A FUNDAMENTAL APPROACH TO SKIDDING RESISTANCE USING THE IFI

Bevan Sullivan, Pavement Management Services

Abstract

Risk assessment is becoming increasingly popular in the filed of pavement engineering; this is primarily due to the role of the pavement manager essentially being a risk manager, whether this is in assessing the probability for premature pavement failure or in the assessment of potential for accidents due to the skid resistance properties of the pavement surface. Pavement managers can never eliminate the risk of failure or the risk to the public. The best that can be done is to manage, understand and reduce risk.

This paper presents a method for evaluating the risk of skidding and loss of control accidents, based on the theory of the interaction between the tyre and the surface macro and micro-texture used in the International Friction Index (IFI), with the addition of Monte Carlo simulation methods to enable the assessment of risk.

It is in this area, that the theory of the IFI surface tyre interaction is explained in relation to the probability of loss of control and skidding type accidents. A Monte Carlo simulation procedure is then developed to calculate the probability of loss of control and skidding accidents, based on the IFI theory. Actual IFI test results are then used to show practical uses of the theory, to minimise risk and assess risk to the road user.

This paper will also show why a reliance on one skid number is often erroneous and can lead to greater overall risk.

(Keywords, IFI, Monte Carlo, Risk, Skid Resistance, Texture)

1. INTRODUCTION

Surface friction of pavements has and always will be of extreme importance in evaluating the safety of a pavement. The FHWA[1] reported that of over 25 million accidents, 19% occurred on wet pavements. For this reason it is imperative for public safety that pavement managers undertake surface friction surveys on a routine and regular basis. Furthermore, the results and meaning of the measured skid numbers must be fully understood.

Traditionally, pavement engineers have relied upon specifications to assess the relative "safety" of the pavement. The problem with this approach is it does not assess the two fundamental questions the engineer should be asking when evaluating a pavements surface friction, namely:

- Is the vehicle going to be able to stop in the required time/ distance?
- Is the vehicle going to be able to negotiate the curve without losing control?

These two fundamental questions are what are of primary concern to the road user (the public). However, often these questions are hidden or lost by the use of arbitrary standards, although standards in some way may address the issue, they invariably will not answer these questions. Knowing this, it is these two fundamental questions that should be regarded as the primary skid resistance performance response measurements, which all agencies should use to assess the adequacy of skid resistance of the pavement.

However, the use of these fundamental response parameters requires the pavement manager to know and understand the interaction between the tyre and the pavement surface in the braking process. The recent development of the IFI[2] has provided pavement engineers with significantly better and more in depth tools for the understanding of this interaction. With the use of the IFI is now becoming accepted throughout world and its use will continue to increase with increasing familiarity, it is the IFI that should be used to answer these questions.

1.1. Objective

The objective of this paper is to develop a full risk based analysis of the fundamental questions regarding skid resistance, using the IFI and to show how reliance on one skid number alone, can lead to erroneous results.

2. THE FRICTION PROCESS

The frictional characteristics of a pavement surface play an important role in road safety; it is for this reason, pavement managers should be concerned with providing adequate levels of friction for all road users and understand the friction process. Additionally, to be able to answer the proposed two fundamental questions facing the pavement engineer, a basic understanding of how the friction process works needs to be known.

2.1. Effective Skid Resistance

2.1.1. Energy System in the Braking Process

When any object (in this case a vehicle) is in motion it posses Kinetic Energy, therefore to stop a moving vehicle, the total Kinetic Energy must be converted in other forms energy, this process is what is commonly referred to as skid resistance. For any vehicle in motion acting under applied brakes, the loss in kinetic energy from basic mechanics is:

Loss in Kinetic Energy = Work done by Friction + Strain energy stored in the system

Equation 1 conservation of Energy in Braking process

What Equation 1 shows is that the effective skid resistance can be considered to consist of two terms, the friction term (F) and the strain distortion term (D), The distortion term is dependent on distortion of the tyre rubber by the surface asperities and the ensuing energy dissipation in the rubber. The friction term (F) is the resistive forces between two opposing surfaces in this case the tyre and the road and is generally called the coefficient of friction (some times referred to as adhesion).

Under any given set of conditions the effective skid resistance (□) is the sum of the frictional term (F) and the distortion term (D) divided by the vertical load.

It should be noted that, since skid resistance measuring machines cannot determine between the two components of friction, the reported friction values by the skid resistance measuring device is the composite of the two friction numbers.

2.1.2. Factors Effecting Skid Resistance

On a dry pavement the friction term (F) is dominant factor in skid resistance, however, it has been shown that the frictional effect (F) diminishes on wet pavements and with increasing vehicle speed and could become negligible in the condition of "aquaplaning". What this means is that on a wet pavement the distortion term (D) is far more important, since the action of stopping is the result of deformation of the tyre by the surface asperities and the ensuing energy dissipation of the rubber.

From this brief description it can be seen that the four variables influencing the skid resistance process can be concluded to be the tyre, travelling speed of the vehicle (ie. relative speed between the two opposing objects), the minute surface structure between the interfacing contact areas (texture) and contamination of the pavement surface.

2.1.2.1.Definition of Slip Speed

In braking process the terms speed refers to the relative speed between the road surface and the tyre, and is called the slip speed. At one extreme case when the tyre is free rolling there is no slip speed i.e. the relative velocity between the tyre and the road surface is zero, at the other extreme, with a fully locked tyre the relative velocity will be equal to the vehicle velocity.

2.2. Surface Texture Effects

As mentioned before texture is a key variable in the friction process and the two main components of the friction (F) and (D) are in fact determined by the two components of surface texture.

2.2.1. Friction (F)

The sliding contact resistance (F) nature is determined by the properties of the material and the degree of polishing of the aggregates (ie. the micro-texture). The micro-texture (fine texture less that 0.5mm) of the pavement is the main contributor to the sliding contact resistance of the pavement surface (F) and is dependant on the tyres actually contacting the pavement surface. Micro-texture is the major factor in determining the wet skid resistance of the pavement surface at low to moderate speeds.

2.2.2. Distortion (D)

Loss of energy caused by non-elastic deformation of the tyre (D) is associated with the surface texture of the pavement (ie. macro-texture (coarse texture 0.5 to 10mm)) with its nature determined by the shape and layout of the aggregates. Macrotexture becomes the dominant factor at higher speeds allowing rapid drainage routes between the tyre and the pavement surface, therefore, allowing micro-texture contact between the tyre and pavement and also causing tyre rubber deformation (hysteric energy loss), even if surface contact does not occur.

When a water film is present on the pavement surface, penetration of the water film can only be achieved if there are sufficient sharp edges in the macro-texture on which the tyre can build up sufficient dry spots to establish a dry contact area between the pavement micro-texture and the tyre.

The faster the macro-texture asperities of the road hit the rubber the less the penetration will occur and therefore the smaller the real contact area. The smaller penetration also leads to less hysteresis energy loss (D).

This leads to:

- The faster the wheel spins the less friction there will be because of the lower contact area.
- The smaller the texture asperities in absolute size the lower the friction value will be.

i.e. the size of the macro-texture is the most dominant factor in determining rate of change in the effective pavement skid resistance.

2.3. The Effective Friction Curve

Because, one of the fundamental reasons for measuring friction is to predict the safe braking profile of the pavement, determination of how the effective friction μ (F+D) varies in a longitudinal braking process must be understood.

Figure 1 shows an effective friction curve, what can easily be seen is that friction is not constant (and should not be, from what was mentioned before) across the full slip speed and varies as a function of slip speed. It is because of this reason the use of one friction number can be totally misleading.

In the first phase of the friction cure the wheel rotation is gradually reduced from free rolling to a locked state (ie. the relative velocity of the wheel increases). What is shown is that there is a distinct maximum point in the in the available friction, this point is commonly called the “critical slip” speed value and corresponds to the peek friction on the pavement surface.

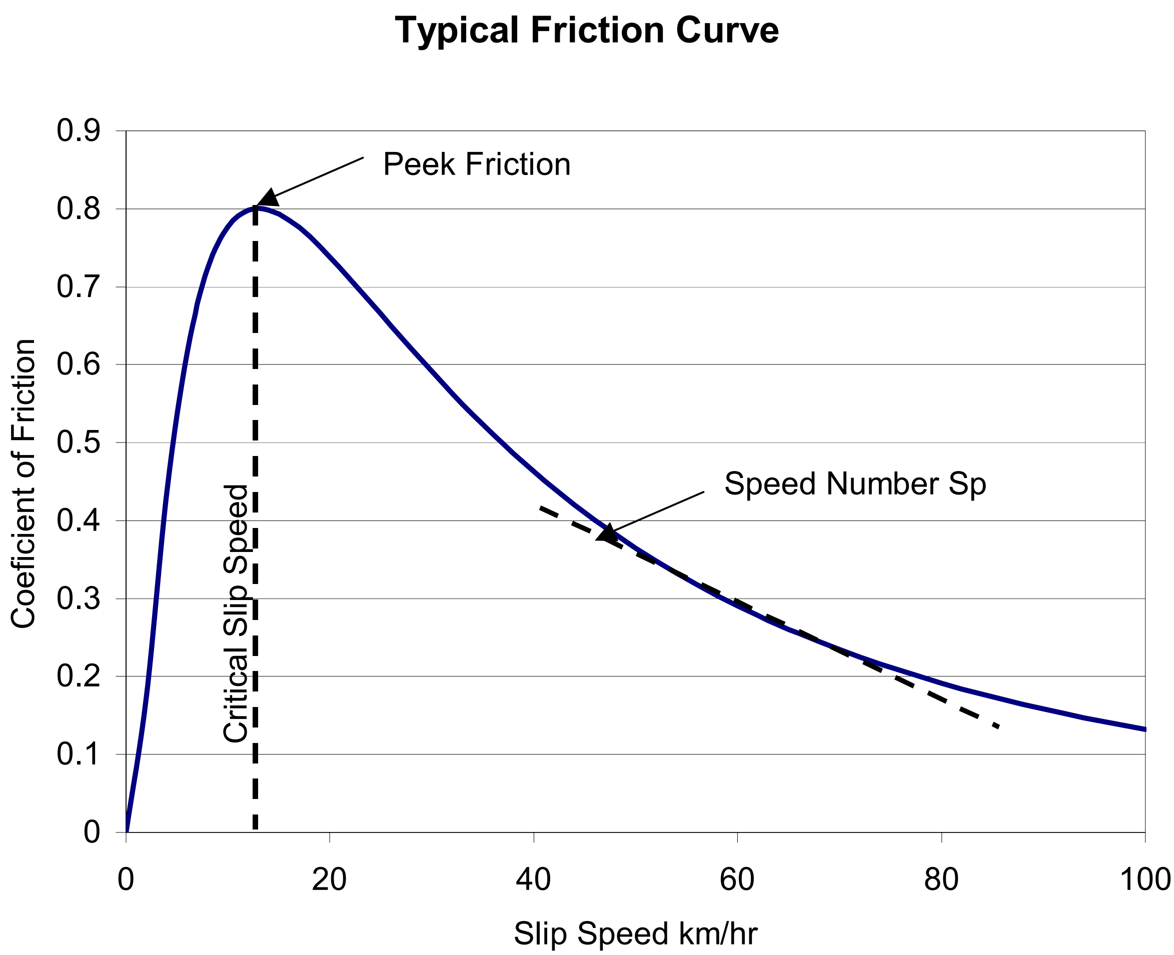

Figure 1 Typical Friction Curve

For values less than the critical slip speed, the tyre has the major influencing factor on the rising part of the curve to the peek friction. The surface becomes the predominant influence on the curve, with higher slip speed after the critical friction point. Where there is decreasing effective friction with increasing slip speed due to the lower overall contact area at higher slip speeds.

2.4. The Use of Friction Numbers

Historically, pavement friction has been measured and recorded as a single number, according to the NCHRP[4] "Recent research however has indicated that a single number index for evaluating friction characteristics of a pavement can be misleading". This is primarily due to the interactive nature of the friction process between the tyre and the road surface and that true friction values can only be obtained from a full-scale measurement incorporating both measurements of the friction and surface characteristics between the two objects. Unfortunately, the use of one friction number is still the practise of many road authorities, which commonly use one number in their specifications.

2.5. Friction Model

The frictional resistive force between any two surfaces is generally expressed in the following expression;

$$F_r = F_n \mu \qquad \text{Equation 2}$$

Where; F_r is the frictional force and F_n is the normal force.

Regrettably, as shown in Figure 1, effective friction μ is not constant across a braking process, where the effective co-efficient of friction μ varies with slip speed, implying that the use of equation 2 averaged across a wide range of slip speeds can and will lead to results that have little to no meaning.

To overcome this PIARC based their harmonisation experiment on the PennState [5] variable slip speed relationship, which modelled the friction process as a function of the slip speed in the post peek friction phase, incorporating both the sliding resistance and texture considerations.

$$\mu_s = \mu_o \exp(s/Vp) \qquad \text{Equation 3}$$

Where; μ_s is the friction at slip speed s

μ_o is the intercept of the friction curve at zero slip speed

Vp is the velocity profile (Velocity susceptibility of friction)

s is the slip speed.

NB the PIARC model only models the 2nd half of the friction curve.

3. HARMONISATION OF FRICTION MEASUREMENT DEVICES

Throughout the world there are numerous methods for measuring and reporting the micro-texture (friction) and the surface texture (macro-texture) of a pavement, many of these evaluation methods have different means and values for reporting of these results.

In 1993 the Permanent International Association of Road Congress acknowledged this problem in the variability in friction measuring devices. In 1993 an international experiment was conducted to “harmonise” the measurements from existing friction measuring devices. From this harmonisation experiment a database of 41 separate pieces of equipment was established. Using this database, regression coefficients were established, so that the measured values from one device can be transformed to the value of any other device, which participated in the PIARC experiments, with the inclusion of a texture a measurement. The results from any device can then be converted to the so-called IFI “Gold values”, which is the standard measurements to which all friction readings should be compared.

3.1. Macro-texture Devices for Speed Constant

The macro-texture of the pavement is the main contributor to the determination of the speed constant (V_p). It was found that a simple linear relationship could be used to determine the speed constant from any piece of texture measurement devices as follows.

$$V_p = a + b \times TX \qquad \text{Equation 4}$$

Where *a* and *b* are experimentally determined constants and TX is the texture measurement form any texture device. To calculate the calibration factors a simple regression analysis needs only to be completed.

3.2. Harmonisation with Friction Devices

The first step in the correlation of the friction measuring devices is to adjust the $\square_s$ to the F60 value. Using the adjusted Penn State Model to IFI slip speed of 60km/hr as given in Equation 5;

μ_s= F60 exp (60-S/Vp) Equation 5

A regression correlation of the measured values is then performed to give the Gold value of F60.

$$F60 = a + b \times FR60$$ Equation 6

A full database of the equipment and their regression coefficients, can be found in ASTM E1960-98[3] which can be used to convert any friction device to the Gold IFI values.

4. CALCULATION OF STOPPING DISTANCE AND TIME PROBABILITY

Considering the proposed two fundamental parameters, the first basic question the pavement manager should be considering, is whether the vehicle can stop in the required distance or time. Taking a vehicle in motion and applying the conservation of energy principal, the energy stored in the vehicle decelerating from *v* to *u* is given by.

$$\frac{1}{2}mv^2 - \frac{1}{2}mu^2 = mg\mu s(friction) + \frac{1}{2}kx^2(hysterisis) \qquad \text{Equation 7}$$

Where *v* is the initial velocity, *u* is the final velocity, the deceleration is given by μg, *k* is the stiffness of the rubber in N/m and *x* is the displacement of the rubber and *s* is the distance travelled in deceleration from *v* to *u*. As mentioned before friction devices collapse both components of friction into an effective coefficient of friction (μ), based on this equation 7 reduces to.

$$s = \frac{v^2 - u^2}{2g\mu} \qquad \text{Equation 8}$$

As described in Section 2 the coefficient of friction (μ) is not a constant in the braking cycle and varies with respect to the relative velocity of the tyre.

Therefore by using the IFI Friction model for F_{60} under a "panic" braking situation (ie. full wheel lock) slip speed v_i is equal to the vehicle speed, then the coefficient of friction at any slip speed is given by:

$$\mu_i = \mu_{60} e^{\left(\frac{60 - v_i}{Sp}\right)} \qquad \text{Equation 9}$$

Where μ_i is the coefficient of friction at slip speed v_i. For small velocity interval (*dv*), the distance travelled in the interval *(ds)*, (simplifying by assuming constant friction across the small interval), is given by.

$$ds = \frac{vdv - dv^2}{g\mu_{60} e^{(\frac{60-v}{Sp})}}$$ Equation 10

In the case of stopping time, from the equations of motion the time interval *dt,* to change velocity *dv* is given by. (Again assuming constant friction across the small velocity *dv* interval)

$$dt = \frac{dv}{\mu_{60} e^{\left(\frac{60-v}{sp}\right)}}$$ Equation 11

If μ_{60} and *Sp* were considered constant in the braking process Equation 12 could simply be integrated between the initial speed and 0, to find the total stopping distance and time. Although, as will be discussed latter in § 4.2, μ_{60} and *Sp* cannot be regarded as constant, so integration is not relevant and numerical methods need to be examined.

4.1. Loss of control accidents

Considering the next proposed fundamental question of whether a vehicle can negotiate a curve at the roadway speed. A vehicle travelling around a bend of radius r with a cross fall of θ degrees, from basic mechanics. The critical velocity (i.e. slide off velocity) is given by:

$$\cos(\theta) mg\mu - \cos(\theta)\frac{v^2}{r} + \sin(\theta) mg = 0$$ Equation 12

Simplifying and solving for v gives

$$v = \sqrt{rg(\mu + \tan(\theta)}$$ or $$v = \sqrt{rg(\mu + \%Crossfall)}$$ Equation 13

In the case of a loss of control accident, loss of control occurs when the available coefficient of friction μ is less than required to keep the vehicle from sliding. From the friction curve in Figure 1 it can be seen that coefficient of friction rises rapidly to a peek point Mu_{peek} if the slip speed of a vehicle in a turning movement exceed this point, it can be considered to have lost control. As the available friction for a vehicle in motion, past this point is always lower than the peek point; thus the friction will not be sufficient enough to stop the sliding of the vehicle.

In the above equation the value of $M\mu_{peek}$ can be substituted into the equation to obtain the maximum speed the curve of radius *r* can be negotiated at without a loss of control.

4.2. Risk Assessment

Like most real world situations, the skid resistant properties μ_{60} , Mu_{peek} and V*p* are not homogeneous on the pavement surface. The properties μ_{60} , Mu_{peek} and V*p* vary in a seemingly chaotic nature on the pavement surface, the distribution of this so called chaotic nature will almost always follow known distributions.

Because of the seemingly "random" nature of the skid resistance measurements, this randomness entails uncertainty in the actual friction numbers. This uncertainty in the input parameters leads to further uncertainty in the output (the proposed fundamental questions). Implying, there will never be a yes/no answer to the question of whether the vehicle can stop in the required distance/time or whether the car will remain in control. This is uncertainty is the definition of risk in engineering.

To be truly able to assess risk in engineering, methods such as Monte Carlo simulation need to be employed; in Monte Carlo simulation, instead of the usual one forecast of performance a hundred or so estimates of performance are made. To make the hundred or so estimates of performance, a hundred or so estimates of the initial state are made, that are, more or less, alike and differ by only no more than the uncertainty in the initial measurements.

By using the physical laws developed in §2 which describe the performance of the system, it can be seen that because of the uncertainty of some of the initial parameters, the hundred or so predictions are not alike. *If there is no basis for saying which of the initial parameters are correct, there is no basis for saying which of the results are correct*.

It is this uncertainty is what then becomes risk.

4.2.1. Stopping Distance

For the case of the stopping distance, it was shown that stopping distance is a f^n(Vp, Vehicle speed, and μ_{60}). The distribution of these parameters can generally be found to follow log-normal distributions; although, this is not always the case and should be investigated on a cases by case basis. If the known distribution of theses input parameters (V_p, Vehicle speed, μ_{60}) are then used as the input parameters for the calculation of stopping distance/time. A realistic distribution of the stopping distance/time will then be obtained from the solution.

The distribution of the stopping distance is achieved by selecting "random" values from the known distribution of $\mu_{60 \text{ and}}$ V_p using approximation methods. The selected values are then used as the input parameters in the prediction model to calculate the distance travelled in the small change of velocity. Random values again selected for all subsequent small velocity intervals, until the velocity of the vehicle is equal to zero. The distances travelled for each velocity interval are then summed to calculate the total stopping distance for case (i).

This process is then repeated for a statistically significant number of iterations and the distribution of stopping distance/time is then obtained. The probability that the stopping distance/time is less or greater than a set distance/time is can then be determined from the distribution results, which then becomes the level of the risk, this process is illustrated in the flow chart in Figure 2.

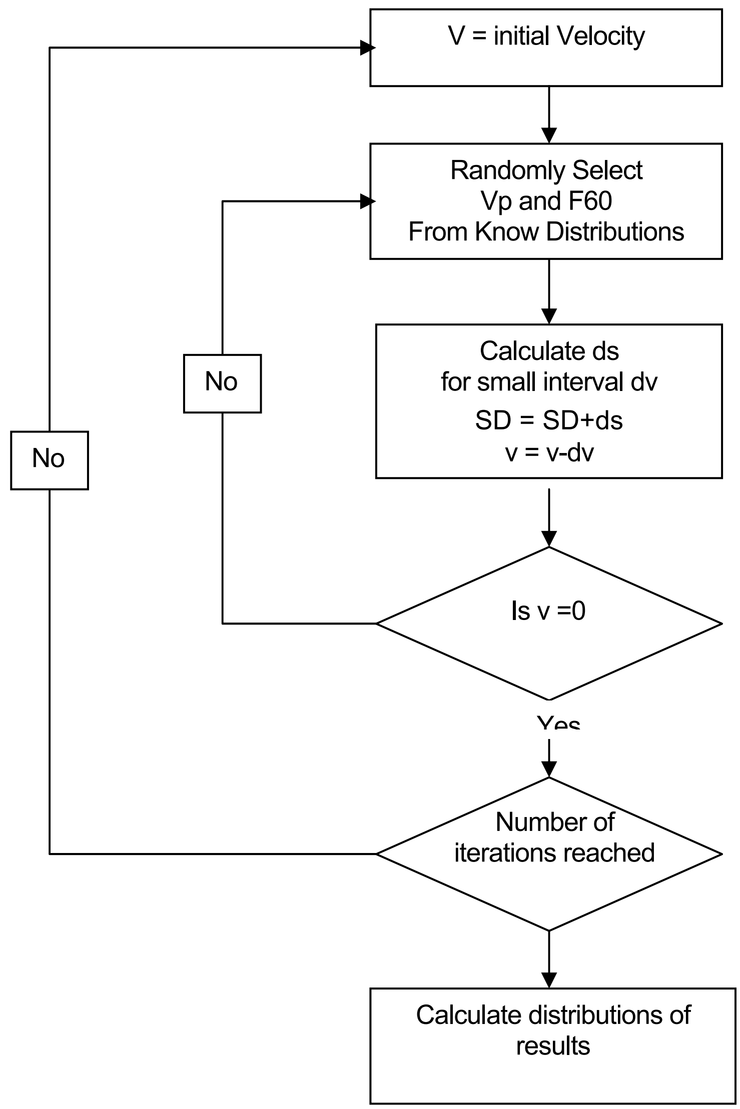

Figure 2 Flow Chart for calculation of Stopping Distance

4.3. Loss of control

Like stopping distance values the μ_{peek} measurements cannot be considered to be homogeneous and the safe negotiating speed around a curve cannot be determined defiantly. Thus only the probability of a vehicle losing control at a set speed on a curve with known radius and known distribution of μ_{peek} and cross fall can be determined. Unlike stopping distance/time, numerical integration methods are not required and the central loop in the flow chart disappears in the probability analysis.

5. Uses of Probability Analysis

5.1. Determining the Best Surface

The final uses of the probability analysis are varied; one of the primary uses found is for the determination of the best surface treatment for new pavements and resurfacing of old pavements, to minimise the risk of skidding accidents, take the following example which are real situations.

Two sections of pavement were in need of resurfacing, the first section was in a residential area with a speed limit of 60km/hr, the second is on a semi-rural road area with a speed limit of 100km/hr.

It was known that both sections have potential skid resistance problems, at the time of resurfacing two high friction surface treatment options where available, with distribution of skid resistance properties shown in Table 1 (obtained form previous sites). The two surface treatment options available were a blast furnace slag and a rhyolite surfacing. What especially should be noticed, is that the rhyolite surface has a higher F_{60} value but a lower velocity profile (ie. it is more susceptible to changes in vehicle speed) with respect to the slag asphalt.

Table 1 Log-normal Distribution Friction Properties

	SLAG		RHYOLITE	
	AVERAGE	STND DEV	AVERAGE	STND DEV
F60	-1.204 (~0.3)	0.220	-1.050 (~0.35)	0.220
Sp(km/hr)	5.011 (~150)	0.629	4.248 (~70)	0.629

Reliance on traditional standards and methods would suggest that the rhyolite surface is the preferable surface for both locations. To check this assumption, the Monte Carlo simulation method, using the IFI theory was then used to determine if this was the case at both locations.

5.1.1. LOCATION 1

Location 1 was at the approach to a set of traffic lights in a 60km/hr zone; it has a required stopping distance of (40m). By using the Monte Carlo simulation with the IFI theory, the probability that the vehicle would not stop in 40m or was determined for both cases, with the results shown in Figure 3 in the form of a cumulative frequency distribution. The simulation revelled that if the slag surfacing was used to resurface this location a vehicle travelling at 60km/hr would have a 38% probability of stopping distance being greater than 40m in adverse driving conditions, with an average stopping distance value of 39.1m

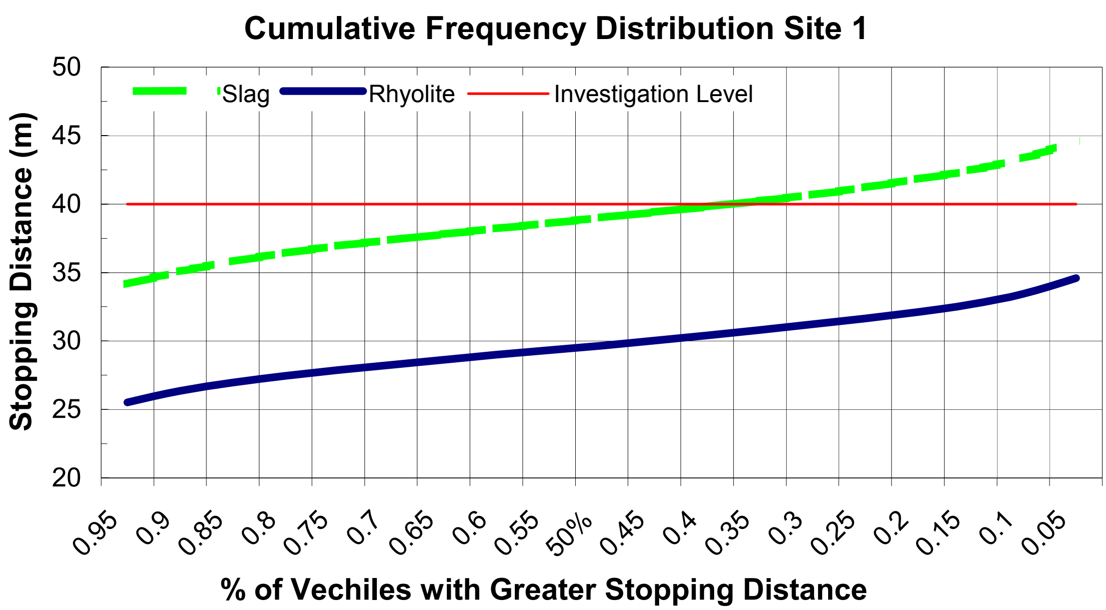

Figure 3 Stopping Distance Distribution Site 1

If the rhyolite surfacing was used to resurface this location; the results indicate that there is a statistically insignificant chance of stopping distance being greater than 40m with an average value of 29.8m.

This indicates, that at relatively low speed the predominate factor in calculating stopping distance is the coefficient of friction and resurfacing the section with rhyolite would provided, by far the lowest overall risk to the public.

5.1.2. Location 2

The second location in the semi rural area, had a stopping site distance determined at 130m. Using the Monte Carlo simulation with IFI theory, the probability that a vehicle would not be able to stop in the 130m, travelling on the two separate surfacing was determined.

The results of the Monte Carlo analysis are shown in Figure 4, in the form of a cumulative frequency distribution. The analysis revels that for a vehicle travelling at 95km/hr, the slag surface would result in a probability of the vehicle not stopping within the 130m of 27% with an average value of stopping distance of 128m.

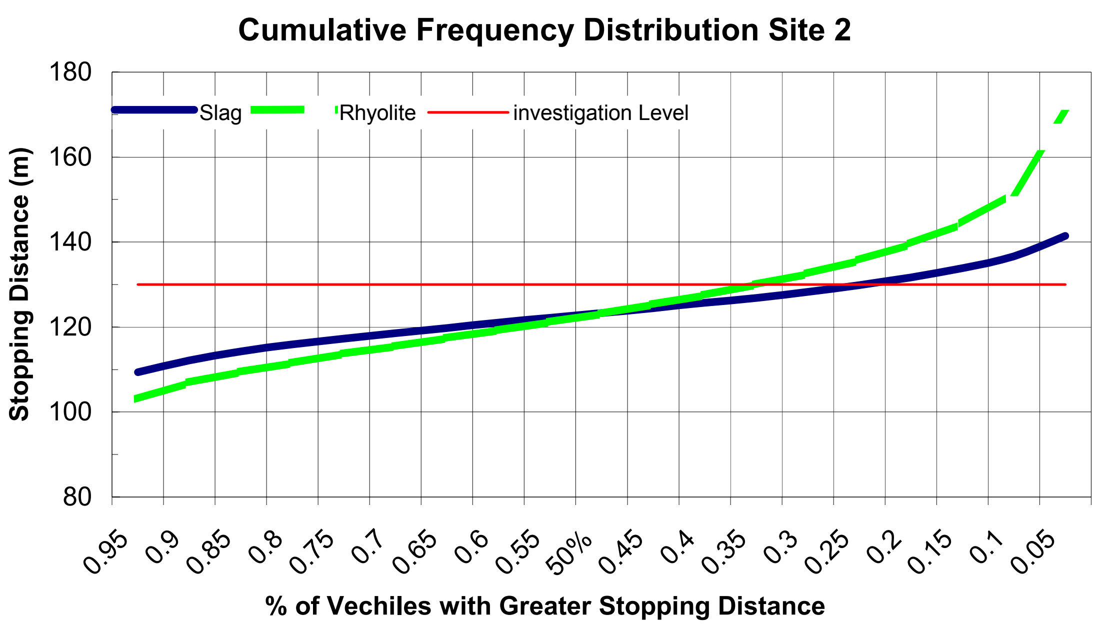

Figure 4 Distribution of Stopping Distance Site 2

The same vehicle travelling on a rhyolite surface would have a probability of not being able to stop in the 130m of 35%, with an average stopping distance of 124m. What this shows is that texture measurements must be included in skid resistance analysis, to give true meaningful results.

From this it can be seen that the surface texture begins to plays the more dominant role in the calculation of stopping distance over the F_{60} value, contradictory to methods still being specified by many road authorities.

To lower the overall risk the slag surface should be chosen, to resurface this location.

5.2. Loss of control

The major use of found for the loss of control analysis (except in the case of accident investigation), was in prioritising resurfacing work on the network basis. This was done by determining the probability that vehicles cannot negotiate the curves on the network at the posted speeds and then ranking those sections in decreasing probability. Figure 5 shows a typical frequency distribution of the calculated critical velocities.

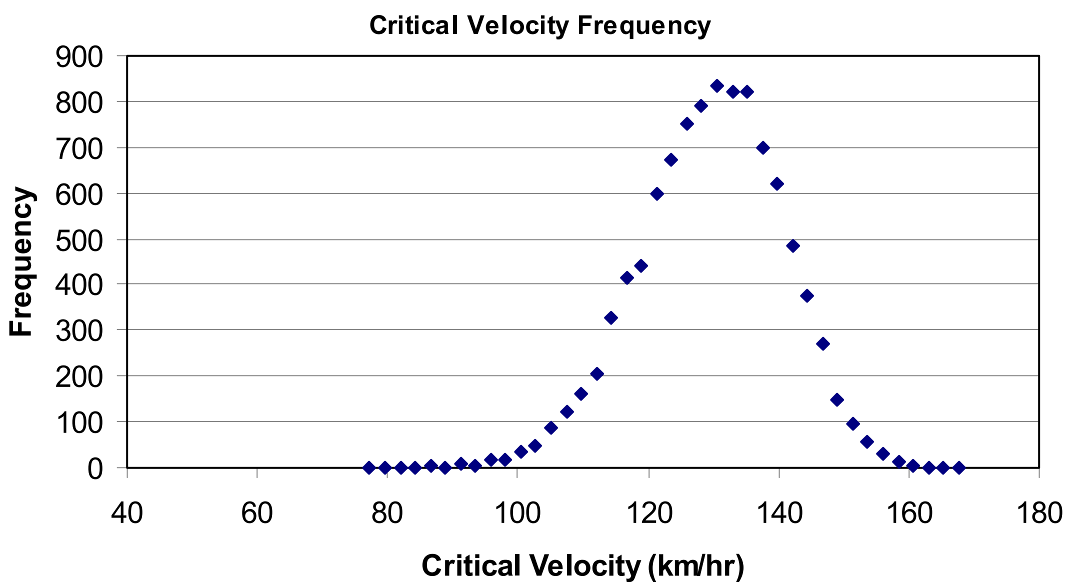

Figure 5 Frequency Distribution of Critical Speeds

6. CONCLUSION

The use of the IFI along with risk-based assessments, can give the pavement engineer a significantly greater understanding of the fundamentals of the skid resistance properties of the pavement as well as the risk involved with their decision. It is unfortunate that may pavement engineers, ignore or do not understand the fundamentals of skid resistance and rely solely on one “skid number”. This reliance on one skid number can often effectively place the road user at greater risk.

This paper showed how the assessment of the skid resistance properties of a pavement is essentially an investigation into risk. The assessment process used in this paper was based on the recently developed IFI, which was shown to account for both components of skid resistance and thus model the whole friction process.

The paper also showed how the use of one friction number can lead to greater overall risk to the road user; as the use of one friction number does not and can not model the whole friction process and thus can give meaningless results.

7.REFERENCES

1) FHWA-PL-94-010 *"Nationwide Personal Transportation Survey"* Federal Highway Administration (FHWA), Washinton, 1993.

2) PIARC Report 01.04.T. *"International PIARC Experiment to Compare and Harmonise Texture and Skid resistance Measurements"* PIARC, France, 1995

3) ASTM E1960-98 "Standard Practice for Calculating International Friction Index of a Pavement Surface" American Society for Testing and Materials, 1998

4) Synthesis of Highway Practice No.291 *"Evaluation of Pavement Friction Characteristics"* National Cooperative Highway Research Program, Transport Research Board, Washington J.J. Henry, 2000

5) *"Skid Resistance Manual*." The Pennsylvania State Transportation Institute, B.T. Kulakowski, D.W. Harwood, D.R. Hiltunen, J.M. Mason, Jr., W.E. Meyer, S.L. Simoneau, and J.C. Wambold, September 1990.

6) "*THE NORSEMTER PRIMER on modern tire-to-roadway surface friction measurement*." Norsemeter, Norway 1995

7) TP-GDL-009 "*VicRoads RTA, A guide to for the measurement and interpretation of skid resistance using SCRIM*" Roads and Traffic Authority NSW, August 1995

8) "*Overview of the International PIARC experiments to compare and harmonise texture and Skid Resistance measurements*", Proceedings of the 3rd International Symposium on Pavements Surface Characteristics, J.J. Henry, Sep 1996

9) "*The determination of skid resistance speed behaviour and side force coefficient of pavements*", Transport Research Record 666, Washington D.C, Shah, V.R and Henry J.J, 1992

10) Pratt D "Skid resistance monitoring in Australia, Steps towards national guide lines and portability of results From PIARC International Experiments."