run survey. The software automatically switches back to the main information window, to allow the data to be saved. 'Start similar survey' is used to commence another testing run survey with identical location, testing length, film depth and similar atmospheric and surface temperature; the only information needing to be changed is the specific testing comments header. This function is used for repeating testing runs for the test section.

Three test runs were completed using the Roadbase software which collects and stores CoF data every 1m. A fourth test run used the Airport software which collects a CoF every 1m but stores the result as a rolling 10m average. The data sets collected by these two systems could later be compared. Three repetitive Roadbase test runs were undertaken to ensure the GripTester produced repeatable results.

4.5 Procedures for testing with the Dynamic Friction Tester

4.5.1 Testing points

A minimum of three specific test location points for the DF Tester were chosen in the line of the left wheel path, aligning with the GripTester section surveys. These locations were representative of the chosen homogeneous sections in terms of texture and roughness and furthermore allowed the consideration of a correlation equation to be developed for varying textures between the GripTester and DF Tester devices for typical New Zealand road surfaces. For a full description of this equipment see appendices A and B.

4.5.2 Setup of the DF Tester

The DF Tester is often used for laboratory experiments but it is also well suited for field testing because of its portability. The equipment setup for field testing that includes the need for water and power to run the

DF Tester is more complex than in laboratory experiments as the operating procedures require full traffic control measures (ie temporarily closing down the traffic lane).

The DF Tester controller sends and receives signals to and from the DF Tester. The CoF (μ) and corresponding rotational speed results generated from a DF Tester test are transmitted back to the controller for storage. Data is stored in a database (.dat) spreadsheet format with skid resistance output for every 0.1km/h.

4.5.3 Traffic control

The DF Tester requires the operator to undertake a stationary test from a 'live' traffic environment. Acknowledgement is given to Franklin District Council (FDC), OPUS International Consultants (the network management operators in FDC) and PMS who all contributed in providing safe temporary traffic control on this research project.

4.5.4 DF Tester procedures

After appropriate traffic control was in place, the DF Tester and associated equipment were set up at the chosen location. First, the test location identifier and then the desired testing speed and number of proposed test runs were inserted into the DF controller. Since the DF Tester was designed for use on lower macrotexture than is typical of New Zealand chip seal surfaces, the tests were undertaken at a lower initial test speed of 60km/h. Higher speeds can cause damage to the synthetic rubbers of the DF Tester device and/or cause the device to move from the test position during a test; both outcomes are undesirable.

After assigning all required information and the execution signal triggered from the DF controller's monitor, the DF Tester begins rotating in the horizontal plane from a stationary position to the speed assigned by the operator. The horizontal plate is then lowered to the surface level where the synthetic rubbers contact the road surface. As the speed of the rotating disk is retarded by the friction developed between the rubber slider – road surface interface, the resultant forces are measured at the corresponding speed for every 0.1km/h interval and transmitted to the controller. A graphical output is shown on the controller's monitor and the CoF values are displayed for 20km/h and 40km/h. Data is stored at the operator's discretion.

5 Results and discussions

5.1 Introduction

Raw data obtained from the GripTester and the DF Tester all required further data processing before the information could be analysed. After the data was categorised, results were plotted into graphical outputs and distinguishable characteristics were identified. An example of the raw data processing and data plots for section A1, Glenbrook Rd, is shown in appendix D and the processed data results are displayed in appendix E.

This section focuses on tying together the different parameters that determine the grip number and attempts to establish any relationships or trends among the variables.

5.2 Grip number variability – part 1

5.2.1 Data group division

The 19 test sections (refer to table 4.2) were further divided into three levels of texture and five levels of road roughness for analysis purposes. The boundaries for these levels are shown in table 5.1. This enabled a comparison and determination if the degree of road roughness had any effect on the degree of macrotexture and other variables such as speed of the test and the GN output. Table 5.1 shows the level determinants for texture (Tx) and road roughness (RR):

Table 5.1 Limits to establish the level of texture and road roughness

Texture level	Texture depth, MDP (mm)
Low	<1.09
Medium	1.10 <Tx <1.69
High	>1.7

Roughness level	NAASRA counts/km
1	<69.1
2	69.1<RR <85.0
3	85.0<RR <103.2
4	103.2<RR <116.0
5	>116.0

Table 5.2 shows the possible combinations of roughness and texture levels; a blank cell represents a combination that is not possible with the data that was obtained. It can be seen that the data has been shortlisted into 10 cell groups. Within the individual groups, testing speeds and GN can be compared as those sections have similar roughness and texture variables. In addition, we can compare and evaluate how the GN may change as we move onto a higher texture area or rougher section of road. The groups will later be identified and referred to their numerical roughness level plus L, M or H (representing low, medium or high texture level)

Table 5.2 Matrix of testing sections sorted and grouped in terms of their texture and roughness

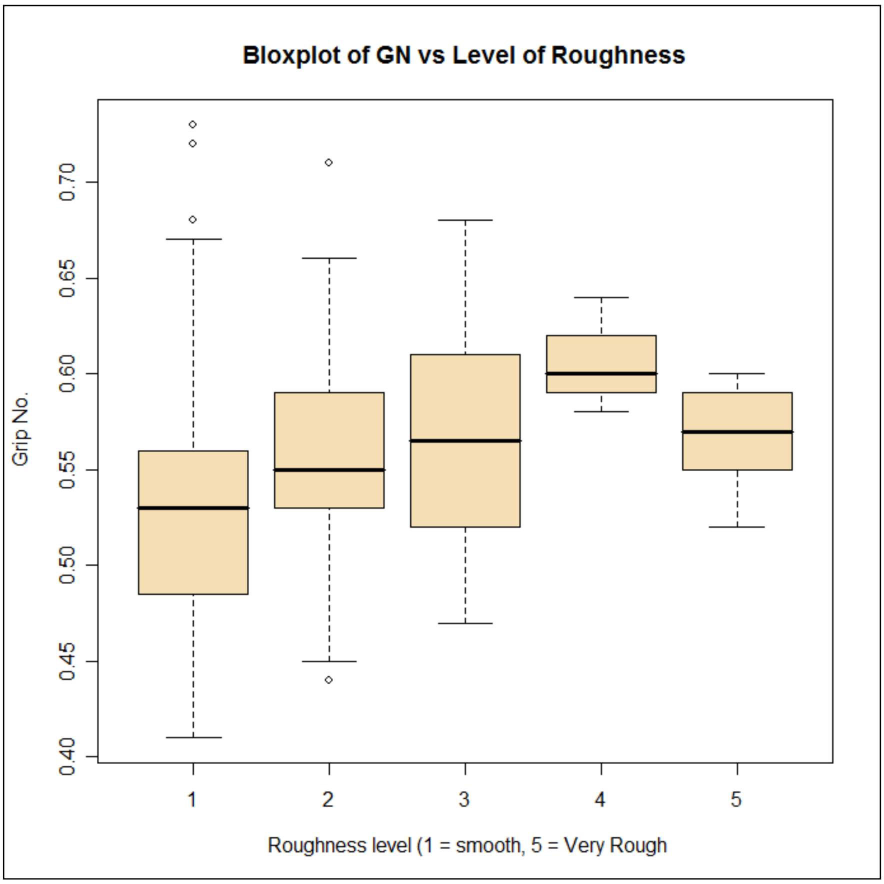
Roughness level	Texture level		
	Low	Medium	High
1 = smooth	D4,D6	C2,D1,D5	A1
2	C1,C3	D2,D3	B1,B3
3		A2,A4	B2,A3
4			F1
5 = rough			F2,F3

The factors GN, test speeds, road roughness and macrotexture were plotted against each other to ascertain if any linear relationships could be formed between them. The primary link that this research sought was to see if there was a relationship between road roughness and GN but also if the GN was dependent on the GripTester test speed and macrotexture.

5.2.2 Statistical analysis of the data

The data was analysed using the University of Auckland 'R' software language and environment for statistical computing and graphics (Department of Statistics, University of Auckland 2010). Figure 5.1 shows a box plot of GN and roughness levels. An analysis of variance was applied to the data. This showed that the mean (not median) of the GNs across the roughness bands was not statistically different in each GN (discussed later in appendix E).

Figure 5.1 Box plot of GN against roughness level



The plot seems to demonstrate a generally steady increase in the mean GN as the road roughness levels increase from smooth to rough. The GN around roughness band 4 appears higher than the other bands but could be misleading as only three measurements constitute that roughness level. Data variation (range) could be seen as decreasing the road roughness; however, this could be explained by the lower number of measurements for roughness levels 3 and 4. The data appears to be normal, other than roughness band 2 being slightly left skewed.

The panel plot shown in figure 5.2 was used to observe if any patterns formed and linear relationships derived. As highlighted, the four most relevant panels are GN vs RR, GN vs Tx, GN vs speed and Tx vs RR. The plots indicate the GN could have an inverse relationship with speed (although the data spread shows that it is not strong). There is no noticeable relationship with texture or road roughness. Texture shows to be positively correlated with road roughness.

Figure 5.2 Panel plot of grip number (GN) against road roughness (RR), texture (Tx) and test speed

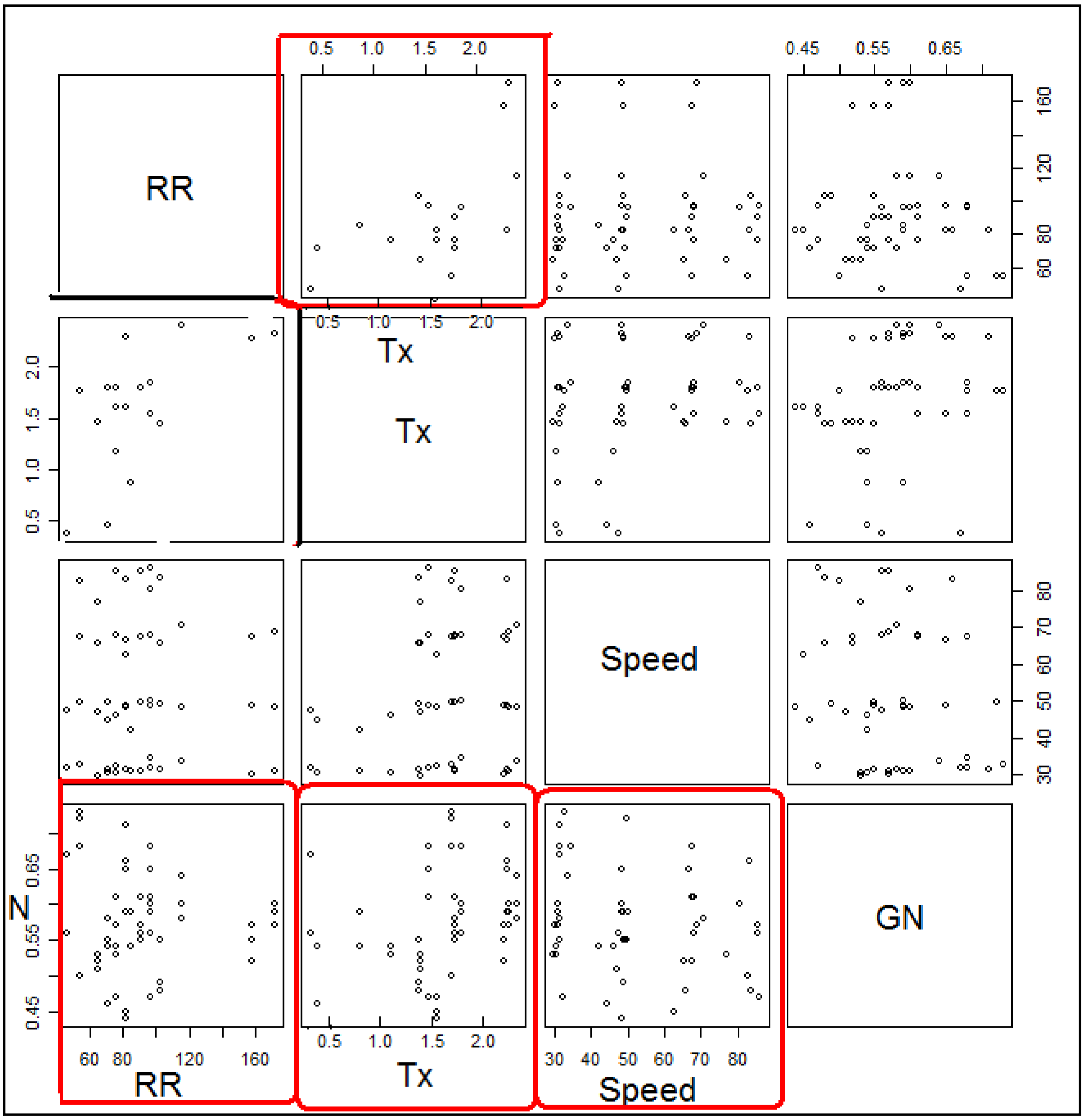


Table 5.3 shows a covariance matrix of how the four variables move in relation to each other. The matrix confirms that the GN does have a negative relationship to speed. The 0.39 between the GN and texture indicates that the GN has a positive relationship with texture even though it was not so obvious from the plots. Nevertheless, this is expected as higher macrotexture would give greater friction, thus a higher GN would result. The 0.61 covariance between roughness and texture highlights the positive relationship between the two variables (also refer to figure 5.3). However, this could be caused by the sampling methodology rather than from a real relationship; the sections with high road roughness were located in rural areas, which relates to the higher macrotexture from the chip seal surfacing in those areas.

Table 5.3 Covariance matrix

	RR	Tx	Speed	GN
RR	1	0.61	0.01	0.08
Tx	0.61	1	0.19	0.39
Speed	0.01	0.19	1	-0.19
GN	0.08	0.39	-0.19	1

Figure 5.3 Linear regression plot of texture against road roughness

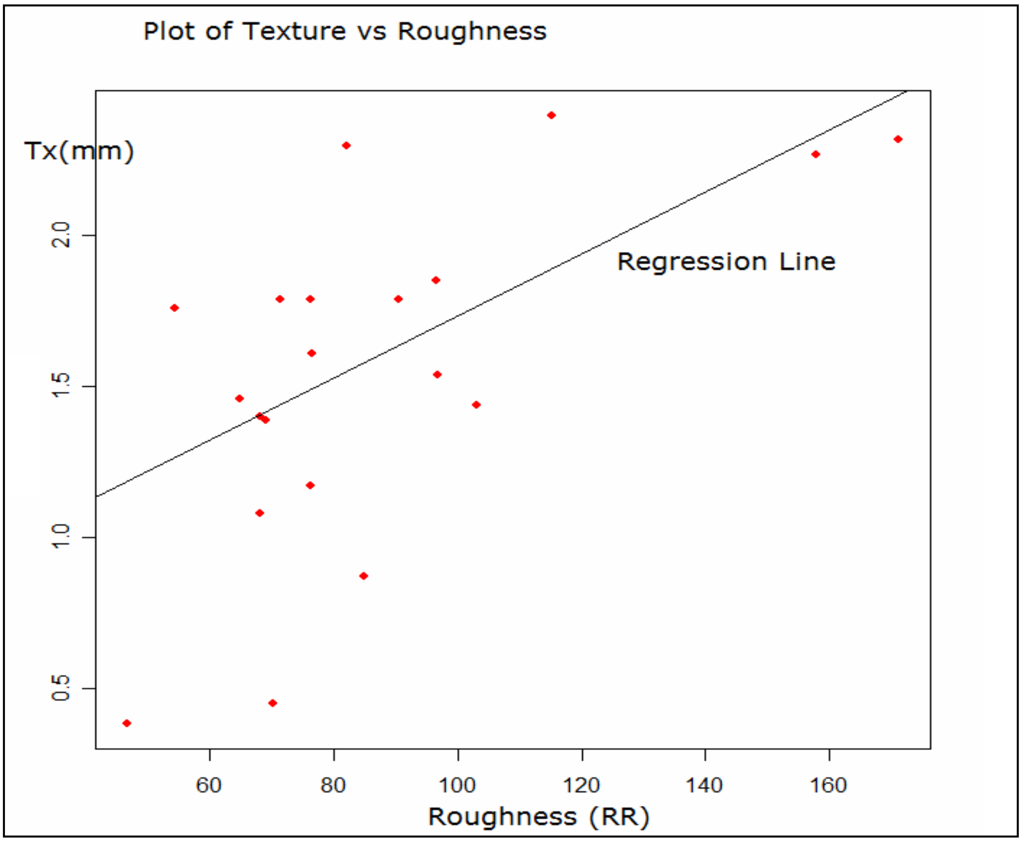
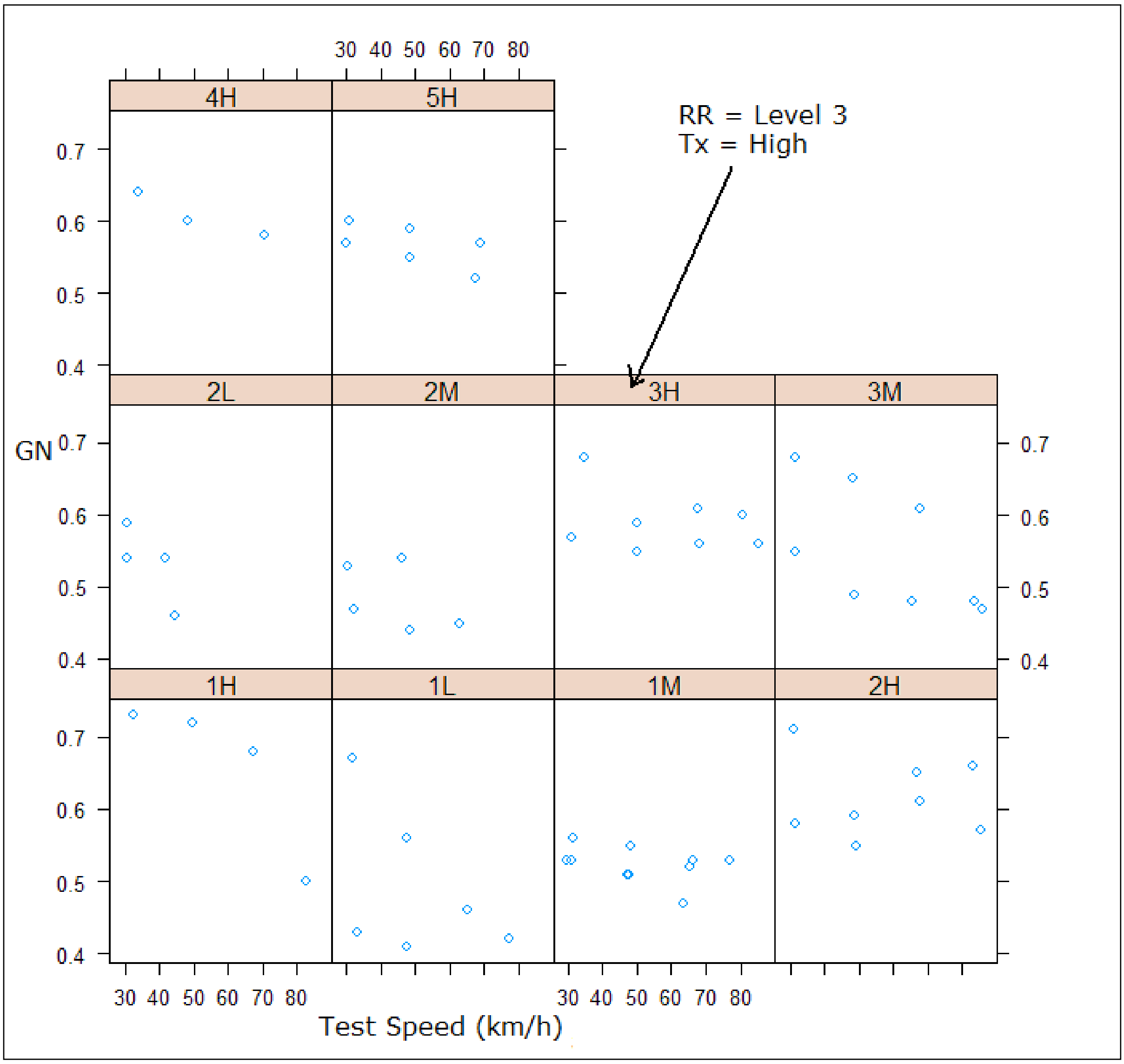


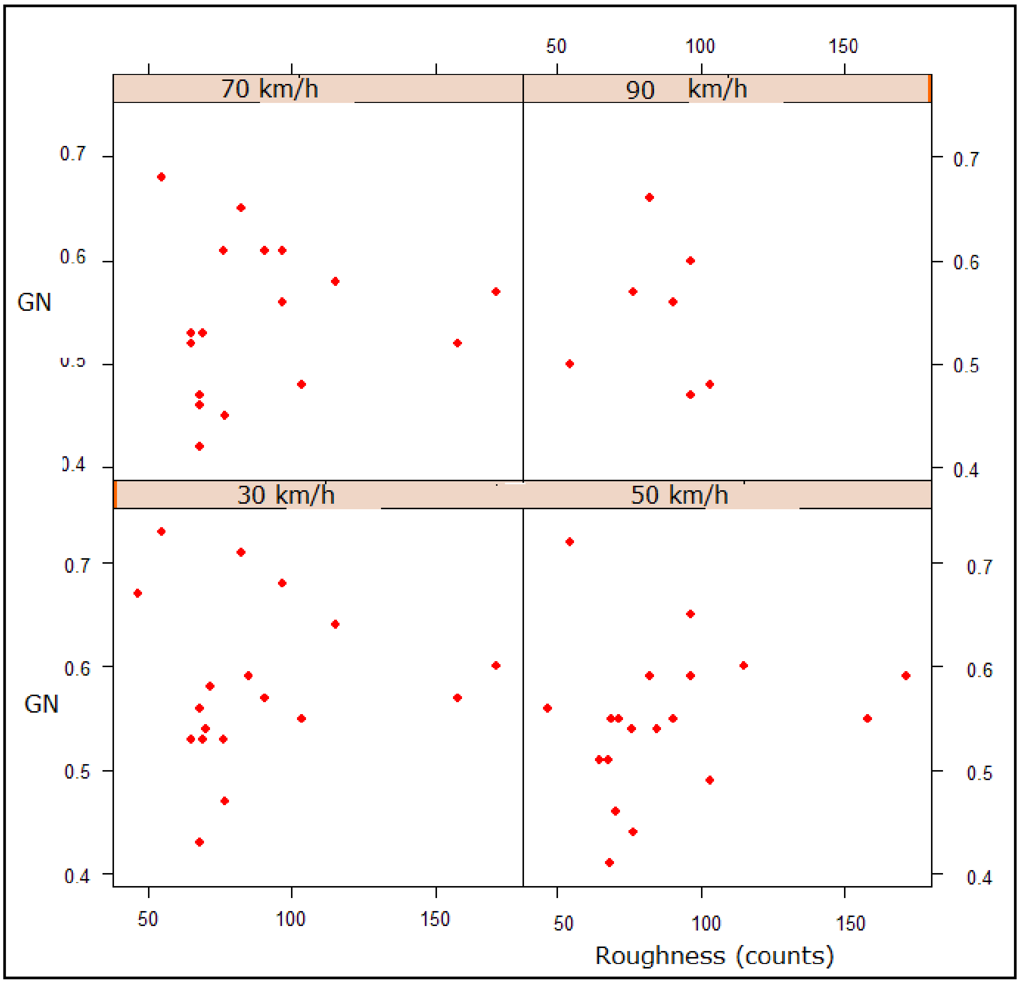
Figure 5.4 shows the grip number plotted against test speed, separated out into their corresponding texture and roughness combination groups. The combinations 3L, 4L, 4M, 5L and 5M were not possible as the data did not fit these categories.

Figure 5.4 Panel plot of GN against test speed, grouped by roughness (1 to 5) and texture (L, M, H)



Overall, we can see that the plots show a general decrease in the GN when increasing the test speeds (this is however not strong for the 2H and 3H categories). However, the test sections grouped together under the same panel may not have consistent features. Figure 5.5 shows similar data to figure 5.4, except the plots are grouped by test speeds rather than by texture and roughness levels. An initial hypothesis of the research was if increasing road roughness affected the measured CoF, ie the GN, then the variance or range at higher speeds would be different from that of lower test speeds where road roughness was thought to have a lesser effect.

Figure 5.5 Panel plot of GN against roughness, grouped by test speed



Nevertheless, the plots do not show any clear relationships between the GN and roughness at each level of speed, nor any shift in points from low to high speeds. There are fewer points in the plots for higher speeds (90km/h) as some test sections were in urban areas where test speeds were restricted to the speed limit.

A linear (fixed effects) model was then applied to the data grouped in the roughness/texture combinations for the following variables:

$$GN \sim Tx + Speed + RR + Tx\_RR\ combination + error\ terms$$

The linear regression analysis (appendix F) showed that the GN is a function of test speed (p = 0.0009) and test section (A1, A2, etc), but not macrotexture (p = 0.99) or road roughness (p =0.509). There are, however, some significant interactions with road roughness and texture. The resultant multiple R-squared was 0.56 meaning that the included co-related variables could explain a little over 50% of the variation in the measured GN from the test sections. Thus, macrotexture and road roughness were not significant variables. The model would therefore need to have only speed and test sections as explanatory variables.

However, as discussed previously it is quite possible that texture and road roughness is confounded with the test sections. The correlation of roughness with texture was 0.61.

Consequently a linear mixed effects model was used to analyse and treat the test sections as random effects. This model (refer to appendix D) showed that both speed and texture remained as explanatory variables but roughness was eliminated.

In view of these findings, it can be concluded that for the tested speed range (30km/h to 90 km/h) and road roughness range (50 to 170 NAASRA counts/km) that the GN is influenced by the test speed and that texture is also a factor (to be further investigated) but that the measured friction coefficient, GN, is not influenced by road roughness.

5.2.3 Data transformations

Each test section has its own GN mean, which is different from the grand mean of all GNs combined. The GN data for all 19 sections was transformed by adding on this difference of means so that every test section had an equivalent mean (which was the grand mean of the GNs).

The purpose of this transformation was to eliminate the variations for each test section. This was undertaken in the hope of improving the plots by removing the variability factor due to different test sections. Three more plots were created to see how a transformed GN could change the linear relationships between the variables: adjusted GN against speed (figure 5.6), road roughness (figure 5.7) and texture (figure 5.8).

Linear regressions using the adjusted GN demonstrate that both road roughness and texture variables are eliminated as factors that can change GN (figures 5.7 and 5.8). Test speed is still a dominant variable that can influence GN, having a negative relationship on the friction coefficient (figure 5.6). However the adjusted R^2 value of 0.23 may indicate poor fitting of the regression line – the cause of the few outliers. If the two outliers at the bottom right of the plot were removed the fitting of the data trend line would be much better.

Figure 5.6 Linear regression of transformed GN against test speed

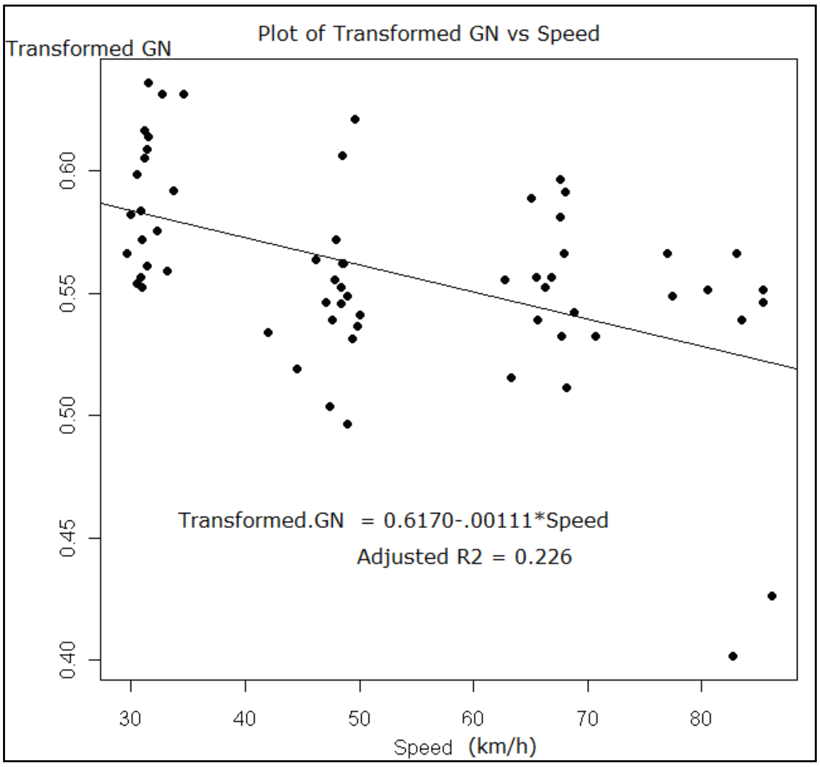


Figure 5.7 Linear regression of transformed GN against road roughness

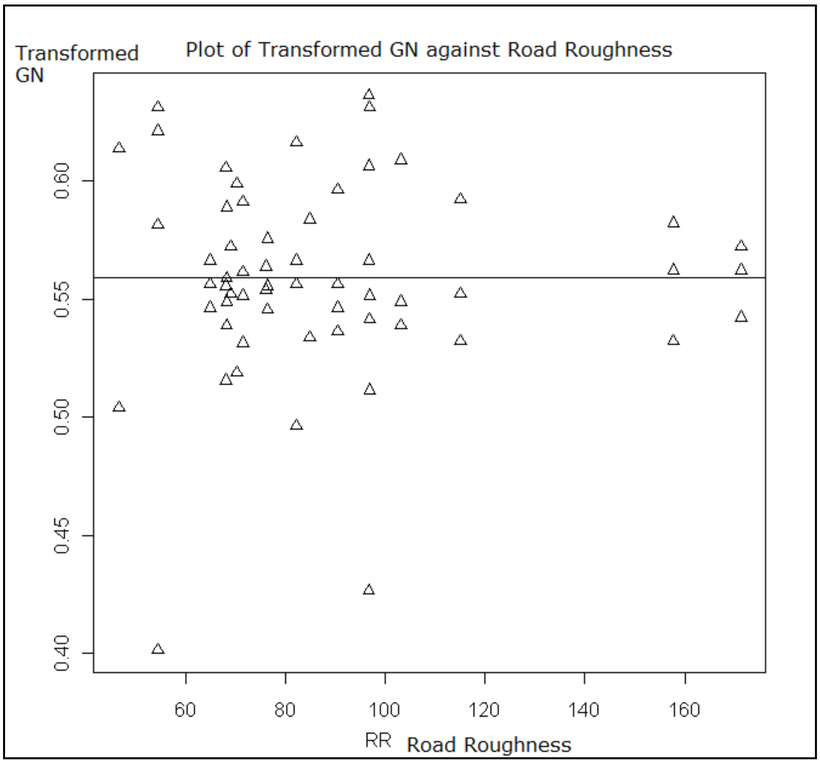
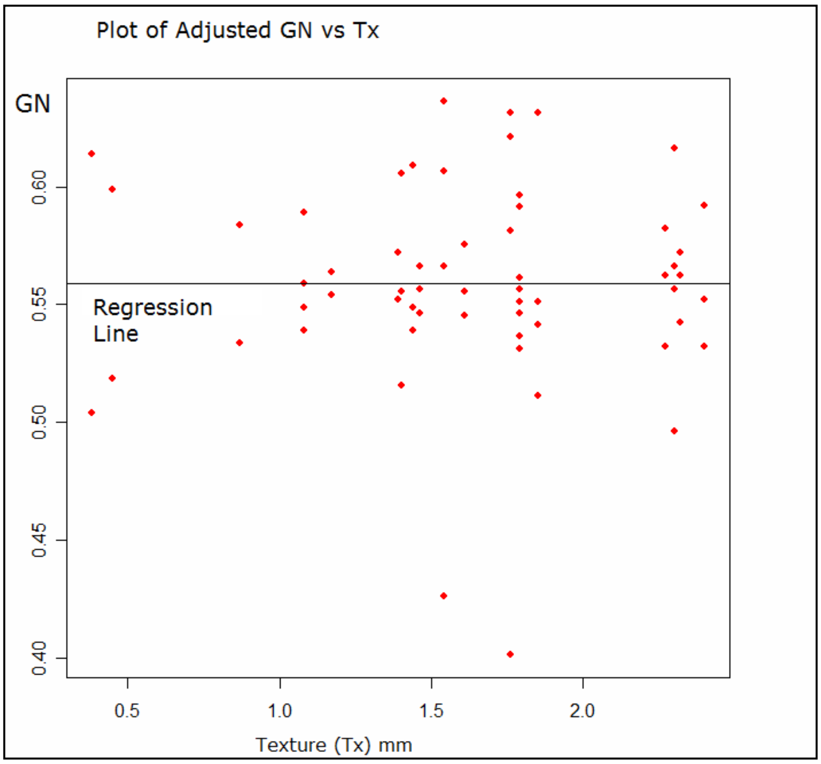


Figure 5.8 Linear regression of transformed GN against texture



5.3 Grip number variability – part 2

The second part of this study focused on how the GN and test speed relationship was affected by macrotexture. An initial hypothesis was that the rate of reduction of GN with increasing test speed would be less on test sections where macrotexture levels were high. This relationship was established previously during the PIARC World Road Association experiment in 1992 and reported in Wambold et al (1995).

The six test sections which had the lowest road roughness readings were chosen to be analysed for their macrotexture effects. These six sections were: A1, C2, D4, D5 and D6, having NAASRA counts between 46.6 and 69.09 counts/km and were considered very low on road roughness levels (refer table 5.4). It was necessary to choose smooth sections (where roughness counts were low) to reduce any road roughness effects on the analysis. In addition, the six sections were also grouped in accordance with their level of texture, as defined in table 5.5.

Table 5.4 Data from test sections A1, C2, D4, D5 and D6, grouped into their texture levels

Test section	RR	Tx	Speed	GN	Tx level
D6	46.64	0.38	31.54	0.67	L
D6	46.64	0.38	47.36	0.56	L
D4	68.25	1.08	33.12	0.43	L
D4	68.25	1.08	47.65	0.41	L
D4	68.25	1.08	65.01	0.46	L
D4	68.25	1.08	77.47	0.42	L
D1	64.99	1.46	29.61	0.53	M
D1	64.99	1.46	47.06	0.51	M
D1	64.99	1.46	65.54	0.52	M
D1	64.99	1.46	76.98	0.53	M
C2	68.08	1.4	31.24	0.56	M
C2	68.08	1.4	47.82	0.51	M
C2	68.08	1.4	63.3	0.47	M
D5	69.06	1.39	30.99	0.53	M
D5	69.06	1.39	48.01	0.55	M
D5	69.06	1.39	66.3	0.53	M
A1	54.51	1.76	32.74	0.73	H
A1	54.51	1.76	49.57	0.72	H
A1	54.51	1.76	67.58	0.68	H
A1	54.51	1.76	82.72	0.5	H

Table 5.5 Texture limits grouping the sections to their texture levels

Tx levels	Tx range	Sections
Low	Tx<1.09	D6, D4
Medium	1.1 < Tx <1.69	D1, C2, D5
High	Tx >1.7	A1

Figure 5.9 plots the GN against speed, grouped by level of texture (L, M and H). With the combined data, the curves in the high and low level texture plots would appear to be of a negative exponential nature. Also, it may appear that the rate of reduction of the GN, with increasing test speeds, is less for medium texture surfaces than for low and high texture surfaces. However, when the plots are linked by road sections, it can be seen that not all GNs form an inverse relationship with test speed and are highly dependent on the test section itself. This is shown by figures 5.10, 5.11 and 5.12 and discussed below.

Figure 5.9 Panel plot of GN against test speed, grouped by texture level

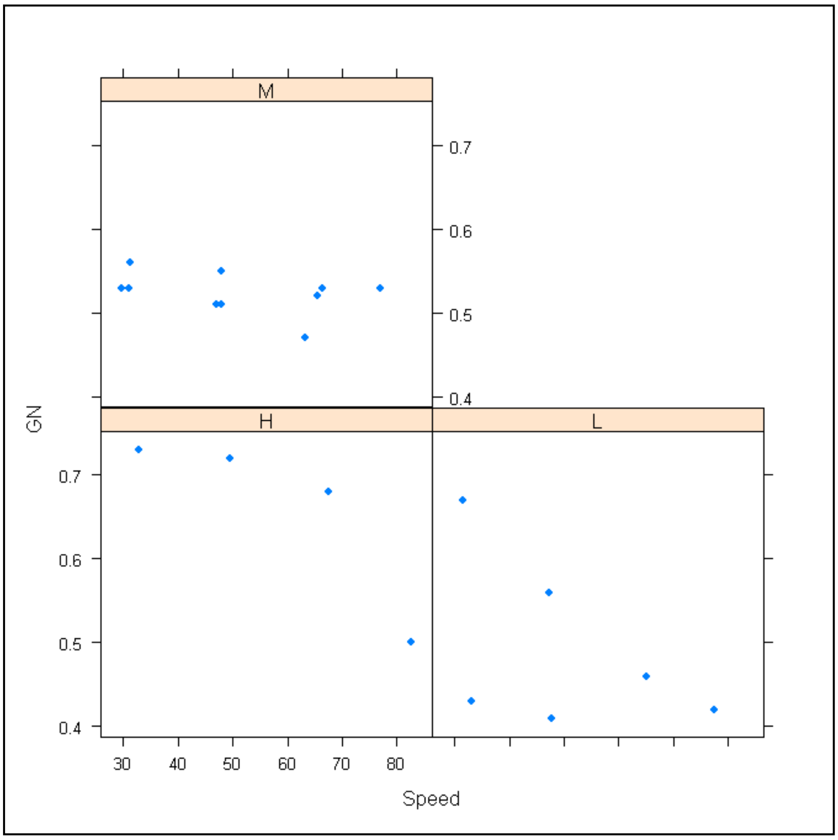


Figure 5.10 Plot of GN vs speed for low texture sections (D4 and D6)

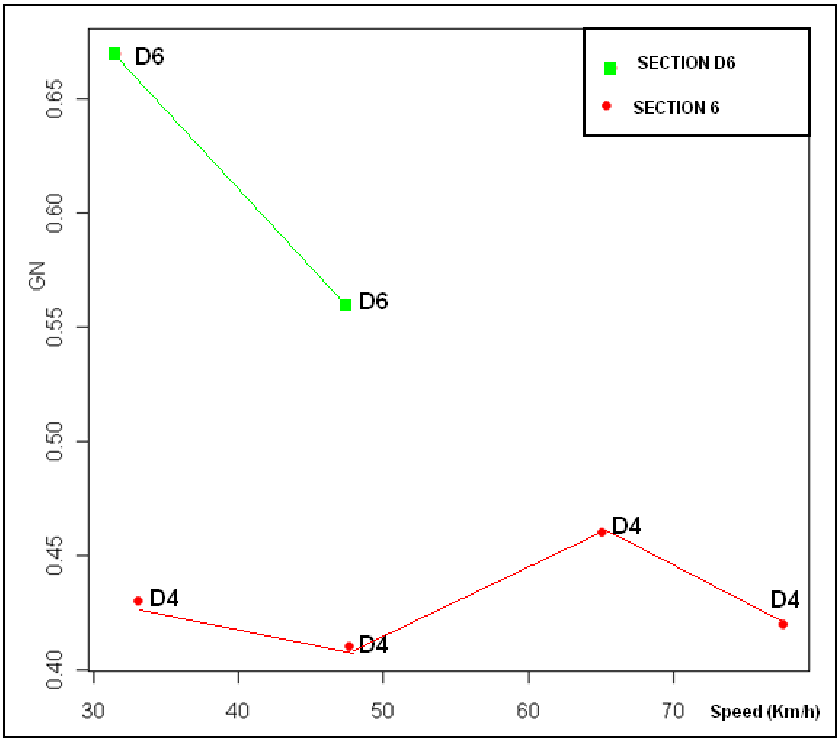


Figure 5.11 Plot of GN vs speed for medium texture sections (C2, D1 and D5)

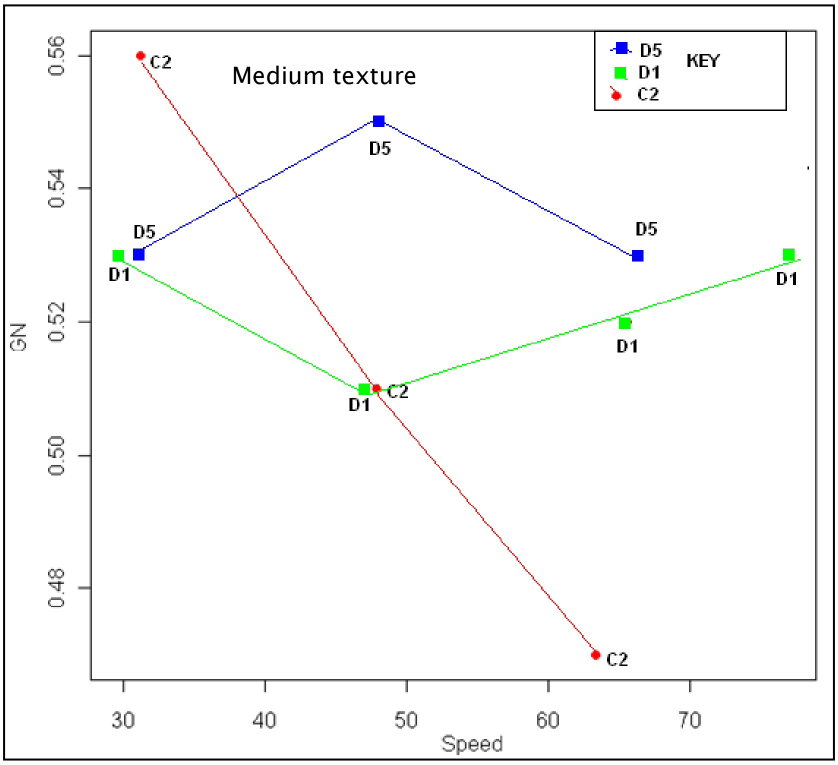


Figure 5.12 Plot of GN vs speed for high texture section (A1)

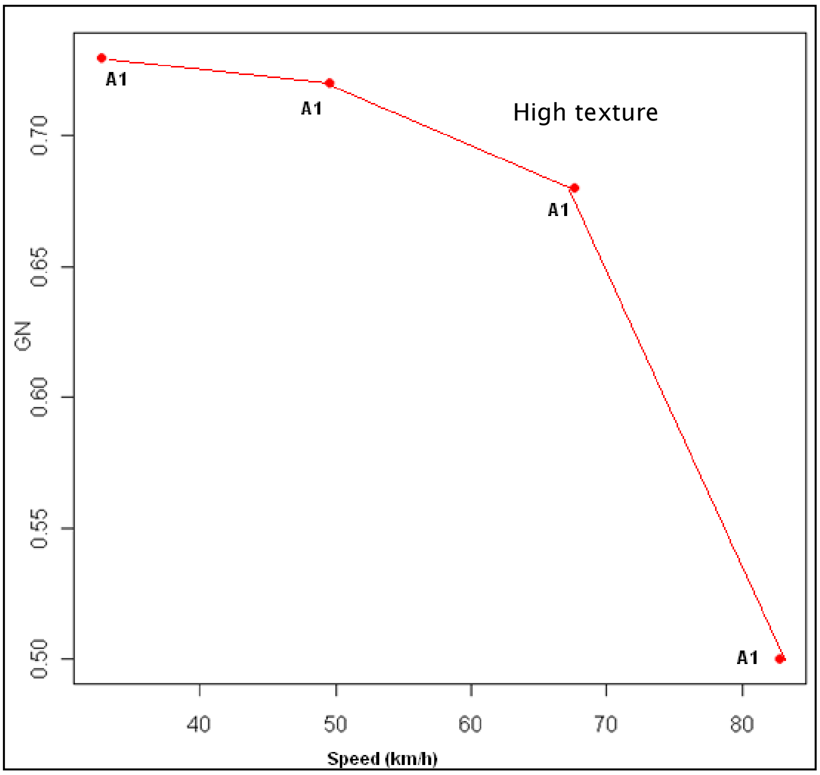


Figure 5.10 shows the GN for section D6 to decrease as the speed increases from 30km/h to 50km/h. However, the relationship between a decreasing GN and increasing speed for all macrotextured surfaces is not conclusive, as we can see a moving up and down trend for section D4. D6 has 0.38mm MPD compared with 1.08mm for D4; this has a possibility of affecting the trends.

Figure 5.11 shows another set of inconclusive trends (D1 and D5) moving randomly and C2 sloping downwards. Although the movements for D1 and D5 seem arbitrary, they do not seem to be volatile and could be the cause of experimental fluctuations.

Figure 5.12 for high texture clearly shows a downward trend of GN as speed increases – this was not expected as the PIARC experiment had found this decreased effect to be more marked on low textured surfaces as there was less time for hysteretic friction to develop. Since A1 was the only section fitting this category, the accuracy of this finding could not be confirmed.

The sections D1, D4 and D5, being in close proximity to each other, also share similar texture MPD and all show some sense of resistance to any loss of GN over the test speed range of 30km/h to 90km/h. When comparing those three sections with D6 (where the texture was halved), C2 and A1 (different areas) indicate that sectional properties may have a more dominant effect on GN changes than texture itself. This leads to the suggestion that there could be some factors relating to the environment or road surface that were not accounted for in this study.

Examining the road characteristics in table 5.6 shows no clear trends that the surfacing material or the years since resurfacing could influence the GN changes (A1, C2, D6 show a reduction in GN with speed and D1, D4 and D5 show no reduction). However, these findings are derived from a small sample of data and more research could be undertaken in this area with a larger sample size with very similar sites, carefully changing one variable at a time to better determine any significance in relationships.

Table 5.6 Surface characteristics of test sections

Section	Surfacing	Age (years)	Speed (km/h)	Tx MPD (mm)
D6	Chip seal 2 coat	1	50	0.38
D4	Chip seal 2 coat	5	100	1.08
D1	Chip seal 1 coat	9	100	1.46
D5	Chip seal 1 coat	9	70	1.39
C2	AC	6	70	1.4
A1	Chip seal 2 coat	2	100	1.76

Another explanation of the variability in the data is that the test wheel track was not followed precisely and markers were not placed accurately. The testing team was unable to close the road down for better control over the test section, so tests were carried out in the presence of 'live' traffic. Distractions from moving traffic add to any other human errors, from driving to marker placing, which can ultimately affect test results.

5.4 GripTester and Dynamic Friction Tester

The research project also enabled an investigation of the relationship in measured CoF between the GripTester (a continuous friction measurement device) and the stationary DF Tester. This section compares three aspects over the same test section: GN at test speeds of 50km/h and 70km/h and COF (μ) by the DF Tester.

CoF measurements were taken at 37 test locations on Glenbrook-Waiuku Road (Glenbrook School area) with the DF Tester. This location was chosen because it passes through the two entranceways into Glenbrook School, where high turning volumes polish the road surface aggregates, giving a reasonable range from low to high CoF. A set of GripTester tests were conducted along the wheel track where the DF Tester measurements were completed. This enabled a correlation to be obtained between the GN and the CoF.

Figure 5.13 below shows a plot of the GN at test speeds of 50km/h and 70km/h (GN50 and GN70 respectively) against chainage or running distance from the beginning of the test section, and DF Tester's CoF (μ) against chainage. The three measurement readings (GN50, GN70 and CoFμ) follow similar patterns moving in unison for most points. The two entranceways where the friction coefficients drop considerably show extensive polishing from high turning traffic volumes and is a useful indicator for matching up the chainages. It can therefore be stated that judging from the pattern bands, the three friction coefficients correspond to each other reasonably well.

Figure 5.13 Plot of GN50, GN70 and CoF against chainage

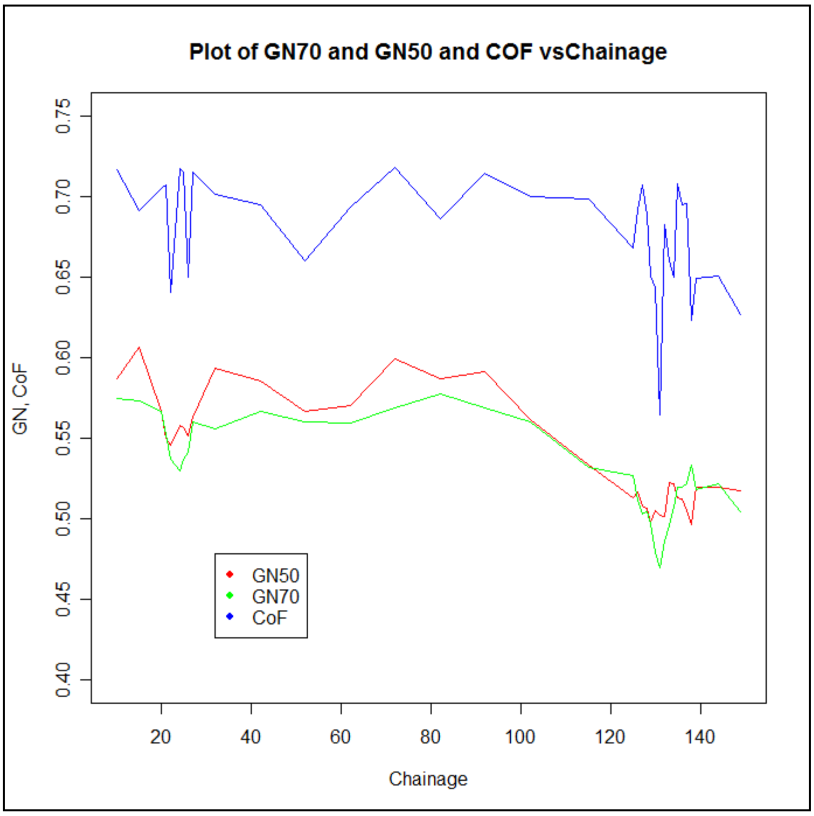
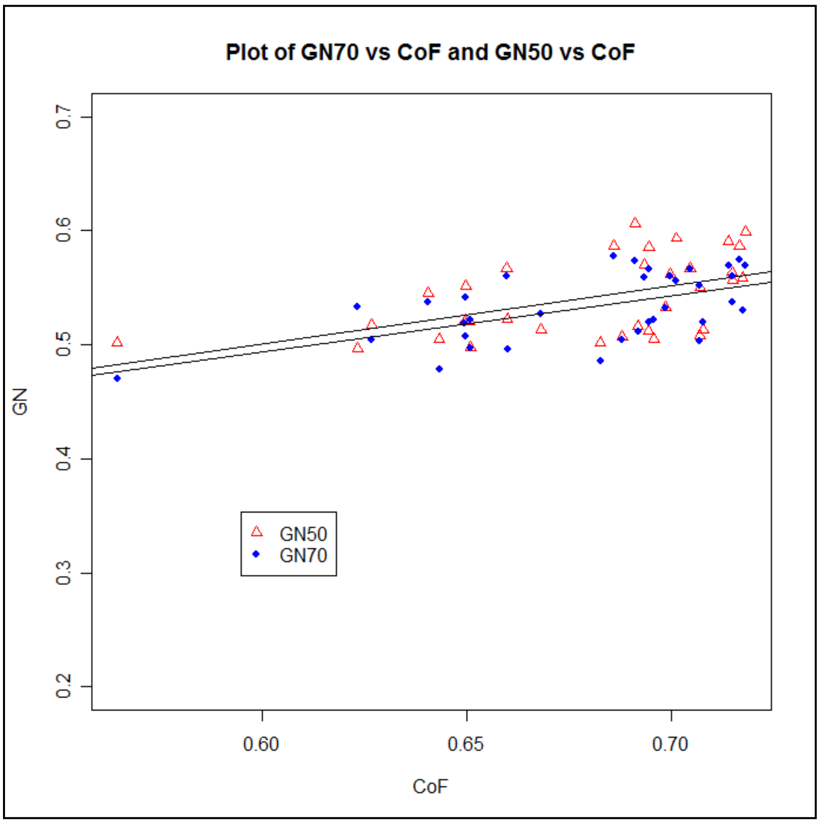


Figure 5.14 plots GN50 and GN70 against CoF for comparison and derivation of the relationship that links GN and CoF. Linear regression was applied to both GN50 vs CoF and GN70 vs CoF, and the two lines are almost indistinguishable. The estimates are 0.193 for the GN50 intercept and 0.198 for GN70, with the difference of 0.00491 proven to be not significant (t-test, 35 degrees of freedom, 0.05). Also, the estimates of the regression line slopes are 0.513 for GN50 and 0.493 for GN70. Once more, the difference of 0.02 in slope is not significant (t-test, 35 degrees of freedom, 0.05). This brings forth the equation between GN and CoF on this site with an MPD of 1.76mm (high texture) to be:

$$GN = 0.5 \times CoF + 0.2$$

The relationship between GN and CoF is relatively independent of testing speeds between 50km/h and 70km/h; and tests undertaken using the GripTester in that speed range would give the same estimates of skid resistance. However, it must be kept in mind that the relationship is valid for this particular test section; any other test sections may give different relationships.

Figure 5.14 Plot of GN50 and GN70 against CoF



6 Conclusions and recommendations

6.1 Conclusions

Both this and previous research have found the DF Tester as a stationary device to be highly repeatable with a coefficient of variation (CoV) ≤2.5%. It has also been shown to be a very useful calibration device for continuous friction measurement devices such as the GripTester. The GripTester can also be reasonably repeatable with a CoV of typically ≤6.0% between multiple test runs when the test device and measuring tyre have been conditioned and warmed up. The CoV can increase up to approximately 11% on a relatively short road section if the tyre is not conditioned prior to the survey.

From the analysis of data collected, not all results concurred with those suggested by theory (eg as measurement speed increases, skid resistance reduces, which it does at a greater rate when the macrotexture is high). This research has raised some further questions about the behaviour of skid resistance and the measurement devices used to determine a measured CoF.

Nevertheless, the following conclusions have been drawn from the research:

- There is a satisfactory linear model of the relationship of the GN with the explanatory variables texture, testing speed and road roughness. Test speed and texture would appear to have an impact on the measurement of the GN, but surprisingly road roughness does not appear to have an influence on the GN as had been hypothesised. More needs to be done in this area to better model the factors influencing the GripTester results.
- Generally, at lower test speeds (less than 75km/h) the GN (on individual road sections) may not be dependent on test speeds, but this depends on the nature and condition of the road surfaces being tested.
- A relationship between the GN obtained from the GripTester and the CoF obtained from the DF Tester was found to be independent of the test speed of the GripTester on the test section used in the research. A good correlation was found between the GripTester and the DF Tester on this site.
- In view of these findings, it can be safely considered that the GN is influenced by the test speed and that texture is also a minor factor (to be further investigated). However this research has shown that the GN as measured by the GripTester is not significantly influenced by road roughness up to 170 NAASRA counts per km and at testing speeds less than 75km/h.

6.2 Recommendations for future research

Future research recommendations include searching for better controlled test sites and larger samples to clarify the effect of texture on the GN and to expose unidentified factors that can influence GripTester output. A greater sample population and site matrix with various skid resistance measurement devices would determine whether some of the unexpected results found in this study were due primarily to the small population size or alternatively due to the GripTester measurement device alone.

7 References

ASTM E501-94 (2000). Standard specification for standard rib tire for pavement skid-resistance tests. In *Book of ASTM standards* (vol 04.03). C. E17.24 (Ed). West Conshohocken, Pa, USA: ASTM International.

ASTM E1911-98 (2002) Standard test method for measuring paved surface frictional properties using the dynamic friction tester. In *Book of ASTM standards* (vol 04.03). C. E17.21 (Ed). West Conshohocken, Pa, USA: ASTM International.

ASTM E1844-08 (2008) Standard specification for a size 10 & 4–5 smooth-tread friction test tire. In *Book of ASTM standards* (vol 04.03). C. E17.24 (Ed). West Conshohocken, Pa, USA: ASTM International.

Austroads (2005) *Guide to the management of road surface skid resistance*. Sydney, Australia: Austroads.

Cenek, PD, DJ Alabaster and RB Davies (1999) Seasonal and weather normalisation of skid resistance measurements. *Transfund NZ research report 139*. Wellington, New Zealand.

Cenek, PD, P Carpenter, NJ Jamieson and PF Stewart (2003) Prediction of skid resistance performance of chipseal roads. *Transfund NZ research report 256*. Wellington, New Zealand.

Cook, D, J Donbavand and CK Kennedy (2004) A review of skid resistance investigatory levels for New Zealand. *Paper presented at the Towards Sustainable Land Transport Conference*, Wellington.

Davis, JR (2006) *Hydroplaning issues*. Accessed 4 April 2013. www.msgroup.org/forums/mtt/topic.asp?TOPIC_ID=200

Department of Statistics, University of Auckland (2010) *The R project*. Accessed 9 August 2012. www.stat.auckland.ac.nz/uoa/sw-the-r-project

de Pont, J and BD Pidwerbesky (2000) Influences of vehicle loading on pavement wear. *Transfund NZ research report 163*.

Descornet, G (1998) Inventory of high-speed longitudinal and transverse road evenness measuring equipment in Europe. *FEHRL technical note 1998/01*.

Do, M, H Zahouani and R Vargiolu (2000) Angular paramater for characterizing road surface microtexture. *Transportation Research Record 1723:* 66–72.

Dunford, A (2008) The Wehner Schulze machine and its potential to improve aggregate specification. *Surface Friction Conference, Managing Road and Runway Surfaces to Improve Safety, CD-ROM Conference Proceedings*, 11–14 May 2008.

Dunlop, R (2003) State highway initiatives – the safety challenge in road engineering. *Paper to NZ Traffic Institute (Trafinz) Annual Conference*, Auckland, New Zealand, August 2003.

Elsenaar, PMW, J Reichert and R Sauterey (1977) Pavement characteristics and skid resistance. *Transportation Research Record 922*: 1–25.

Findlay Irvine (2005) *Highways – griptesterMK2 skid resistance tester*. Accessed 5 Dec 2005. www.findlayirvine.com/products/prod_det.php?sectorId=16&productId=106

Giles, CG (1957) The skidding resistance of roads and the requirements of modern traffic. *Paper presented at the Proceedings of the UK Institution of Civil Engineers.*

Greenwood Engineering (2012) *Profilograph*. Accessed 8 June 2012. www.greenwood.dk/profilograph.php

Hajek, JJ, TJ Kazmierowski and G Musgrove (1998) Switching to international roughness index *Transportation Research Record 1643*: 116–124.

Henry, JJ (2000) *Evaluation of pavement friction characteristics* (No. NCHRP Synthesis 291). Transportation Research Board, National Research Council.

Henry, JJ (2003) Measurement of wet runway friction and the international friction index. *Paper presented at the 1st Annual Australian Runway and Roads Friction Testing Workshop,* Sydney, Australia, 5–7 August 2003.

Highways Agency (2004) HD 28/04. Skid resistance. In *Design manual for roads and bridges* (Vol 7). London, UK: Highways Agency.

Hosking, JR (1976) Aggregates for skid-resistant roads*. TRL laboratory report 693*. Crowthorne, UK: Transport Road Research Laboratory.

Hosking, R (1992) Road aggregates and skidding*. TRL state of the art review no.4*. Crowthorne, UK: Transport Research Laboratory.

Land Transport New Zealand (2004) *A companion document to the Austroads guide to traffic engineering practice. Part 4. Treatment of crash locations*. Wellington: Land Transport New Zealand.

Ministry of Transport (MoT) (2012). *Motor vehicle crashes in New Zealand 2011.* Yearly report 2012, Statistical Statement Calendar Year 2011. Wellington: MoT.

NZ Transport Agency (NZTA) (2010) *T10 Specification for state highway skid resistance management.* Wellington: NZTA.

Nippo Sangyo (2005) *Product guide – ASTM: E 1911-98*. Accessed 5 December 2005. www.nippou.com/en/products/dft.html

O'Flaherty, CA (Ed) (2002) *Highways – the location, design, construction and maintenance of pavements.* 4th edition. Oxford: Butterworth Heinemann.

Oliver, JWH, PF Tredrea and DN Pratt (1988) Seasonal variation of skid resistance in Australia. *Australian Road Research Board special report no.37*. Vermont South, Victoria.

Pazzaglia, R and GS Nelson (1993) *United States of America patent no. 5,245,856.*

Perera, RW, SD Kohn and S Bermanian (1996) Comparison of road profilers. *Transportation research record 1536*: 117–124.

PIARC World Road Association (2003) *Road Safety Manual*: R2ute market.

Prozzi, JJ (2001) Modelling pavement performance by combining field and experimental data. Unpublished PhD, University of California, Berkeley.

Roe, PG and SA Hartshorne (1998) The polished stone value of aggregates and in-service skidding resistance. *TRL report 322*. Crowthorne, Berkshire: Transport Research Laboratory.

Rogers, MP and T Gargett (1991) Skidding resistance standard for the National Road Network. *Highways and Transportation 38*, no.4.

Sayers, MW (1995) On the calculation of IRI from longitudinal road profile. *Presented at the 74th Annual Meeting of the Transportation Research Board.*

Sinhal, R (2005) The implementation of a skid policy to provide the required friction demand on the main road network in the United Kingdom*. Paper presented at the International Conference Surface Friction Roads and Runways – Improving safety through assessment and design*, Christchurch, New Zealand, 1–4 May 2005.

Stevenson, H (1997) Chipseal microtexture and polishing. *New Zealand Engineering (NZE) 1997 52*, no.1.

Transit New Zealand (Transit NZ) (2002) T/10 Specification for skid resistance investigation and treatment selection. Wellington: Transit NZ.

Transit New Zealand and Roading NZ (2005) *Chipsealing in New Zealand*. Wellington.

Viner, HE, R Sinhal and AR Parry (2005) Linking road traffic accidents with skid resistance – recent UK developments. *Paper presented at the International Conference, Surface Friction, Roads and Runways – Improving Safety through Assessment and Design*. Christchurch, New Zealand. 1–4 May 2005.

Wambold, JC, CE Antle, JJ Henry and Z Rado (1995) *International PIARC experiment to compare and harmonize texture and skid resistance measurements*. Madrid, Spain: PIARC Technical Committee on Surface Characteristics C.1.

Wilson, DJ (2006). An analysis of the seasonal and short-term variation of road pavement skid resistance. Unpublished PhD, The University of Auckland, Auckland.

Wilson, DJ and PM Black (2008) Comparison of skid resistance performance between greywackes and melter slag aggregates in New Zealand. In *International Conference on Managing Road and Runway Surfaces to Improve Safety, CD-ROM Conference Proceedings,* 11–14 May 2008.

Wilson, DJ and PM Black (2009) The skid resistance performance of natural New Zealand aggregates using a dynamic friction tester. *Quarterly Journal of Engineering Geology and Hydrogeology 42,* no.1: 61–72.

Appendix A: GripTester device

The GripTester device is a continuous friction measurement device that utilises the braked wheel method and is shown in figure A.1a. It is a three-wheeled skid resistance tester that was originally designed by Findlay Irvine Limited, Scotland in 1987 for airport runway operations. It can be towed behind a vehicle with an automatic water delivery system or pushed by hand by the operator. The GripTester has one test wheel that is braked and two bogey driving wheels (figure A.1b). Its mode of operation is the simultaneous measurement of drag force (F_d) and load force (*Q*) on a single treadless ASTM specified rubber test tyre (standard specification) of 254mm diameter, during braked skidding at approximately 15% of the survey speed. The fixed slip of the test tyre is achieved by means of a chain and sprocket transmission. The test wheel axle features strain gauges to measure the tractive longitudinal and dynamic vertical forces acting on the test tyre. The GripTester reports the surface friction coefficient as a grip number (*GN*) which is the fraction of tractive drag force (F_d) over the load force (*Q*):

$$GN = \frac{F_d}{Q}$$

Where: *GN* = braked friction force coefficient by means of a GripTester (ranges from 0 to 1.2)

F_d = drag force (horizontal)

Q = weight force (vertical)

GripTester surveys typically use an automated (or manual) water delivery system that provides a 0.25mm water film depth beneath the testing tyre. The water film depth can be varied if required. The *GN* is measured every 1m but is typically reported as an average over every 10m length.

Figure A.1 The GripTester (Findlay Irvine 2005)

a) GripTester (side view)

b) GripTester measuring wheel and chain transmission

The GripTester is commonly used for friction measurements on airport pavements, for research purposes and more recently for monitoring road networks in the UK, Europe, Australia and New Zealand. The braked wheel device can be operated in push mode of 5km/h up to a maximum speed of 130km/h. It is relatively easy to transport (at approximately 85kg weight) and can be used with any towing vehicle. The GripTester has only one test wheel, and therefore results are typically obtained for the left wheel path of a road lane only, which is usually the wheel path with the lowest measured surface friction. However, results can be obtained from the right wheel path separately, given appropriate on-road traffic management. Improvements to the axle system in the Type D GripTester have resolved the earlier problems that were associated with the measurement of skid resistance on bends.

The GripTester is compact and highly manoeuverable and is a flexible tool that allows testing on road, air pavement and footway surfaces and is relatively inexpensive to operate.

Appendix B: Dynamic Friction Tester device

The Dynamic Friction Tester (DF Tester) is a stationary skid testing device developed by Nippo Sangyo Co. Ltd. The DF Tester device (see figure B.1a) was designed in Japan mainly to measure the dynamic coefficient of friction on road surfaces. However, it can also be used as a static device to determine the friction on laboratory-prepared samples, paved surfaces of footpaths, promenades and amusement parks, and on floor surfaces of buildings and gymnasiums. It has been found to be very stable with time and to give highly repeatable measurements, and has been chosen as the standard reference in the recently revised IFI ASTM International Standard (Henry 2003). The testing procedure and methodology is described in ASTM Standard Test Method E-1911 (2002).

The DF Tester consists of a horizontal disk that spins with its plane parallel to the test surface. The spinning disk is fitted with three spring-loaded rubber sliders centred on a diameter of 284mm. These contact the paved surface as the disk rotational speed decreases due to the friction generated between the sliders and the paved surface. The DF Tester can be used for laboratory investigations and in the field on actual paved surfaces. The disk is brought to the desired rotational velocity, corresponding to the maximum tangential velocity of the sliders (V up to a maximum of 90km/h). Water is introduced in front of the sliders and the disk is lowered to contact the test surface so that it bears the full velocity of the disk and model assembly. The torque is monitored continuously as the disk rotational velocity reduces due to the friction between the sliders and the test surface. The torque signal is reduced to a measurement of friction by converting the torque to the force on the sliders and dividing by the weight of the disk and motor assembly. The coefficient of friction (μ) is then calculated as follows:

$$\mu = \frac{F}{Q}$$

Where: μ = coefficient of friction as measured by the DF Tester

F= torque force (horizontal)

Q = weight force on the three rubber sliders (vertical)

By holding Q constant and substituting K (a constant of proportionality) for $1/Q$,

$$\mu = K.F$$

Thus, the coefficient μ varies in direct proportion to F. The DF Tester has a main motor-driven unit that consists of a fly wheel and disc with three rubber sliders (refer to figures B.1a and B.1b) attached by leaf springs, and a control unit. The sliders are pressed onto the test surface by the weight of the device through three rollers. Each slider is loaded to 11.8N by the leaf springs. The disc and the fly wheel are connected by a spring balance mounted along a circle on which the rubber sliders are fixed. Due to the forces on the rubber sliders, displacement occurs in a spring balance. This displacement is converted to an electrical signal attached to the opposite side of the disc. The signal is output through a slip ring and brush, both of which are mounted on a driving shaft. The speed of rubber sliders is measured from the output of a rotational speed dynamo. The friction at 20, 40, 60 and 80km/h is recorded and the friction–speed relationship is plotted as shown in figure B.1c.

The slider assembly consists of a steel backing plate to which is bonded a 6 x 16 x 20mm rubber shape as shown in figure B.1b. This shape provides a contact pressure of 150 kPa. The rubber compound is synthetic rubber as specified by ASTM E501 (2000) and is required to have a shore hardness of 58 ± 2.

Figure B.1 Dynamic Friction Tester (DF Tester) components (Nippo Sangyo 2005)

a) DF Tester main unit **b) DF Tester spinning disk and rubber sliders** **c) DF Tester typical result output.**

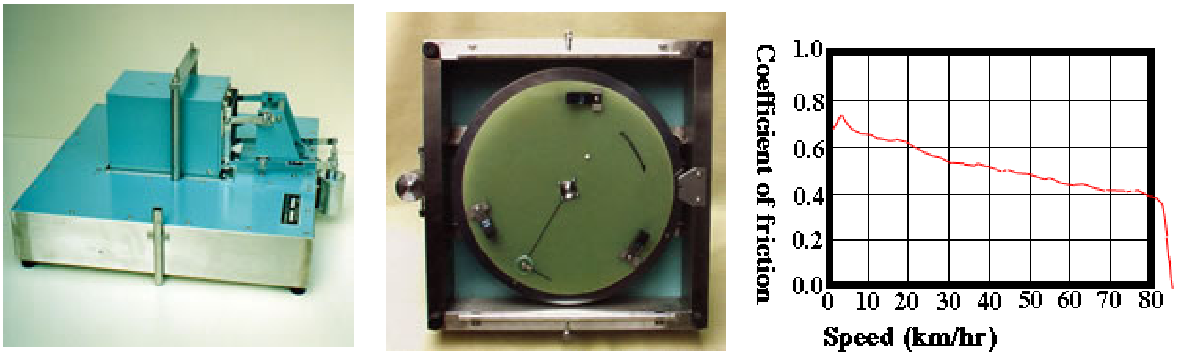
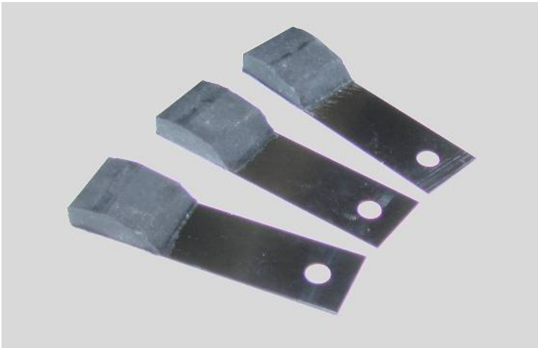


Figure B.2 DF Tester rubber sliders



The DF Tester has the advantage of being able to measure the friction as a function of speed over the range of zero to 80km/h. A test result of 0.60 DFT20 signifies the DF Tester coefficient of friction (*μ=0.60*) at a spin speed of 20km/h. A significant benefit of the DF Tester is that while being a stationary device, it has a significantly larger contact area than the British Pendulum Tester, and is less affected by individual aggregate chips. It has been found to produce stable and highly repeatable measurements over time. These benefits enable the use of this device as a calibration device for other continuous friction measurement devices such as the GripTester and ROAR (Wambold et al 1995).

Appendix C: Accelerometer calibration

Regular calibration of the accelerometer was carried out during the project to confirm that the accelerometer outputs were valid. The calibration procedures for the Sensotec Accelerometer are simple as it is a tri-axial accelerometer. The calibration of the accelerometer includes exposing a positive one unit of gravitational force when rested on its upright position with the appropriate axle measuring the acceleration. The accelerometer is also then exposed to a zero gravitational force when placed on its side and negative one unit of gravitational force when the accelerometer is laid upside down.

In order to obtain accurate results during calibration, the tri-axial accelerometer was laid on a levelled surface. The calibration process commenced with connecting the accelerometer to the amplifiers, LabJack[2] and a laptop computer. The accelerometer was then placed on the levelled surface on an upside-down, side and upright position in turn (figures C.1, C.2 and C.3). Since the acceleration readings fluctuate slightly, it was necessary to record three readings for each of the three sides using the LJStream[3] program as illustrated in table C.1. The readings were then averaged and plotted onto a voltage against a gravity diagram (refer to figure C.4). The gradient of voltage against gravity divided by the gain provides the correction factor for the accelerometer.

The result obtained from the calibration of the accelerometer is shown in table C.1:

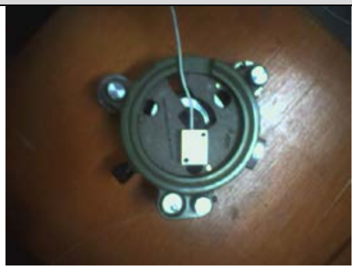
Table C.1 Accelerometer calibration results

Gravitational force	Voltage (volts)			
	Reading 1	Reading 2	Reading 3	Average
-1g	8.1065	8.1432	8.1445	8.1314
0g	7.0202	7.0257	7.0193	7.0217
+1g	5.9347	5.9163	5.9145	5.9218

Figure C.1 Upright position

Figure C.2 Sideway position

Figure C.3 Upside down position

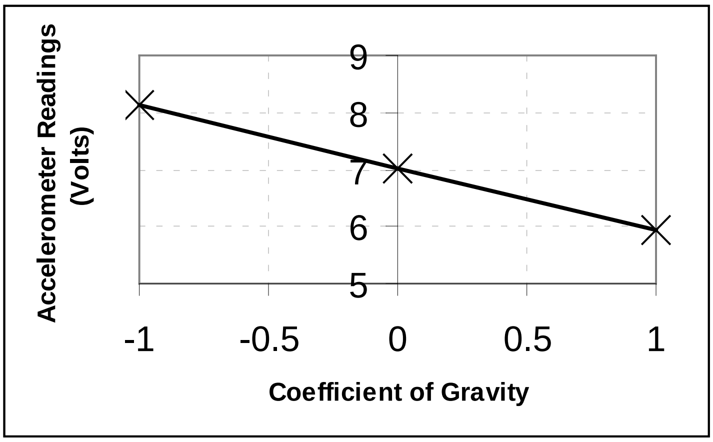


The sensitivity (+/-10g) of the Sensotec Accelerometer was 3.320 mV/g.

[2]LabJack is a USB or Ethernet-based measurement and automation device that provides analogue inputs, outputs and digital inputs, outputs.

[3]LJStream is the software that Labjack uses to read, graph and write to file up to four channels. It scans data at a rate ranging from 50 to 300 scans per second.

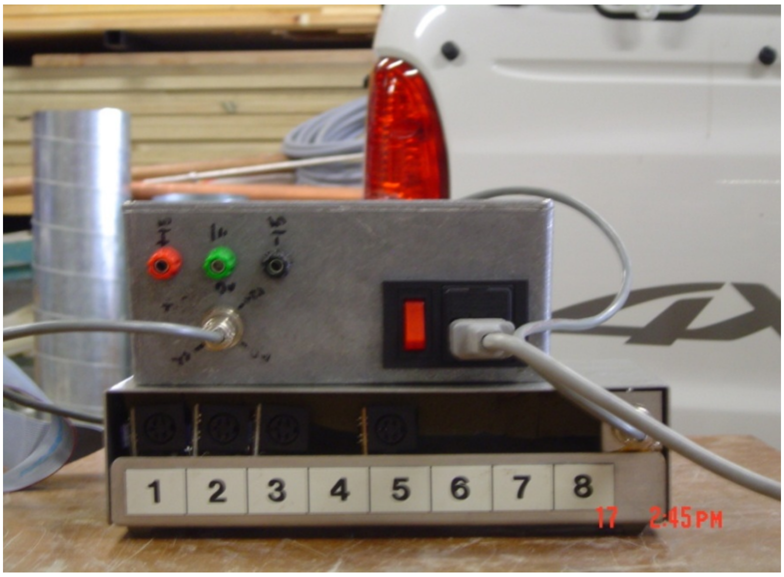
Figure C.4 Accelerometer readings against gravity diagram



C1 Amplifying device

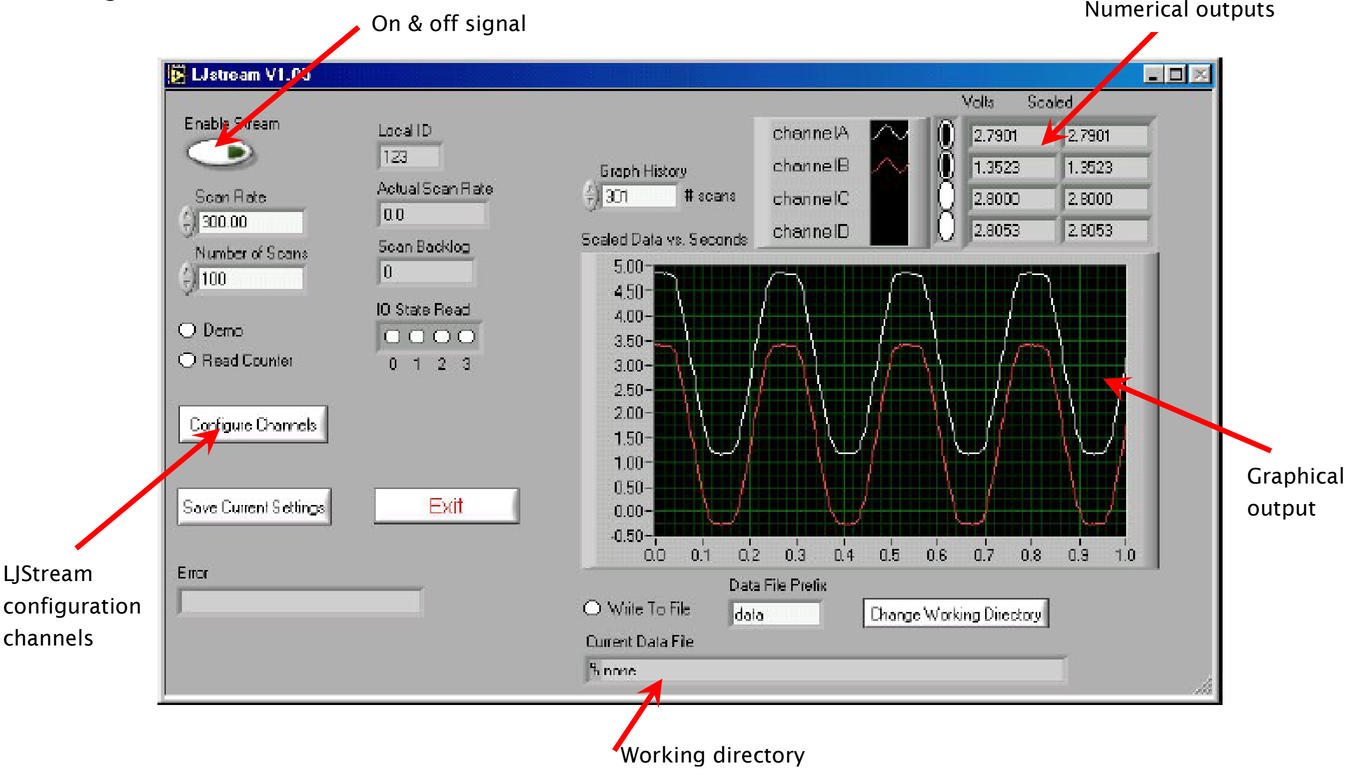
The Sensotec Accelerometer is a standard accelerometer design with a limited voltage output. In order to obtain usable readings an amplifying device was needed to increase the output voltages. The amplifier used in this experiment had amplifying gain that increased the output voltage 100 times. The amplifying device allowed up to eight separate inputs and was connected to a 15 volt DC (direct current) power supply (see figure C.5).

Figure C.5 Amplifier and DC power supply



This research project used LabJack's precision-timing crystal and high-speed sample buffer in 'stream mode' (the data is acquired from a maximum of four channels at a speed of 1200 samples per second) to transfer data continuously from the source to the PC. Figure C.6 shows the interface of LJStream, which consists of an 'on & off' signal, the user-assigned scan rate, and numerical and graphical outputs. The LJStream channel configuration allows the user to supply the scale factor of the accelerometer after calibration and thus the LJStream will calculate the outputs according to the scaled functions.

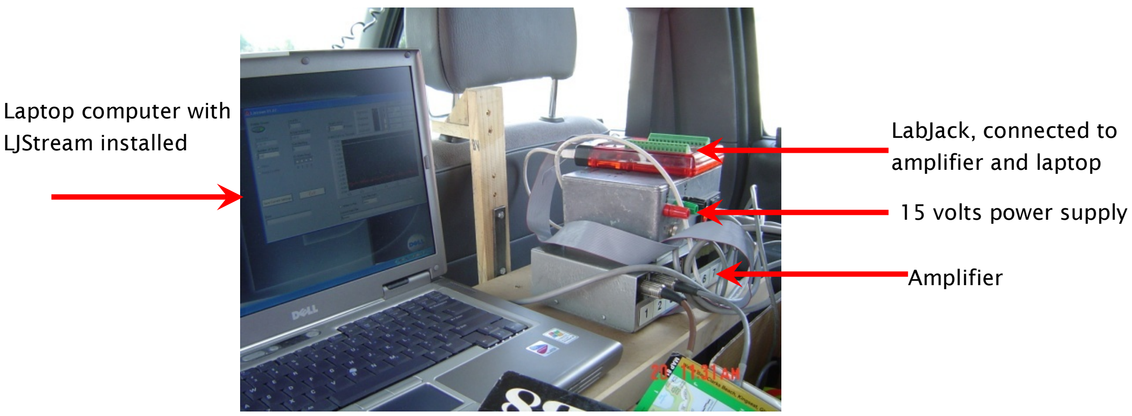
Figure C.6 LJStream interface



C1.1 Accelerometer and data capture setup

The Sensotec Accelerometer is a delicate measuring device which can be easily damaged or supply inaccurate results due to moisture and/or dust. To provide a stable operating environment the accelerometer was secured in a waterproof aluminium case. It was then fastened to the GripTester's measuring axle to measure the vertical accelerations (or vertical movements) experienced during testing due to the unevenness (or roughness) of the road surface. In order to obtain precise measurements, a levelling bubble was used to ensure that the accelerometer was parallel to the ground surface. Protective tape secured the accelerometer and its cables to the axle to prevent wearing or damage. The results provided by the accelerometer by itself were too small to analyse and therefore, the amplifying device was used to increase the voltage output by 100 times. The LabJack was connected to the amplifying device to the laptop computer (with LJStream installed) via the USB cable in the back of the towing vehicle and is shown in figure C.7.

Figure C.7 Accelerometer related equipment setup in the back of the vehicle



Appendix D: Processing and analysing raw data

Raw data obtained from the GripTester and DF Tester all required further data processing before the information could be analysed. After the data was reformatted, results were plotted into graphical outputs and descriptive statistical parameters were calculated.

Due to the large amount of data and graphical plots and results produced in this research, only an example is provided to demonstrate the process.

D1 Processing raw GripTester data

The Roadbase data is stored in database table format which can be opened with Microsoft Access software. Macro templates were developed in Microsoft Excel using Visual Basic Application (VBA). The template allowed up to three Roadbase survey runs (10m averaged) to be processed and compared with one airport run (1m) for each test location and/or test speed undertaken.

Raw test data headers, recorded grip number (GN), test operating speed and the water flow from the airport and Roadbase database were imported into the Excel template (refer to figure D.1 as an example). Four similar formatted worksheets were created for each of the testing speeds of 30km/h, 50km/h, 70km/h and 90km/h.

Figure D.1 GripTester macro template after raw data imported

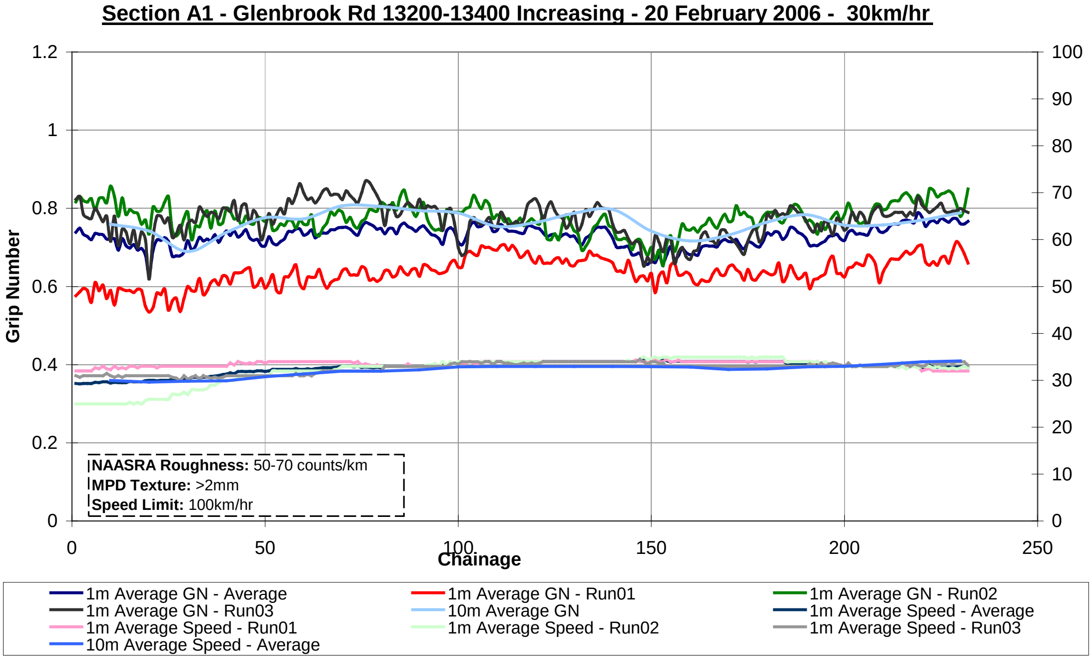
Roadbase - 1m average												
Run 1						Run 2						
Run Header		Raw Data			Markers	Run Header		Raw Data			Markers
Description	Value	ID	GNaverage	Speed	AveIndex	Description	Value	ID	GNaverage	Speed	AveIndex
Roads S/W Version -	1.2.0	1	0.5766667	32	302	Roads S/W Version -	1.2.0	1	0.8166667	25	304
GT Number -	GT281	2	0.5866666	32		GT Number -	GT281	2	0.83	25	
GT Mark -	MK2	3	0.595	32		GT Mark -	MK2	3	0.82	25	
Axle Type -	D-type	4	0.59	32		Axle Type -	D-type	4	0.8166667	25	
Tyre Details -	ASeries-1123-dfg	5	0.56	32		Tyre Details -	ASeries-1123-dfg	5	0.825	25	
DPR Details -	0.785; 1000; 02-May-05	6	0.61	32.7		DPR Details -	0.785; 1000; 02-May-05	6	0.7966667	25	
Average Length -	1	7	0.59	32.5		Average Length -	1	7	0.825	25	
Operator Offset -	1	8	0.6033334	33		Operator Offset -	1	8	0.8266667	25	
Survey Name -	Franklin S.A	9	0.57	32.5		Survey Name -	Franklin S.A	9	0.815	25	
Target Speed -	30	10	0.59	32.3		Target Speed -	30	10	0.8566667	25	
Water Film -	0.25	11	0.5533333	33		Water Film -	0.25	11	0.83	25	
Surface Condition -	Dry	12	0.595	32.5		Surface Condition -	Dry	12	0.78	25	
Weather -	Cloudy and calm	13	0.5933333	32.7		Weather -	Cloudy and calm	13	0.8266667	25	
AmbientTemperature -	25	14	0.59	32.5		AmbientTemperature -	25	14	0.785	25	
Operator -	Wendy Noel	15	0.59	33		Operator -	Wendy Noel	15	0.7966666	25.3	
Start Date -	20/02/2006	16	0.585	33		Start Date -	20/02/2006	16	0.79	25	
Start Time -	11:34	17	0.5933333	32.7		Start Time -	11:40	17	0.7866667	25.3	
Survey Length -	1339	18	0.59	33		Survey Length -	1055	18	0.76	25	
Comments	Warmup Run01	19	0.55	33		Comments	A1 Run02	19	0.77	25.7	

After the raw GripTester data had been processed by the macro templates it was sorted into test speeds. As noted earlier, raw data obtained from the GripTester included the GNs in respect of the section displacement from the predefined starting point of the test section.

Figure D.2 displays an example of a graphical output illustrating the relationship between the GN obtained and the displacement of the test section of section A1 (Glenbrook Road – see table 4.2). This section has NAASRA roughness ranging from 50 to 70 counts per kilometre and a macrotexture depth of at least 2mm.

As shown in figure D.2, there were two sets of results. The top set of graph series (Y1 axis) shows the results as measured from the GripTester. The lower set of data (Y2 axis) shows speed (in km/h) of the GripTester recorded for each test survey.

Figure D.2 Grip number (GN) against section displacement for the testing speed of 30km/h



As shown in figure D.2 (an example graph) the results obtained from the first 1m average test run are lower when compared with subsequent test runs. This pattern is repeated each time a new location set up for the GripTester occurs and is thought to be due to the measuring tyre and axle strain gauges needing to have some 'test measuring distance' to be 'conditioned'. This effect has been seen on previous projects and by other researchers and is more acute when short test sections such as in this research project are used. For this reason, it was decided to call the first run a 'warm-up run' and not to include the results in subsequent analysis.

As also shown in figure D.2 the 10m averaged test run result understandably varies or oscillates vertically less when compared with the results obtained for every 1m test run as it reports an average of 10 test points at one time. The 10m averaged result follows reasonably close to the mean of the other three runs (except the first 30km/h 1m averaged results) and it is therefore reasonable to conclude that both the Airbase and Roadbase software produce the same coefficient of friction; however, post processed and therefore reported in a different manner. The 1m test runs would better reflect what occurs to the GripTester on road sections that have high road roughness as it could be expected that the variations around the true mean result would be higher with the 1m testing methodology.

The results obtained from test section A1 illustrate the site section was relatively homogenous. The GNs obtained during the testing for the entire section only fluctuated slightly around the GN value of 0.8; many of the other sections demonstrated their results in a similar way.

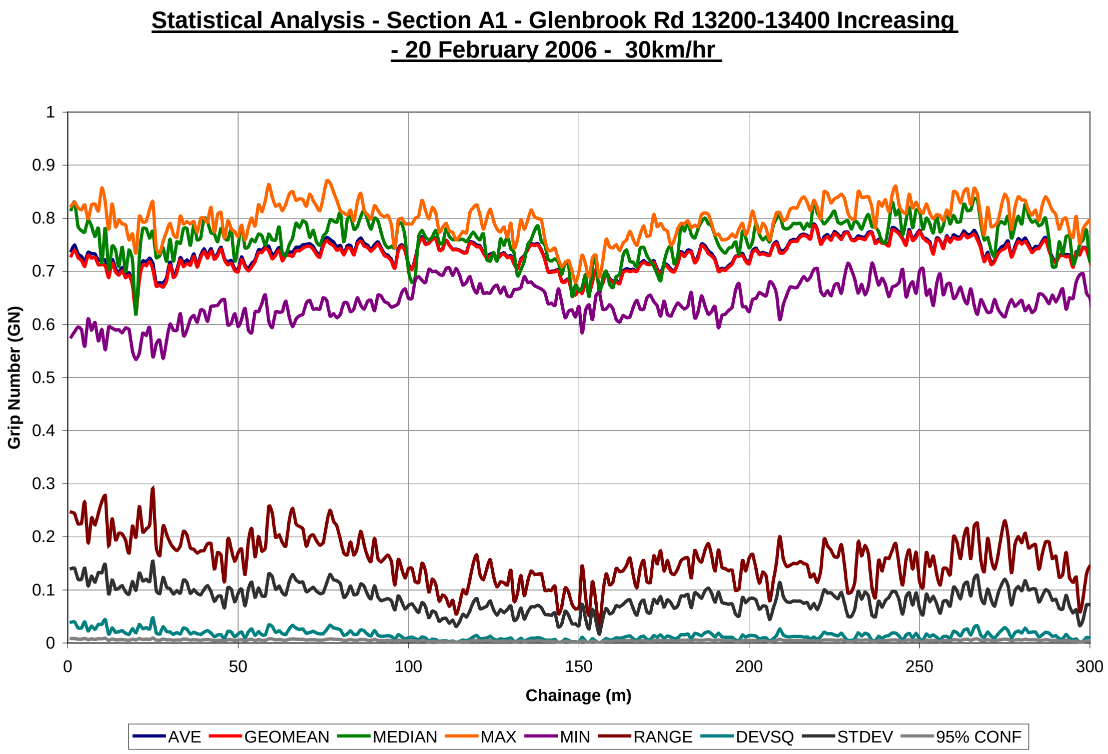
D2 Descriptive statistical analysis

A descriptive statistical analysis of the processed test run results was plotted to quickly visually evaluate the similarities and/or variations between the three 1m averaged results for each of the test speeds. This was intended to assist the understanding of the repeatability and reliability of the GripTester results as well as to be a comparison for other friction-measuring devices such as the DF Tester. This analysis was undertaken between the three 1m averaged results because only one test run was performed with the 10m averaged mode of operation. The following descriptive statistical parameters were calculated and plotted using the following macros in the Excel template:

- sample average
- geometric mean
- median
- maximum
- minimum
- range
- variance
- standard deviations
- 95th percentile confidence limits.

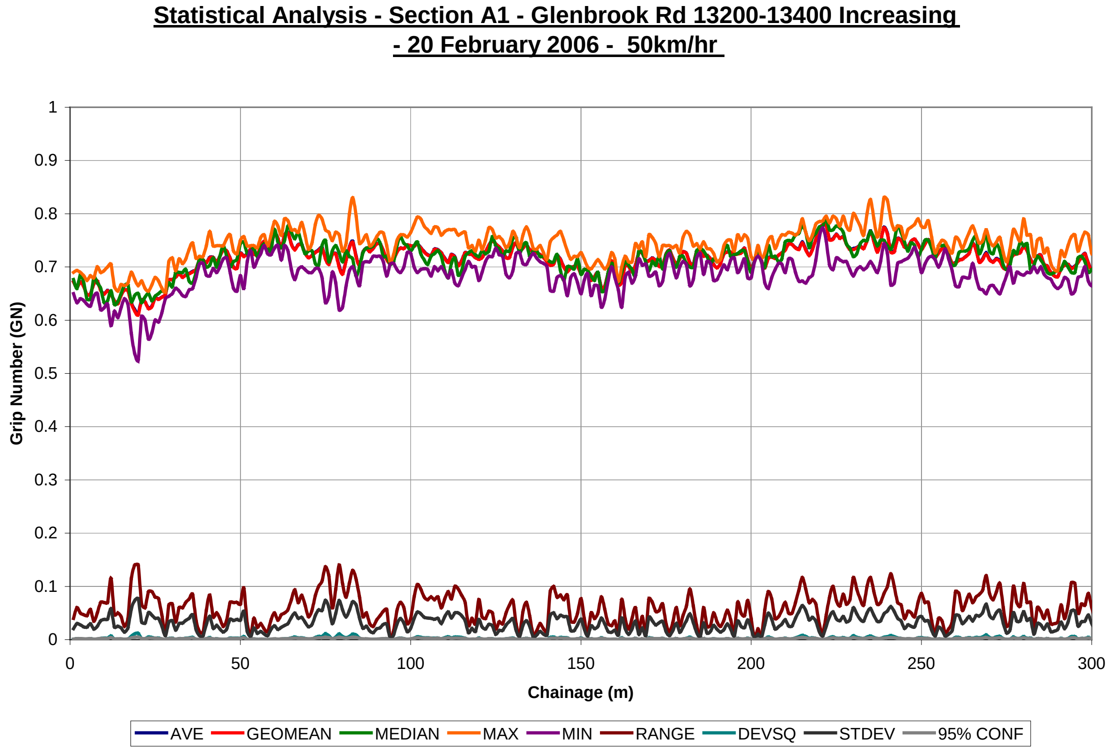
Figure D.3 is an example of the GN plotted against the section displacement for the same test section as figure D.2. The higher set of data plotted in figure 5.3 shows the sample parameters in terms of the GN and the lower set of data series on the graph represents the descriptive statistical variables: variance, standard deviations and the 95th percentile confidence interval between the test runs.

Figure D.3 Comparison between grip number and distance for test speed 30km/h



In this situation, the standard deviations shown in figure D.3 were relatively high, due to the first GripTester survey needing to be eliminated from the analysis as it had not yet been fully 'conditioned' (as discussed above). This effect can be shown by studying a different test speed descriptive statistical plot where the GripTester tyre and axle were fully conditioned. Figure D.4 shows the same example test section, but with a test speed of 50km/h and immediately after the 30km/h test runs. The variation analyses such as the standard deviation, range and variance had a significantly lower level compared with figure D.3, demonstrating the effect of the much lower 'warm-up run' when the tyre and axle have not been adequately 'conditioned'.

Figure D.4 Comparison between grip number and distance for test speed of 50km/h



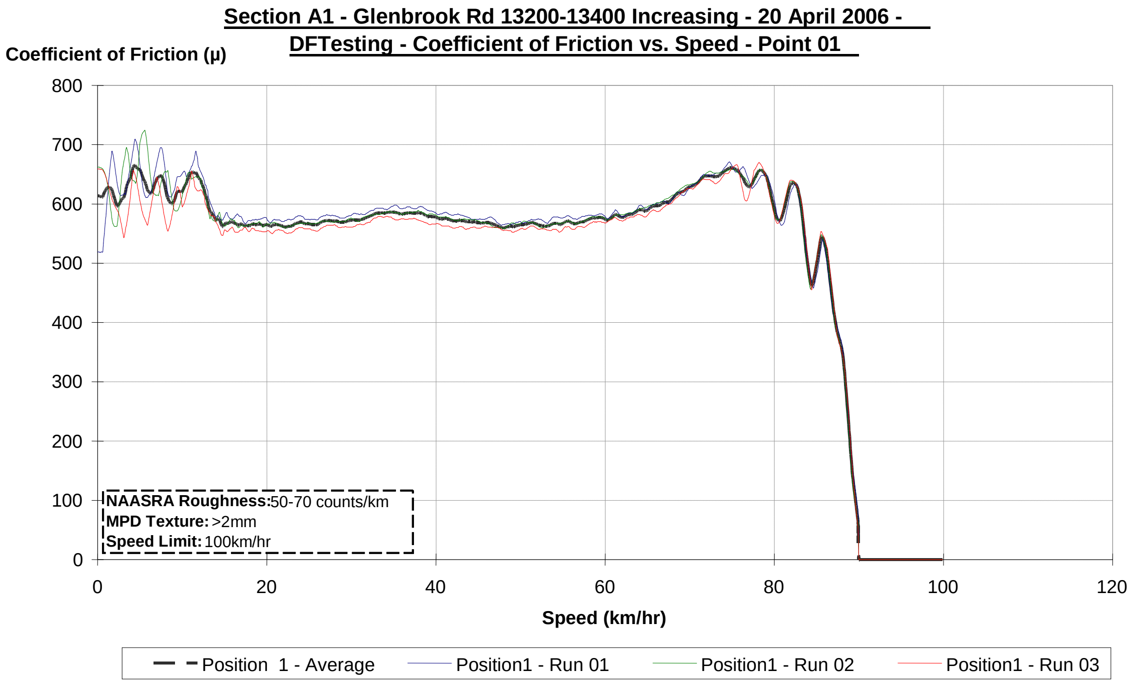
D4 Processing Dynamic Friction Tester data

The results generated by the DF Tester were also stored as database file format (.dat). Further macros were written to import and analyse the data.

D4.1 Methodology for analysing Dynamic Friction Tester results

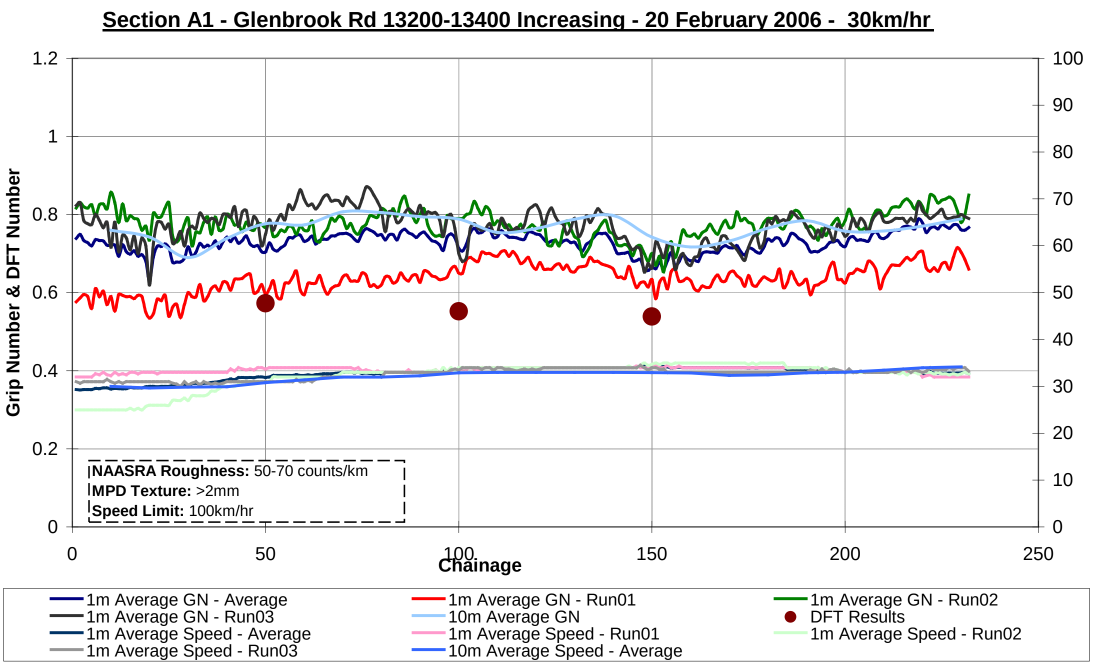
Three testing points were selected within each of the test sections which provided three sets of raw data. These were then imported into Excel where they were analysed and the data point plotted to produce three separate graphs. The results of this are shown in figure D.5.

Figure D.5 DF Tester results (CoF) against slip speed



The graphical plot shown in figure D.5 is an example of the DF Tester results against slip speed, which were extracted from the first position situated at the 50th metre from the origin of section. As the DF Tester grinds to a halt when the rotational disk speed is less than approximately 15km/h the reported result becomes erratic and should not be used. The other end of the graph should similarly not be used. As shown in figure D.6, the position chosen was tested with three identical test runs to ensure the DF Tester provided repetitive and reliable data.

Figure D.6 Grip number and coefficient of friction against section displacement



The DF Tester CoF results were taken with a slip speed of 20km/h. In this research, results obtained from the DF Tester data were averaged between 20km/h and 40km/h slip speed. Table D.1 shows this comparison for three equivalent positions on the test section. The table shows this at a 30km/h speed at a macrotexture of >1.7mm. Comparison tables were constructed for each position within all of the test sites.

Table D.1 Statistical analysis for GripTester and DF Tester (30km/h)

Roughness: NAASRA 50-70 counts/km. Macrotexture: >1.7 mm							
Statistical analysis	**Section ave GN30**	**Time slice**			**Ave DFT20**		
		50m	**100m**	**150m**	**P1**	**P2**	**P3**
Mean	0.733	0.704	0.713	0.666	0.565	0.546	0.535
Maximum	0.797	0.767	0.790	0.700	0.575	0.562	0.548
Minimum	0.641	0.597	0.650	0.633	0.554	0.535	0.521
Range	0.156	0.170	0.140	0.067	0.021	0.027	0.027
Standard deviation	0.083	0.094	0.071	0.033	0.011	0.014	0.014
Variance	0.015	0.018	0.010	0.002	0.222	0.402	0.369
95% confidence interval	0.005	0.006	0.004	0.002	0.001	0.001	0.001
Coefficient of variation	0.113	0.133	0.100	0.050	0.019	0.026	0.025

As shown in table D.1, statistical calculations for the GripTester are shown under the three 'Time slice' columns. The statistical calculations for each of the time slices were obtained respectively according to the same displacement to the first point (P1), second point (P2) and third point (P3) of the DF Tester results. Table D.1 clearly shows the DF Tester variations were considerably lower than those of the GripTester; this indicates that the results obtained from the DF Tester were more repeatable. This would be expected as the DF Tester is a stationary device and therefore a repeat test is over the exact same location. The GripTester, however, relies on the skills of the driver to try and drive over the same line and is therefore more variable.

Appendix E: Processed test data results

Table E.1 is a summary of the road roughness and surface textures for each of the test sites. The actual road roughness and textures were measured with the PMS laser profilograph and the base road roughness and textures were obtained from the RAMM database.

Table E.1 Summary of test site roughness and texture

Test section	Road roughness		Surface textures	
	Measured	RAMM	Measured	RAMM
A1	54.51	50-70	1.76	>2
A2	96.73	90–110	1.54	>2
A3	96.94	90–110	1.85	1-2
A4	103.19	90–110	1.44	1-2
B1	71.46	70–90	1.79	>2
B2	90.55	90–110	1.79	>2
B3	82.22	70–90	2.30	>2
C1	70.23	50–70	0.45	<1
C2	68.08	50–70	1.40	<1
C3	84.96	70–90	0.87	<1
D1	64.99	50–70	1.46	>2
D2	76.21	50–70	1.17	1–2
D3	76.50	70–90	1.61	1–2
D4	68.25	50–70	1.08	1–2
D5	69.06	70–90	1.39	1–2
D6	46.64	70–90	0.38	<1
F1	115.15	110–130	2.40	>2
F2	171.20	>130	2.32	>2
F3	157.75	110–130	2.27	>2

Table E.2 shows the actual roughness of the six test sections and the corresponding averaged GN and DF Tester result obtained from the two skid resistance measuring devices during the experimental testing on site.

Table E.2 Summarised GripTester results for the very low roughness test sections

Test section	Roughness (counts/km)	Texture (mm)	Test speed (km/h)	Grip number	DFT speed (km/h)	CoF
D6	46.64	0.38	31.54	0.67	30.00	0.71
			47.36	0.56	50.00	0.67
A1	54.51	1.76	32.74	0.73	30.00	0.55
			49.57	0.72	50.00	0.54
			67.58	0.68	70.00	0.58
			82.72	0.50		
D1	64.99	1.46	29.61	0.53	30.00	0.61

Test section	Roughness (counts/km)	Texture (mm)	Test speed (km/h)	Grip number	DFT speed (km/h)	CoF
			47.06	0.51	50.00	0.54
			65.54	0.52		
			76.98	0.53		
C2	68.08	1.40	31.24	0.56	30.00	0.74
			47.82	0.51	50.00	0.71
			63.30	0.47		
D4	68.25	1.08	33.12	0.43	30.00	0.66
			47.65	0.41	50.00	0.60
			65.01	0.46		
			77.47	0.42		
D5	69.06	1.39	30.99	0.53	30.00	0.68
			48.01	0.55	50.00	0.56

Table E.3 shows another six sites that were classified as low road roughness with the targeted roughness bandwidth between 70 and 90 counts/km.

Table E.3 Summarised GripTester results for the low roughness test sections

Test section	Roughness (counts/km)	Texture (mm)	Test speed (km/h)	Grip number	DFT speed (km/h)	CoF
C1	70.23	0.45	30.58	0.54	30.00	0.62
			44.54	0.46	50.00	0.61
B1	71.46	1.79	31.45	0.58		
			49.41	0.55		
			67.99	0.61		
			85.39	0.57		
D2	76.21	1.17	30.49	0.53	30.00	0.72
			46.20	0.54	50.00	0.58
D3	76.50	1.61	32.25	0.47	30.00	0.73
			48.38	0.44	50.00	0.63
			62.73	0.45		
B3	82.22	2.30	31.24	0.71	30.00	0.66
			48.92	0.59	50.00	0.64
			66.80	0.65		
			83.01	0.66		
C3	84.96	0.87	30.81	0.59	30.00	0.53
			42.03	0.54	50.00	0.54

Table E.4 summarises the GripTester and DF Tester results obtained for test sections that had targeted NAASRA road roughness between 90 to 110 counts/km.

Table E.4 Summarised GripTester results for the medium roughness test sections

Test section	Roughness (counts/km)	Texture (mm)	Test speed (km/h)	Grip number	DFT speed (km/hr)	CoF
B2	90.55	1.79	30.82	0.57	30.00	0.70
			49.85	0.55	50.00	0.57
			67.61	0.61		
			85.40	0.56		
A2	96.73	1.54	31.55	0.68		
			48.54	0.65		
			67.97	0.61		
			86.10	0.47		
A3	96.94	1.85	34.59	0.68	30.00	0.67
			50.05	0.59	50.00	0.62
			68.14	0.56		
			80.52	0.60		
A4	103.19	1.44	31.45	0.55	30.00	0.57
			48.98	0.49	50.00	0.53
			65.58	0.48		
			83.48	0.48		

A high road roughness test section was located on Rukuhia Rd in Waipa District Council (F1) for a targeted roughness range between 110 and 130 counts/km. Test section F1 was situated on a very low traffic volume arterial road and the measured data is shown in table E.5.

Table E.5 Summarised GripTester results for the high roughness test sections

Test section	Roughness (counts/km)	Texture (mm)	Test speed (km/h)	Grip number	DFT speed (km/h)	CoF
F1	115.15	2.40	33.72	0.64	30.00	0.71
			48.41	0.60	50.00	0.62
			70.70	0.58		

The last classification of road roughness was the very high road roughness (ie >130 NAASRA counts/km). Only two test sites in Rukuhia Rd of Waipa District Council were selected – refer to table E.6.

Table E.6 Summarised GripTester results for test sections with very high roughness bandwidth

Test section	Roughness (counts/km)	Texture (mm)	Test speed (km/h)	Grip number	DFT speed (km/h)	CoF
F3	157.75	2.27	29.99	0.57	30.00	0.65
			48.60	0.55	50.00	0.60
			67.74	0.52		
F2	171.20	2.32	30.94	0.60	30.00	0.70
			48.48	0.59	50.00	0.59
			68.80	0.57		

Appendix F: Output code from 'R' statistical package

```
lm.ML.1 <- lme( GN ~ Tx + RR + Speed, data = NZTA_B, random = ~1|Level.RR_Tx)
summary(lm.ML.1)
VarCorr(lm.ML.1)
intervals(lm.ML.1)
```

```
Linear mixed-effects model fit by REML
Data: NZTA_B
      AIC       BIC   logLik
 -117.6881 -105.3254 64.84404

Random effects:
Formula: ~1 | Level.RR_Tx
       (Intercept)   Residual
StdDev:  0.04144471 0.05730872

Fixed effects: GN ~ Tx + RR + Speed
              Value        Std. Error    DF   t-value     p-value
(Intercept)   0.5979541    0.05107920    49   11.706410   0.0000
Tx            0.0674392    0.03116254    49   2.164110    0.0354*
RR            -0.0007870   0.00059645    49   -1.319448   0.1932
Speed         -0.0014722   00042901      49   -3.431691   0.0012**
Correlation:
      (Intr) Tx     RR
Tx    -0.275
RR    -0.467 -0.616
Speed -0.364 -0.166  0.090

Standardised within-group residuals:
Min           Q1            Med          Q3           Max
 -1.86830027   -0.73082997   0.08280153   0.68889343   2.80593785

Number of observations: 62
Number of groups: 10
```

```
>VarCorr(lm.ML.1)
Level.RR_Tx = pdLogChol(1)
              Variance       StdDev
(Intercept)   0.001717664    0.04144471
Residual      0.003284290    0.05730872
```

```
intervals(lm.ML.1)
Approximate 95% confidence intervals

Fixed effects:
                lower           est.            upper
(Intercept)     0.495306597     0.5979540988    0.7006016010
Tx              0.004815711     0.0674391879    0.1300626645
RR              -0.001985592    -0.0007869832   0.0004116259
Speed           -0.002334338    -0.0014722173   -0.0006100967
attr(,"label")
[1] "Fixed effects:"

Random effects:
 Level: Level.RR_Tx
                lower           est.            upper
sd((Intercept)) 0.01830692      0.04144471      0.09382592

 Within-group standard error:
                lower           est.            upper
                0.04690745      0.05730872      0.07001637
```

```
lm.df <- lm( GN ~ Tx  + speed + RR + level.RR_Tx, data = NZTA_B)

summary(lm.df)
```

```
lm(formula = GN ~ Tx + Speed + RR + Level.RR_Tx, data = NZTA_B)
Residuals:
      Min       1Q    Median       3Q      Max
-0.120583 -0.032715 -0.003345  0.036078  0.129010

Coefficients:
               Estimate Std. Error t value Pr(>|t|)
(Intercept)    0.8245105  0.0892505  9.238 2.61e-12 ***
Tx            -0.0007912  0.0666631  -0.012 0.990579
Speed          -0.0015027  0.0004245  -3.540 0.000888 ***
RR            -0.0014352  0.0021549  -0.666 0.508526
Level.RR_Tx1L -0.1688868  0.0804213  -2.100 0.040898 *
Level.RR_Tx1M -0.1268659  0.0571262  -2.221 0.031019 *
Level.RR_Tx2H -0.0104163  0.0499246  -0.209 0.835593
Level.RR_Tx2L -0.1245396  0.1216675  -1.024 0.311049
Level.RR_Tx2M -0.1616163  0.0750810  -2.153 0.036305 *
Level.RR_Tx3H -0.0108121  0.0885478  -0.122 0.903316
Level.RR_Tx3M -0.0415289  0.1171693  -0.354 0.724534
Level.RR_Tx4H  0.0258701  0.1114599   0.232 0.817426
Level.RR_Tx5H  0.0537955  0.2147394   0.251 0.803236
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.05612 on 49 degrees of freedom
Multiple R-squared: 0.5558,     Adjusted R-squared: 0.447
F-statistic:  5.11 on 12 and 49 DF, p-value: 1.885e-05
```

Appendix G: Glossary

AADT	annual average daily traffic volume
AAV	aggregate abrasion value
ABS	anti-lock braking system
ADT	average daily traffic
AGD	average greatest dimension of the sealing chip (mm)
AIV	aggregate impact value
ALD	average least dimension of the sealing chip (mm)
AP	accelerated polishing
APM	accelerated polishing machine
ARRB	ARRB Group Limited (formerly ARRB Transport Research, Melbourne, Australia)
ASTM	American Society for Testing and Materials (now known as ASTM International)
AVE	average
BC/BCR	benefit–cost ratio
BFC	braking force coefficient
BPN	British Pendulum number
BS	British Standard
CEN	Committee for European Normalisation
CoF	coefficient of friction
CoV	coefficient of variation
CVD	number of HCVs/lane/day ≥3.5 tonnes
Dec/'decreasing'	linear referencing position – decreasing direction of travel
DF Tester	Dynamic Friction Tester device
DFT20	Dynamic Friction Tester CoF at 20km/h slip speed
DPR	distance per rotation
dTIMS	Deigton's Total Infrastructure Management System
EN	European normative
ESC	equilibrium SCRIM coefficient
ESR	equilibrium skid resistance
GN	grip number (CoF from GripTester device)
GN50	grip number at 50km/h g
HCV	heavy commercial vehicles
HMA	hot mix asphalt
HSD	high-speed data
IL	investigatory level
Inc/'Increasing'	linear referencing position – increasing direction of travel
IPENZ	NZ Institution of Professional Engineers

IRI	International Roughness Index
ISO	International Standards Organisation
km	kilometres
km/h	kilometres per hour
LA	local authority
LCV	light commercial vehicles
LGA	Local Government Act 2002
LTMA	Land Transport Management Act 2003
LTSA	Land Transport Safety Authority
LWP	left wheel path
μ	DF Tester CoF value
MAX	maximum value
MIN	minimum value
MPD	mean profile depth
MSSC	mean summer SCRIM coefficient
MTD	mean texture depth
MWD	Ministry of Works and Development
NAASRA	National Association of Australian State Roads Authority
NRB	National Roads Board
NZ dTIMS	Implementation of Predictive Modelling for Road Management software
NZS	New Zealand Standard
OGA	open-graded asphalt
OGPA	open-graded porous asphalt
PCC	Portland Cement Concrete
PMS	Pavement Management Systems Ltd
PSD	particle size distribution
PSMC	Performance Specified Maintenance Contract
PSV	polished stone value
QA	quality assurance
r	coefficient of correlation
R^2	coefficient of determination
RAMM	NZTA road assessment and maintenance management database
RCA	road controlling authorities
RIMS	Road Information Management System
RMA	Resource Management Act 1991
RNZ	Roading New Zealand
RoAR	road analyser and recorder machine
rpm	revolutions per minute
RR	road roughness

RRL	Road Research Laboratory (UK)
RRU	Road Research Unit
RS	reference station
RTRRMS	response-type road roughness measuring systems
RWP	right wheel path
SC	sealing chip
SCRIM	Sideway-force Coefficient Routine Investigation Machine
SFC	sideway friction coefficient
SFC50	sideway-force coefficient at 50km/h
SLP	stationary laser profilometer
SMA	stone mastic asphalt
SMTD	sensor measured texture depth
SN40, SN64	skid number at 40mph, skid number at 64km/h (US locked wheel tester)
SNZ	Standards New Zealand
SRV	skid resistance value
STDEV	standard deviation
t	tonne
T_d	texture (macrotexture) depth (mm)
T_f	traffic factor
TL	threshold level
TMP	traffic management plan
TNZ	Transit New Zealand
TOC	total organic carbon
TPH	total petroleum hydrocarbons
TRRL	Transport and Road Research Laboratory (UK)
TRL	Transport Research Laboratory (UK)
UK	United Kingdom
US, USA	United States of America
v/l/d	vehicles per lane per day
vpd	vehicles per day
VTI	The Swedish National Road and Transport Research Institute