TRANSPORT RESEARCH LABORATORY

High and low speed skidding resistance: the influence of texture depth

Prepared for Pavement Engineering Group, Highways Agency

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Executive Summary

The provision of adequate friction between the tyre and the road surfacing, especially in wet conditions, is a key factor contributing to road safety. Over many years, research has enabled specifications to be developed which allow newly-laid surfacings in the UK to be designed to provide adequate skidding resistance performance for their expected life. These requirements are further supported by Standards for the skidding resistance of in-service roads which include routine monitoring of low-speed skidding resistance.

Since the time of the research on which current standards are based, traffic volumes have increased. Also, an increasing number of proprietary materials have been developed that were not covered by the earlier work. Therefore, given the importance attached to skidding resistance policy in the UK, the Highways Agency commissioned further research which would re-visit the earlier work and assess the influence of texture on the relationship between high- and low-speed skidding resistance for the wide range of surfacings now used on UK trunk roads. This report describes the main programme of this project and the results of the first phase of analysis.

For the new project, it was necessary to make direct measurements of locked-wheel friction over a wide range of speeds. The Highways Agency purchased a K J Law T1290 Pavement Friction Tester (PFT) for this purpose. This device measures locked-wheel wet friction, *Fn*, using a standard tyre mounted on one wheel of a purpose-designed trailer, at speeds up to 130km/h (80mph). The test wheel is momentarily locked and released under computer control; the load and drag forces are recorded at 0.01s intervals throughout the braking cycle.

A database has been built from measurements of friction and texture depth on a wide range of surfacing types. This includes examples of all the major surfacing types used on main roads in the UK, together with some additional surfacings on the TRL test track. Where possible, a range of levels of low-speed skidding resistance and a range of texture depths representative of each surfacing type have been sampled.

At each site, SCRIM (sideway-force coefficient routine investigation machine) was used to measure low-speed friction and provide a comparison with routine measurements on the network. The texture depth was recorded at the same time as sensor-measured texture depth (SMTD). The PFT was used to measure *Fn* at the site, at five speeds ranging from 20 to 130km/h. Some 2000 individual friction measurements on 133 sites at 21 locations make up the database analysed for this report.

As expected, the results showed that friction falls with speed. It was found that a quadratic equation provided the best representation of the friction versus speed relationship for the smooth test tyre. Individual equations were developed for each site, with excellent correlation to the measured data. This provided a means of determining the friction at any intermediate speed on each site with considerable confidence.

The analysis has led to a number of important general observations:

- For the smooth tyre, friction reached its lowest level by about 100km/h.
- The level of high-speed friction of a surfacing depends to a large extent on the low-speed friction. This was an expected finding, but the work now provides firm evidence for it.
- Friction on surfaces with a low texture depth falls more rapidly with speed than for high-textured surfaces.
- Texture depth has a marked impact on friction loss at slow speeds. This is an important finding because hitherto it has often been assumed that texture depth is not a significant factor for low-speed roads.
- The effect of texture depth on loss of friction was similar for all impermeable materials. This is a significant finding because it means that the historic distinction between transverse-textured and random-textured materials may be inappropriate.
- The effect of texture depth on loss of friction was found to be greatest below about 0.7mm SMTD. Above this level, increased texture had a relatively small effect.

It has also been possible to show that an empirical model can be developed which will allow high-speed friction to be reliably predicted from measurements of SCRIM Reading and SMTD for most surfacings, although porous materials may behave differently from impermeable materials.

The results of this work confirm the basis of current standards, which were derived from earlier research, and point the direction that further research and specifications should take.

1 Introduction

A key aspect of road safety is the provision of adequate friction between the tyre and the surfacing, especially in wet conditions. As a result of research in the 1970s (Salt and Szatkowski, 1973, Salt, 1977), the Department of Transport was able to introduce Standards for newly-constructed surfacings designed to provide improved skidding resistance performance for the expected life of the surfacing. However, traffic volumes continued to grow, with increased wear and tear on road surfacings, and in the late 1980s the provisions were developed further by the introduction of Standards for the skidding resistance of in-service roads.

It has been known for many years that friction falls as vehicle speeds increase and that the extent to which this falls is governed by the texture depth of the surfacing. However, at the same time as the Skidding Standards were developed, a study into the relationship between the texture of road surfacings and accidents (Roe, Webster and West, 1991) suggested that accident risk increased as texture depth reduced and that, therefore, the texture depth of in-service roads might also need to be taken into account in future standards. That work also indicated that macrotexture may be of greater importance at low speeds than had previously been thought.

Given the importance attached to skidding resistance policy in the UK, in 1995 the Highways Agency commissioned further research in order to reassess the earlier work and the influence of texture on the relationship between high- and low-speed skidding resistance for the wide range of surfacings now used on UK trunk roads. This report describes the main programme of work, the results of the first phase of analysis and briefly discusses some of the practical implications which emerge.

2 Terms to describe the friction and texture of road surfacings

2.1 Terms for friction

The term ‘friction’ is used to describe the forces resisting motion when two surfaces are in contact. The ‘coefficient of friction’ is defined as the force resisting motion divided by the vertical load. In the context of roads, the force resisting motion is developed between a vehicle tyre and the road surface. Thus, in any specific situation, ‘friction’ depends upon a combination of factors which include the properties of the particular tyre rubber, the materials forming the road surface, any contaminants or lubricants (such as water) which may be present at the interface, and the ability of either the tyre or the road to remove them. Tyre/road friction in dry conditions is generally high but the presence of even a very thin film of water dramatically reduces the coefficient of friction. For this reason, tyre/road friction is normally studied in wet conditions.

When dealing with roads, specific terms and measurements are used which describe the behaviour of the road under standardised conditions. The term ‘skidding resistance’ is used to refer to the extent to which the road contributes to friction. This is a general term and, unless otherwise qualified, refers to wet conditions.

Skidding resistance can be measured in a number of ways, usually involving sliding some form of rubber over the wet road and measuring the forces developed under a known load. Vehicle-based systems use a test wheel of some kind, usually with a standardised tyre, to measure the sliding forces. Skidding resistance varies with vehicle speed and, therefore, this factor is commonly standardised for network monitoring. The load is usually fixed and, depending on the equipment, is either assumed to be constant or is measured dynamically. There are three main approaches:

- ***sideway-force***

  With this technique, the force developed on a rotating wheel, set at an angle to the direction of travel, is measured to give a ‘sideway-force coefficient’ (SFC). This method is particularly suitable for continuous measurements of long lengths of road because the test tyre rotates and therefore wears comparatively slowly. However, for practical purposes, the method can only measure skidding resistance at slow speeds. This limitation is a result of angling the test wheel while allowing it to rotate; the rate at which the rubber in the contact patch slides in the forward direction is always significantly less than the speed of the test vehicle. The SCRIM (sideway-force coefficient routine investigation machine) is the well-known UK example of this technique.

- ***fixed-slip***

  With this method, the friction is developed by a tyre running in line with the direction of travel but forced to rotate more slowly than the vehicle speed would require, and is thus constantly slipping. As with sideway-force, the actual slip speed of the tyre is slower than the test vehicle speed. The GripTester is an example of this method.

- ***locked-wheel***

  This method measures the force on a wheel which is sliding but not rotating, and therefore the slip speed is the same as the speed of the test vehicle. The Pavement Friction Tester (see Section 3) uses this technique. This is the only approach which can measure sliding friction directly over a wide range of speeds.

In this report the following terms are used:

- *skidding resistance* and *friction* are used widely in their general sense, according to context;
- *friction number (Fn)* is used when referring specifically to measurements made with the Pavement Friction Tester. Section 3 gives more details of how these measurements were made for this study. Throughout this report *Fn* refers to the locked-wheel friction measured using a smooth tyre and a nominal water depth of 1mm. Where appropriate, a subscript indicates a specific speed;

- *SCRIM Reading (SR)* is used when referring specifically to SFC measurements made with SCRIM. An SR represents the ratio of the sideways-force divided by the load, multiplied by 100[1]. Throughout this report, SR refers to wet-road measurements at the standard vehicle speed of 50km/h;
- *braking force coefficient (BFC)* is a general term often used to describe locked-wheel friction measurements. In this report, it is used specifically to refer to earlier measurements of locked-wheel friction made with the small-wheeled BFC trailer, developed at the then Road Research Laboratory in the 1960s (Sabey, 1966).

2.2 Terms for texture

Traditionally, road surface texture has been used as a general term to describe the rugosity of the surfacing. It has different components which make different contributions to tyre/road interaction. The most familiar of these is that deeper textures reduce the extent to which skidding resistance falls as speed increases. Texture can be described in a number of ways and various procedures have been devised to quantify different aspects.

Traditionally, texture has been described in terms of two components:

- *microtexture*, the fine component of the texture formed by the small interstices on the surface of aggregate particles or fine grains in the matrix of the surrounding material;
- *macrotexture*, the coarser texture formed by the general shape of, and the spaces between, the particles or grooves in the surfacing.

However, in recent years, road surface texture has also been analysed in terms of its profile along the road and distinctions made between amplitude and wavelength. This has led to a number of attempts to define more precisely and quantitatively what the terms mean. The reader is referred to the report on the International PIARC Experiment to Compare and Harmonise Texture and Skid Resistance Measurements (Wambold, et al, 1995) for a detailed discussion of this topic. These developments have introduced a further component:

- *megatexture*, which, although its effect on friction is not clear, has been shown to be important in relation to tyre/road noise generation; it is the component of the profile of a surfacing with wavelengths in the range 50 - 500mm.

The introduction of the concept of megatexture means that the term *macrotexture* now has a more restricted and specific meaning in relation to texture wavelengths than has been the case in the past when it was simply a general term for the coarser part of the texture. These concepts are important when it comes to measuring texture and understanding the meanings of the terms used in this report.

[1]*This value is not the same as the SCRIM Coefficient (SC) used, for historical reasons, for comparison with investigatory levels in the Skidding Standards (SC = SR x 0.0078).*

2.2.1 Describing the form of surface texture

The surface texture of a road can be formed in a variety of ways, depending upon the nature of the surfacing material. When texture was commonly formed by scattered aggregate particles bound to the surface by bitumen, or by brush-marks on concrete, the distinction was straightforward. However, with the advent of permeable surfacings and an increasing number of proprietary materials in recent years, there are now a number of forms which texture may take.

Two principal terms are used in this report to describe the texture of surfacings in the horizontal plane:

- *random* texture, which does not follow any specific direction or pattern;
- *transverse* texture, which is formed from roughly parallel striations following a line perpendicular to the normal direction of traffic and is typically formed by brushing wet concrete or sawing grooves in hardened material.

The ways in which texture is formed also differ in the vertical plane and, in this report, the terms *positive* or *negative* are used to describe them:

- *Positive* texture is formed by particles or ridges which protrude above the plane of the surface. Typically, such textures are formed by applying chippings to an essentially smooth surface and rolling them (as in rolled-asphalt or surface dressing, for example). Positive texture may also be formed by removing the surrounding matrix to expose aggregate particles (such as in exposed-aggregate concrete or a weathered asphalt). The term also describes the texture formed on transversely brushed concrete;
- *Negative* texture is a term often applied to materials in which the texture largely comprises voids between particles whose upper surfaces form a generally flat plane. It can also be used to describe grooved concrete, especially where the grooves have been sawn after the original brush-marks have been worn away by traffic.

In addition to these terms, it is also necessary to distinguish between textures which have different internal structures within the surface layer. These relate primarily to the ability of the material to permit the flow and drainage of water within the structure of the surfacing:

- *porous* texture allows some water to pass through the body of the wearing course material as, for example, porous asphalt;
- *impermeable* materials do not allow water to penetrate the surface and flow through the texture in between the particles that form the surface; rolled asphalt, surface dressings and concrete are examples of impermeable textures;
- *sub-surface voids* are textures which are not porous but allow water to be held within the surfacing and to pass between inter-connected voids just below the running surface. However, the interconnection of the voids is not as great as in porous materials. Some of the new thin surfacing materials have this type of texture.

Judging which of these categories applies to a particular surfacing type is, at present, somewhat subjective, particularly in relation to positive and negative texture and permeability.

2.2.2 Measuring road surface texture

2.2.2.1 Microtexture

Microtexture exists on a microscopic scale. The PIARC International Experiment definition, for example, suggests peak-to-peak amplitudes in the range 0.001 to 0.5mm (Wambold et al, 1995). It is therefore very difficult to measure and, at present, no means exist to monitor microtexture directly on a practical scale. Therefore, where a factor is needed to quantify its effect, a surrogate has to be found. Low-speed measurements of skidding resistance are often used for this purpose because microtexture is the dominant factor influencing skidding resistance at low speeds.

2.2.2.2 Macrotexture

There are two approaches to quantifying the coarse component of road surface texture. One of these is to measure its average depth, usually in either of two general ways:

i use a volumetric technique to physically fill the spaces beneath the peaks with a known volume of material, measure the area covered and calculate the average depth of the texture;

ii make a sequence of displacement measurements along the line of the surface profile, usually using a laser, and then calculate a value to represent the average texture depth.

Examples of these methods are:

- *sand-patch (SP)* which measures the average depth below the plane containing the highest points in the surfacing;
- *sensor-measured texture depth (SMTD)* which is essentially the root-mean-square texture calculated from a sequence of displacement measurements, and is the method used by the various TRL texture meters;
- *mean profile depth (MPD)* is broadly equivalent to the sand patch, calculated from a detailed profile measurement; this will be the basis of future international standards and various organisations are investigating the means of measuring texture routinely in this way.

These methods all relate to the surface texture depth and, on a given surfacing, will correlate with one another. However, they do not necessarily give the same values. They all suffer from the same defect in that, because they work with samples over large areas or lengths compared with the macrotexture wavelength band, they also inevitably include a component of megatexture. They therefore should be properly described as measurements of *texture depth* rather than measurements of *macrotexture*.

The second approach to quantifying coarser texture is to compute amplitudes in wavelength bands. This is done by measuring a very detailed profile and then, by Fourier analysis techniques, breaking it into its component wavelengths and hence determining the average amplitudes in the required bands.

Throughout this report, all measurements of texture are *texture depths*, using the SMTD method, in millimetres. This method was used because it was the only technique currently available for routine measurements of continuous lengths of road at traffic speeds.

3 The Pavement Friction Tester

A key requirement of the project was the measurement of skidding resistance over a wide range of speeds. Although SCRIM is capable of running at vehicle speeds of up to 100km/h, the resulting slip speed between the test tyre and the road is relatively slow because it uses an angled wheel. Also, in order to make an assessment across the full range of typical vehicle speeds on in-service roads, an ability to measure skidding resistance directly at up to 130km/h was needed. The earlier work was carried out using a special trailer with a small single test wheel mounted to follow the centre line of the towing vehicle. For this project, the Highways Agency acquired a K J Law T1290 Pavement Friction Tester (PFT), which was delivered early in 1996.

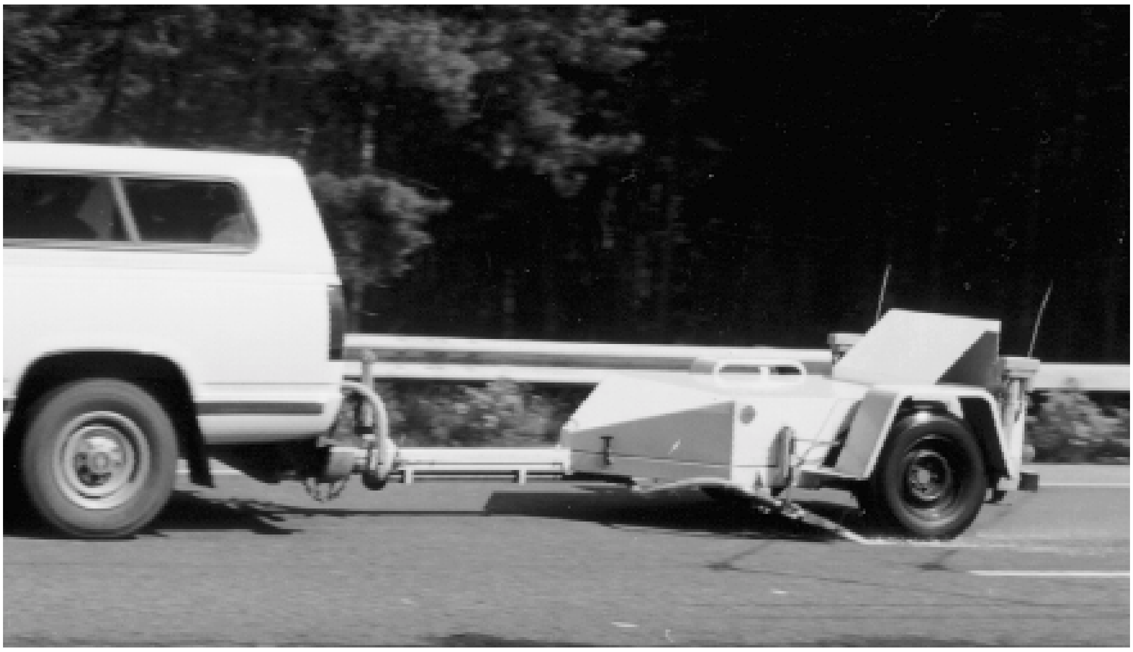
The PFT (Figure 1) is based on standard equipment used in the United States with some modifications to make it more suitable for this research. It uses the locked-wheel principle to measure friction and is designed to make measurements in accordance with the ASTM Standard E274 (ASTM,1990). It comprises a towing vehicle (in this case a Chevrolet Silverado 3.5 ton pick-up truck) and a purpose-built test trailer. The trailer has two wheels with hydraulically-applied disc brakes actuated by a compressed-air servo system. On the UK machine the left-side trailer wheel is fitted out as the test wheel. The test-wheel axle is fitted with a two-axis force transducer which measures the vertical force (load) and horizontal force (drag) on the wheel. Shaft encoders enable the speeds of both wheels to be measured. The load bay of the truck contains a water tank, the trailer-brake air compressor and power supplies for the electrical equipment. The control console, an on-board computer (to control the tests and record the data) and a printer are fitted in the crew cab of the truck.

When a test is initiated, water is pumped from the tank through a special nozzle on the trailer to wet the road surface in front of the test wheel. The pumps are geared to the truck drive shaft so that the flow rate automatically increases as the vehicle speed increases to maintain the nominal water depth. Either of two values of water depth, 0.5mm or 1mm, may be selected. The actual depth of the water above the contact surface of the road will depend upon the texture of the surfacing.

For the purposes of this project, the PFT was operated using the five-stage test cycle defined in E274. These stages are:

- start water pump before testing (0.5s);
- brake-test wheel from rolling to locked (lock-up must occur in less than 2s);
- allow locked test-wheel to settle (0.5s);

a Rear view showing trailer with water nozzle in ‘parked’ position



b Side view, carrying-out a wet locked-wheel test (trailer wheel not rotating while vehicle is moving)

Figure 1 The Pavement Friction Tester

- calculate locked wheel friction (1s);
- allow test-wheel to spin-up to vehicle speed (0.5s).

The times in brackets for the individual stages are the default settings for the equipment, but each may be varied by the operator. The load and drag forces, together with the trailer and test wheel speeds, are recorded at 0.01 second intervals throughout the whole cycle. The friction is calculated automatically from these measurements.

Figure 2 illustrates graphically the results of a typical skid cycle, in this case a 50km/h skid on a rolled asphalt surfacing. It can be seen that there is inevitably some ‘noise’ in the results, which is why calculations of *Fn* are made as the average over a one-second period. In order to determine values in other parts of the cycle, such as the ‘peak friction’, it is normal practice to use a five-point moving average rather than the instantaneous readings shown here.

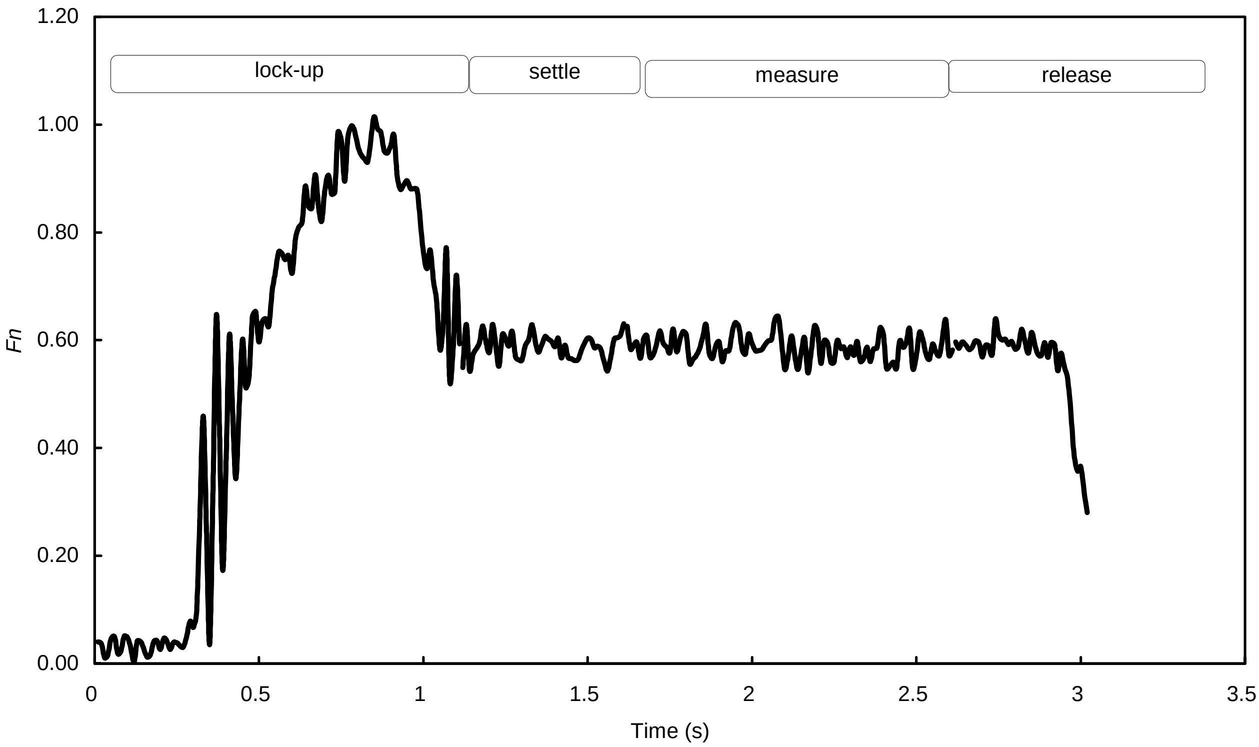


Figure 2 Graphical representation of the results from a typical locked-wheel braking cycle

All PFT measurements included in this report are of locked-wheel friction, made using the E274 test cycle at 1mm nominal water depth and a smooth tyre (ATSM E-524, ASTM, 1988).

4 Methodology

The primary objective of this research was to reassess the influence of texture on the relationship between high- and low-speed skidding resistance, taking into account the wide range of surfacings now used on UK trunk roads. In order to achieve this, a database has to be built from measurements of friction and texture depth from a number of locations, chosen to provide examples of as many types of surfacing as was practicable.

Potential sites were inspected and judged as suitable for inclusion in the database, based primarily upon the surfacing types present and their condition, but also taking into account the suitability of the location for testing with the PFT at the range of speeds involved. Examples of all the major surfacing types used on main roads in the UK, including some newer proprietary materials were identified. Specialised surfacings such as calcined bauxite-based high-friction materials were excluded because, by their nature, they are usually used at high-risk sites unsuitable for high-speed testing. Some additional surfacings from the TRL test track were also included. As far as possible, a range of levels of low-speed skidding resistance (a surrogate for microtexture) and a range of texture depths representative of each surfacing type have been included.

4.1 Initial site screening

At each location, SCRIM was used to provide a continuous measure of low-speed friction for an initial screening of the levels of microtexture on each surfacing at the site. At the same time, a corresponding record of texture depth (SMTD), was obtained using the high-speed texture meter (HSTM) (Roe, 1992) or one of its derivatives such as a texture sensor mounted on the SCRIM machine. Both the SR and SMTD values were recorded as averages over successive ten-metre lengths of road.

From the SCRIM and texture measurements, individual sites were selected for further study using the PFT. The selection criteria were that the SCRIM Reading (SR) and SMTD should be as uniform as possible over an approximately 200m length. This length of uniform material was needed to accommodate the variable length of road covered by the locked-wheel skids over the range of different speeds. Where possible, a number of examples of different levels of SR or SMTD were identified for each surfacing type at each location.

4.2 Measurements with the PFT

For each skid site identified, the PFT was used to make full locked-wheel measurements at a range of speeds. Normally, five target speeds (20, 50, 80, 110 and 130 km/h) were used. The skids were triggered at different points for the different speeds so that all the skids on the site were centred as closely as possible to a fixed point on the road.

Generally, three replicate passes were made at each speed. In some situations, the traffic management arrangements or road layout precluded measurement at the highest speed, in which case the fastest practical speed was used.

Where time permitted, similar measurements were also made using a ribbed tyre, but at the time of writing these tests have yet to be analysed.

The recorded *Fn* values were used to generate an equation for the relationship between friction and speed for each site. At the equipment evaluation stage of the project, it had been found that a quadratic relationship provided the best general fit over a range of surfacings and this basic model has been used throughout (see Section 7). Using this approach ensured that all the data at each site were taken into account and automatically corrected for any speed variations which inevitably occurred. Also, individual skids which were obvious outliers for whatever reason (for example, wrong test line) could be disregarded. Further, the best-fit model allowed subsequent calculation of *Fn* at any selected standard speed regardless of whether the actual measurements were made at that particular speed.

5 Sites studied

For this report, some 2000 individual smooth-tyre friction measurements, made at 133 sites in 21 locations, have been analysed. The practical requirements for high-speed testing meant that most sites were on dual carriageways or motorways. All the main surfacing types used in the UK are represented and some of the surfacings were the only examples of their type in the UK.

The surfacing types represented may be grouped in terms of their texture characteristics as described in Section 2.2.1, and are listed below. Proprietary surfacings have been given generic descriptions (Laws, 1998). The abbreviations used in later tables and graphs are in brackets.

- *Random, positive, impermeable texture*
  - hot-rolled asphalt with pre-coated chippings (HRA)
  - surface dressing (SD)
  - fine cold asphalt (FCA)
  - exposed-aggregate concrete (EAC)
- *Transverse texture*
  - brushed concrete (BC)
  - tined concrete (TC)
  - grooved concrete (GC)
- *Random, negative, porous texture*
  - porous asphalt (PA)
  - paver-laid surface dressing (PLSD)
- *Random, negative texture with sub-surface voids*
  - thin polymer-modified asphalt concrete (TPMAC)
  - stone mastic asphalt (SMA)
- *Other (test track) surfaces*
  - mastic asphalt without pre-coated chippings (MA)
  - Bridport gravel/quartzite mix macadam (BQ)

The number of sites of each type, together with the ranges of low-speed skidding-resistance levels and texture depths of these materials are given in Table 1. Their distribution is illustrated in Figure 3, which shows the 100m average SMTD and SR for each PFT measurement site. The SCRIM measurements in this graph are acting as a surrogate for microtexture, as explained in Section 2.2.2.1. It should be borne in mind that these sites were deliberately chosen to provide a range of values that can occur on the different surfacings; they are not necessarily typical of the materials on the network as a whole.

It is noteworthy that, apart from one site (the mastic asphalt on the TRL test track), there are no sites with SCRIM readings below 47. This is partly because such sites are rare on the trunk road network: (SR = 45 is equivalent to the lowest skidding resistance investigatory level in the Skidding Standards). Figure 3 demonstrates that, for measurements at the 50km/h vehicle speed used in the tests on these surfacings, there is very little correlation between SR and texture depth.

Table 1 Ranges of SCRIM Reading and Texture depth for each type of surfacing studied

Surfacing type	*Number of sites*	*SCRIM Reading*			*SMTD (mm)*		
		mean	*maximum*	*minimum*	*mean*	*maximum*	*minimum*
HRA	21	62	77	51	1.4	2.0	0.9
SD	15	68	78	49	0.7	1.3	0.3
FCA	2	76	76	76	0.3	0.4	0.2
EAC	10	60	64	56	1.0	1.2	0.8
BC	39	64	76	49	0.4	1.0	0.2
TC	2	54	58	51	0.5	0.6	0.4
GC	6	66	73	58	0.7	0.9	0.4
PA	9	68	79	54	0.9	1.3	0.7
PLSD	10	67	74	60	1.0	1.4	0.7
TPMAC	4	66	67	65	0.8	1.0	0.5
SMA	13	62	69	47	0.9	1.0	0.6
MA	1	12	12	12	0.2	0.2	0.2
BQ	1	53	53	53	1.4	1.4	1.4

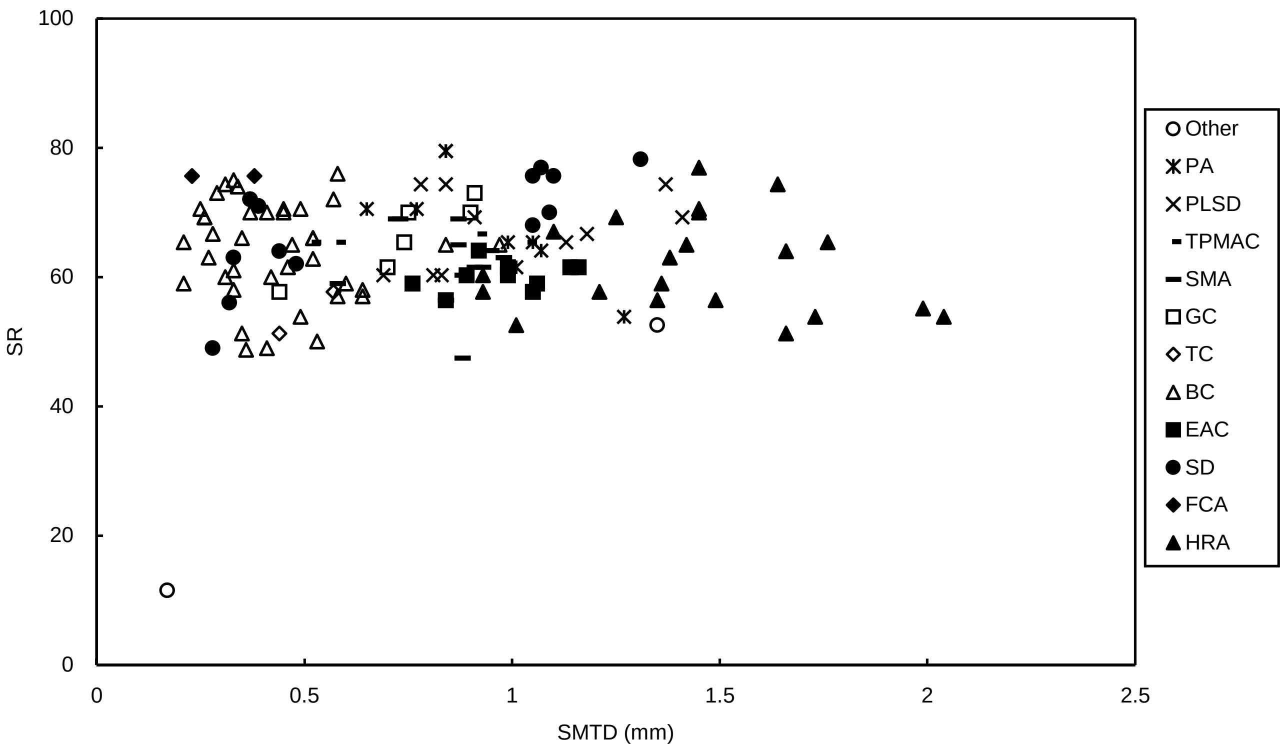


Figure 3 Distribution of SCRIM readings and texture depth levels for the sites studied

6 Relationship between PFT and SCRIM

It is frequently stated that SCRIM measures low-speed skidding resistance and it is often considered that this refers to the fact that the machine normally makes its measurements at 50km/h, which is relatively slow compared with general traffic speeds on de-restricted roads. However, it is important to realise that, as a result of the 20^o angle on the test wheel, the actual speed at which the SCRIM tyre slides over the road as the side-force is generated is much slower, 17 km/h.

It is of interest, therefore, to consider the SCRIM results in relation to those from the PFT at a comparable speed. This also provides a link between the measurements made for this study and those made as part of the routine skidding resistance monitoring programme on the road network. To make the comparison, the mean PFT Friction Number at 20km/h (Fn_{20} , the direct measurement speed nearest to 17km/h) has been plotted against SCRIM Reading, for each skid site in Figure 4.

The relationship is strongly linear, with a correlation coefficient of R = 0.76 for 131 data points when two statistical outliers (the mastic asphalt and one SMA site) are excluded. There is some scatter, almost certainly due to the fact that the SR values are averages of continuous measurements over 100m whereas the Fn_{20} values are from single skids, 5.5m long, at the centre of the corresponding length. This relationship indicates that it would be viable to use SCRIM running at 50km/h as a surrogate for very low-speed PFT measurements in future work should that prove desirable on sites where very low-speed running is impractical.

7 Relationship between friction and speed

As mentioned in Section 4.2, it was established at an early stage of the work that the best form for the equation of the relationship between speed and the friction measured by the PFT with the smooth tyre was of the form

$$Fn_s = B_0 + B_1 s + B_2 s^2$$

where Fn_s is the friction measured by the PFT at a speed, s, and B_0, B_1 and B_2 are coefficients.

Best-fit empirical models of this form, with different values for the three coefficients, were derived for all the skid sites in the database. The measurements for all the sites showed an excellent fit to the model form. Of the 133 equations, 99 had correlation coefficients of 0.96 or greater and the lowest correlation coefficient was 0.87. This means that the probability of the relationship occurring by chance is much less than 0.1%. This level of correlation gives considerable confidence in using the equations to calculate *Fn* values at speeds other than those measured directly.

Figures 5 and 6 illustrate the relationships obtained with selected examples of random and transverse-textured surfacings respectively. Each graph plots the individual *Fn* measurements, at the actual speeds achieved, together with the corresponding quadratic best-fit line. Each Figure contains four lines, showing different combinations of high and low SR and SMTD. In these examples, all the lines had correlation coefficients of 0.99 or better. It should be borne in mind that these Figures are for the purposes of illustration only; they do not encompass all SR or SMTD values which might be obtained from these types of surfacing.

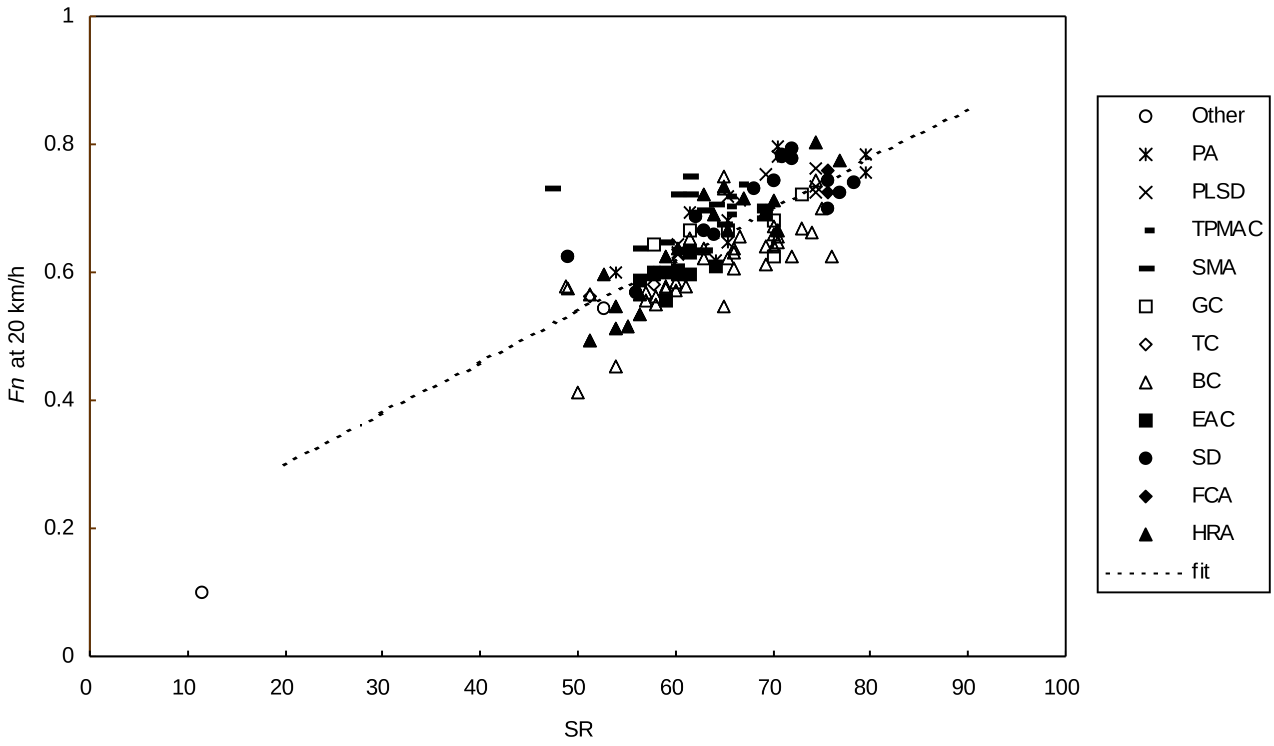


Figure 4 Relationship between SCRIM reading and Fn_{20}

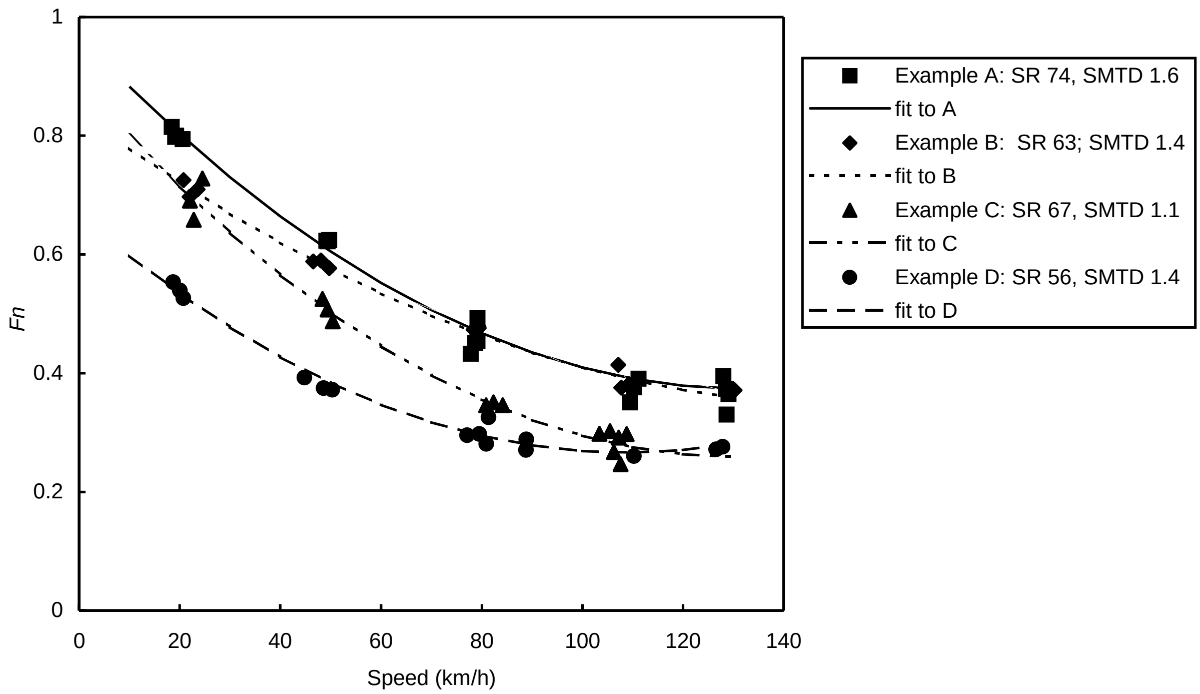


Figure 5 Examples of friction versus speed curves from random–textured surfacings

The examples in Figures 5 and 6 are typical of the curves obtained on all the surfacings studied. The low-speed value on each line reflects the underlying microtexture. Friction falls rapidly as speed increases and, for most surfacings, *Fn* has reached a minimum value at a speed of approximately 100km/h. The minimum value is clearly influenced by texture depth, with low-textured surfaces showing the largest falls in friction.

In many instances the recorded friction was found to increase slightly between 100 and 130km/h (the effect can be seen on some examples in Figures 5 and 6), and this is the reason why a quadratic model provided a better fit to the data than alternatives. An alternative model, such as an exponential, would have provided a reasonable simulation of the initial fall in friction, but would not have been able to reflect the 'turn-up' effect. The small effect is not of

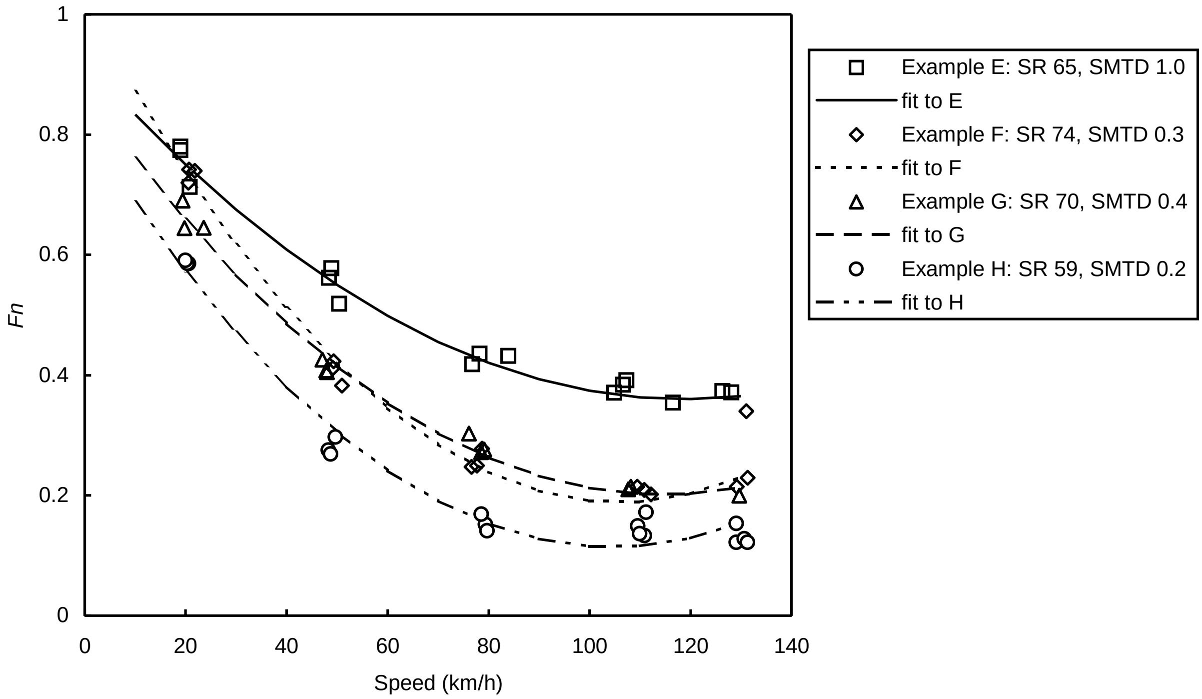


Figure 6 Examples of friction versus speed curves from transverse–textured surfacings

practical significance for this study, and would need much more work to explain, but some suggestions may be offered as to why it occurs.

When intimate contact is made under high contact pressures, momentary bonding occurs between the tyre rubber and the road surfacing. This process is known as adhesion. In wet conditions, adhesion can only occur when there is sufficient time and contact pressure for water to be displaced from the interface. As speed increases, water is less easily removed and so friction falls. However, the tread rubber is also deformed as it passes over protuberances in the surface. When this happens, the energy absorbed by the tyre is not all regained when the rubber returns to its normal shape. This process is known as hysteresis and results in heat being generated in the tyre. This mechanism becomes increasingly important when the tyre is sliding (as in the locked-wheel case) and also at higher speeds.

The two most likely reasons for the ‘turn-up’ effect are:

- an increased dominance of hysteresis over adhesion at the higher speeds; or
- increased influence of adhesion due to a reduced water film thickness when the fastest measurements were made.

The former would be an effect due to the tyre and road, the latter could result from a deficiency in the PFT’s watering system at very high speeds. Hysteresis can also generate locally-high temperatures in the tyre surface layer, which in turn lead to molecular delamination and apparent ‘melting’ of the rubber. This was frequently observed after 130km/h test runs, but whether this was simply due to hysteresis or exaggerated by there being insufficient water has not been investigated.

Whatever the mechanism involved, the effect was small and does not influence the findings of the work relating to the effect of texture depth on the relationship between high- and low-speed friction. The fact that friction appears to increase at the high speeds does not imply that it is safer to travel at 130km/h than at 100km/h; skidding resistance should not be confused with stopping distance. For most of the subsequent analysis, the term ‘high-speed’ refers to speeds of 100km/h or more, usually represented by the value for friction at 100km/h, Fn_{100} , calculated from the quadratic model for the site concerned.

8 The direct relationship between low- and high-speed friction

The principles of skidding resistance have sometimes been oversimplified to the extent that there is a popular misconception that microtexture gives low-speed friction and therefore only matters at low speeds and that macrotexture (more properly, texture depth) gives high-speed friction and is only of importance at high speeds.

More careful consideration would suggest that friction at high speeds must be dependent upon friction at low speeds. That is to say, with insufficient microtexture to penetrate the water film and make adequate contact with the tyre, high-speed friction will inevitably be low, regardless of any texture depth that may be present to limit its fall with speed. However, hitherto there has been limited experimental evidence to demonstrate the point.

In order to examine this, friction values at 20km/h (Fn_{20}) and at 100km/h (Fn_{100}) were calculated from the friction/speed model for each site and plotted against one another, as seen in Figure 7.

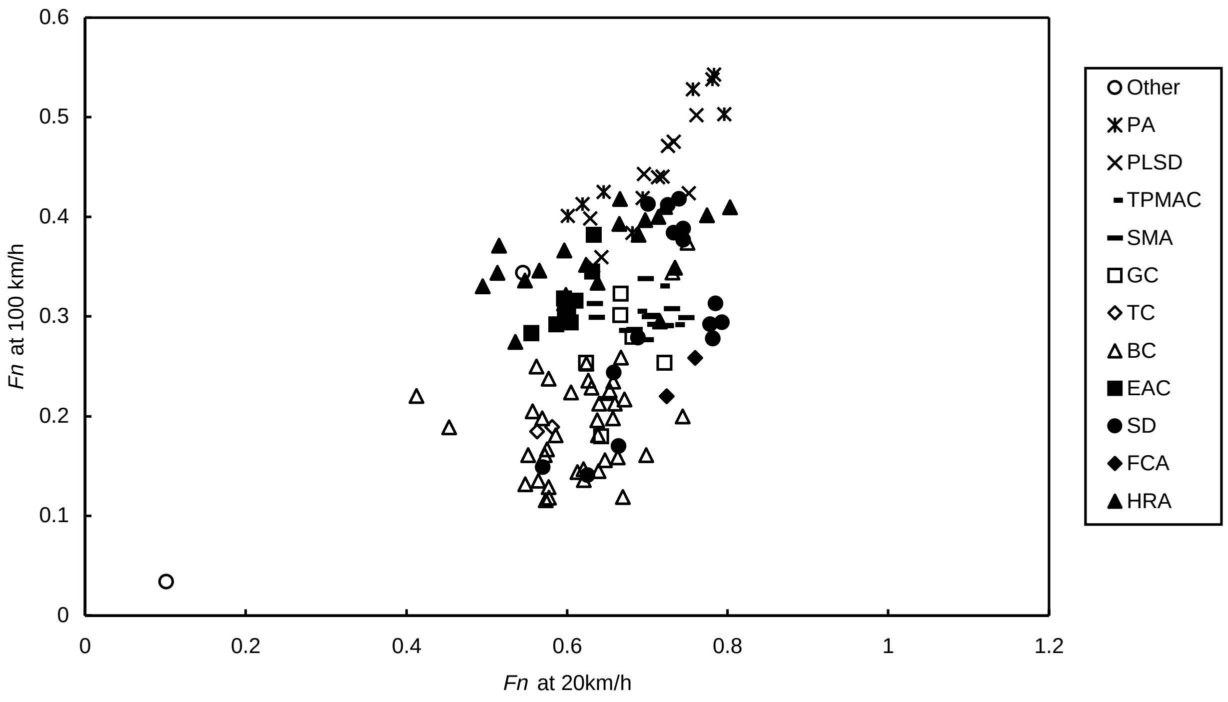


Figure 7 The relationship between Fn_{20} and Fn_{100}

This graph shows quite clearly that if Fn_{20} is relatively low, then Fn_{100} is also relatively low and vice versa. This analysis provides clear evidence of *micro*texture being important at both low and high speeds. However, it is also clear that the relationship would not be represented adequately by a simple linear relationship between the two parameters. As expected, high-speed friction is influenced by other characteristics which, of course, include texture depth.

9 The influence of texture depth on friction at different speeds

9.1 The direct relationship between texture depth and friction

In order to illustrate the influence of texture depth on friction as speed changes, the friction at each site at a chosen speed was calculated from the appropriate friction/ speed model and plotted directly against texture depth in a series of graphs. Figures 8 - 11 show the relationships for 20km/h, 50km/h, 80km/h and 100km/h respectively.

A number of observations can be made from these four graphs:

i *As speed increases, the general level of friction decreases at all levels of texture depth*. The scale of the effect becomes less marked at higher speeds, as would be expected from the quadratic form of the friction versus speed relationship (Section 7). It can also be seen that, as speed increases, the points on the graph group more closely together as the relative influence of microtexture diminishes.

ii *As speed increases, low-textured surfaces lose friction at a faster rate than high-textured surfaces*. This effect becomes more noticeable at textures below about 0.7mm sensor-measured texture depth.

iii *Texture depth has an impact on friction at lower speeds*. Figures 8 and 9 show that, although at 20km/h there is no direct relationship between texture depth and friction, by 50km/h the friction of the lowest-textured surfacings has already fallen markedly. This is an important point because, hitherto, it has been generally assumed that texture is not necessary for low-speed roads.

iv *All the impermeable surfacings, including both transverse and random textures, exhibit similar behaviour*. This is in contrast to the work of the 1970s in which data were interpreted as showing different responses for the two types of texture (see, for example, Salt, 1977).

v *The friction at some sites with a porous texture is less affected by speed*. It is likely that the measurement method used here does not adequately represent the texture of these materials.

9.2 Texture depth and the relative change in friction with speed

It has been seen that the lowest-textured materials appear to exhibit the greatest loss in friction with increased speed. However, the actual level of friction also depends upon the microtexture and this may influence the apparent changes. In the 1970s work, this problem was addressed by considering the relative change in friction, measured as braking force coefficient (BFC) over the speed range

50-130km/h and plotting this against texture depth as measured by the sand-patch method. The data were interpreted as showing a linear relationship, but with different relationships for asphalt materials compared with brushed or grooved concrete (these equate to the ‘random impermeable’ and ‘transverse’ textures of the present study). Porous asphalt and the proprietary negative-texture surfacings had not been fully developed at that time.

The results of that work were used as the basis for setting the standards for the texture depth of new surfacings. For asphalt wearing courses, for example, it was found that a sand-patch texture depth of 1.5mm corresponded to a loss of BFC between 50 and 130km/h of approximately 10% and this was adopted as a minimum level for newly-laid materials.

It is of interest, therefore, to carry out a similar analysis for the PFT data. Figure 12 shows the percentage change in *Fn* between 50 and 130 km/h (the same speed range as the 1970s work) calculated and plotted against SMTD for each site.

Although there is some suggestion of a trend, with relative loss of friction decreasing as texture increases, there is no evidence of a strong form of relationship. There are a number of reasons why this might be, including the obvious differences between the friction measurement methods such as the test-wheel size and road-wetting procedures. Also, the methods for measuring texture depth were very different. Further, as can be seen in some of the lines in Figures 5 and 6, the PFT data often show a slight up-turn in the friction/speed curve between 100 and 130km/h which will inevitably affect the relative change from 50-130km/h. (This effect may also have been present in the original work; there are instances in the records where BFC was lower at 80km/h than at 130km/h).

As commented on in Section 7, the friction/speed curves for the present study showed that a significant proportion of friction is lost between 20 and 50km/h and, at most sites, the minimum friction has been reached by 100km/h. Therefore, it is more appropriate to consider the effect of texture on the relative loss of friction between 20 and 100km/h. Figure 13 shows this relationship.

The trend is much more marked in this case and these results do not show two separate relationships for the two main types of texture but that all the data can be represented by a single model. However, the porous, negative-textured materials tend to lie above the general trend.

In the earlier work, for asphalt wearing courses a 1.5mm sand patch texture depth was found to relate to about a 10% loss in BFC. However, at the approximate equivalent texture level for these results (1.3mm for SMTD measured with a traffic-speed device), the PFT measurements show a much greater loss in *Fn*, in the region of 30-50%. This effect is most likely to be attributable to differences between the two friction measurement methods. Two key differences, for example, are that the early work used a small, narrow-tyred wheel and the road was wetted using spray-bars on tankers, which gave little control of water depth.

9.3 Texture depth and the relationship between high- and low-speed friction

Section 8 showed that there is some relationship between high- and low- speed friction and it was suggested that texture depth could be a variable which would also affect the form of that relationship. Section 9.1 also showed that texture depth has a marked effect on the friction measured at different speeds. The next stage of the analysis was to see whether it would be possible to link these factors into a single model relating high- and low-speed friction. This analysis is in its early stages at the time of writing, but some initial results are reported briefly.

Other workers have suggested models for predicting friction at any speed from a friction measurement at a known speed, and texture depth. The ‘Penn State Model’, which formed the basis of the analysis in the International PIARC Experiment to Compare and Harmonise Texture and Skid Resistance Measurements is one of these (Henry, 1996).

A first step for the present study has been to attempt to find a model to predict high-speed friction from a SCRIM measurement and texture depth. It has been found that, if the porous negative textures and the mastic asphalt are excluded, a good relationship is obtained using a model of the form:

$$Fn_{100} = aSR + b(1 - e^{-SMTD}) + c$$

where a, b and c are empirically derived constants.

A linear regression of Fn_{100} against the value predicted from the equation above gave a correlation coefficient of 0.93. Figure 14 shows this prediction, with the line of unity (y=x) drawn in for comparison. The good fit of the model can be clearly seen, and it is also clear that some other factors will need to be considered to model the response of the excluded surfacings. It is of interest to note that the one model includes both random-impermeable and transverse-textured surfacings.

The analysis is continuing, but the early indications are that it may be possible to develop a means of reliably estimating the high-speed locked-wheel wet friction on a site from SCRIM and SMTD measurements. This offers the possibility that, in the future, both components of skidding resistance could be brought together in defining the performance requirements for a road surface.

10 Discussion

10.1 The importance of texture at low speeds

Figures 8-11 showed that the general level of friction fell with increased speed and that there was a marked drop between 20 and 50km/h. In order to quantify this effect, the sites were grouped into bands according to their texture depth, regardless of surfacing type, and the average absolute falls in *Fn* from 20-50km/h, 50-80km/h and 80-100km/h were calculated for the different texture levels. The results of this analysis are shown in Figure 15.

This demonstrates clearly that, on average, there is a markedly greater loss of friction between 20 and 50 km/h than between 50 and 80 km/h and a relatively small change

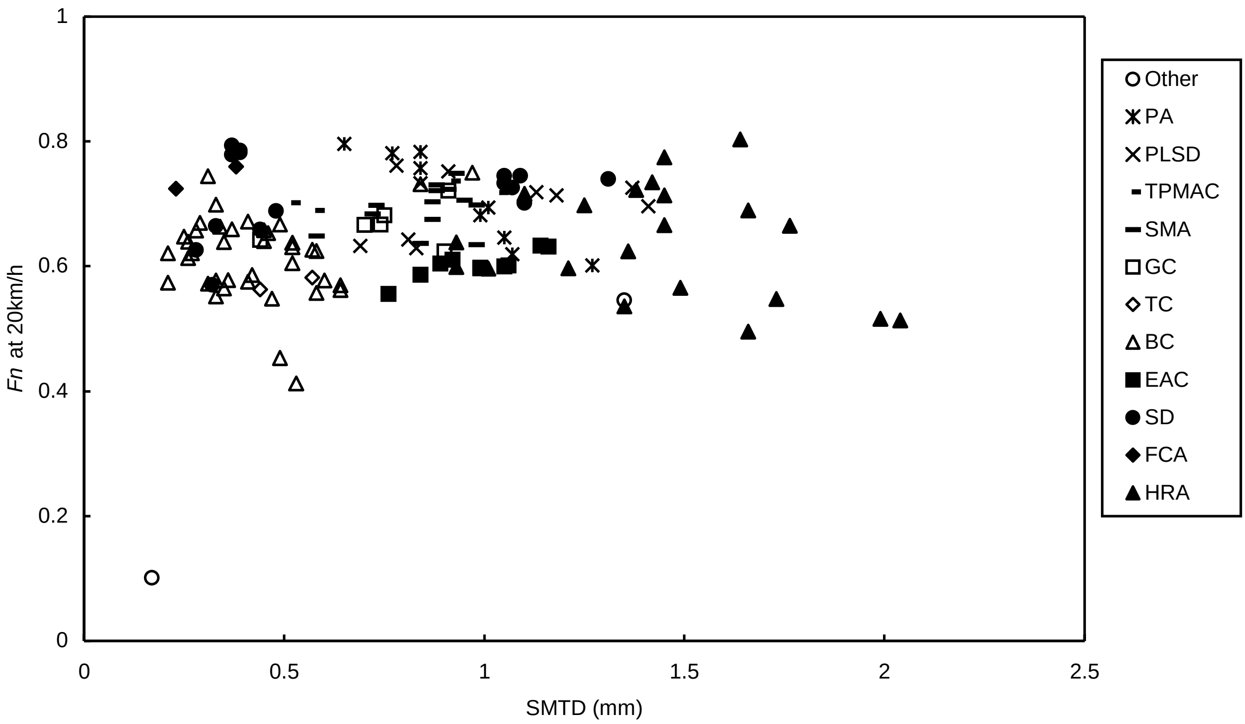


Figure 8 Relationship between locked–wheel friction and texture depth at 20km/h

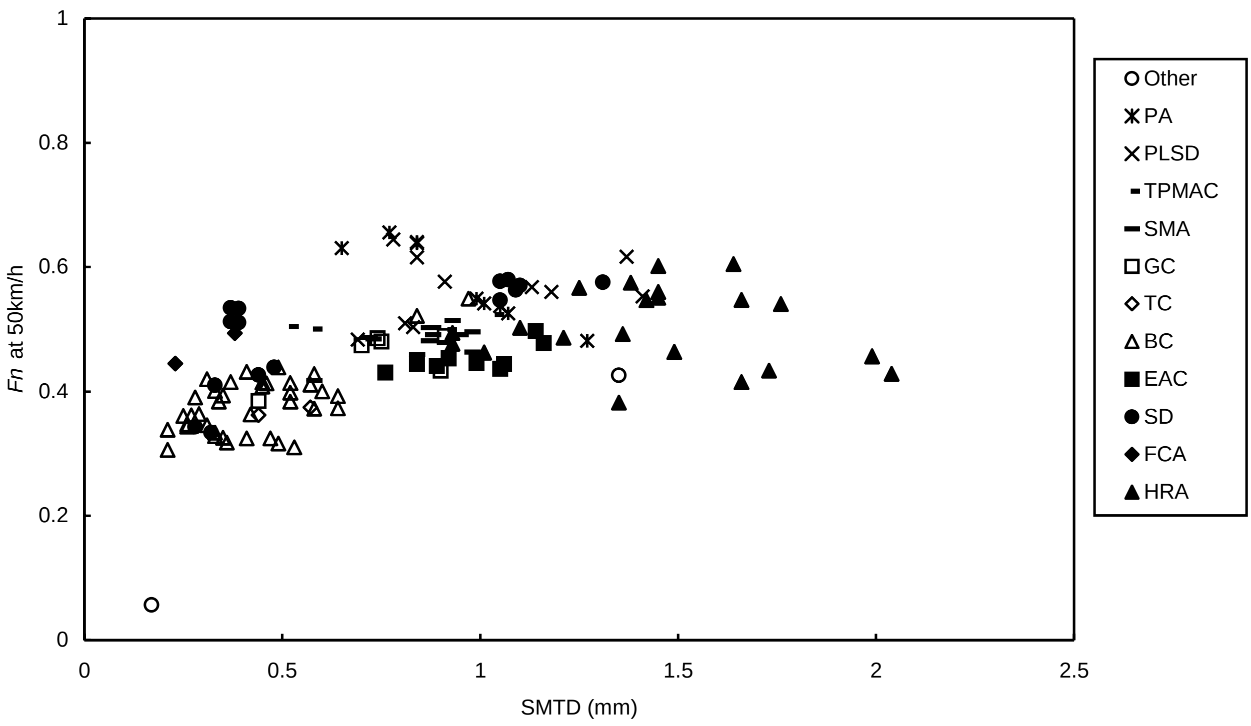


Figure 9 Relationship between locked–wheel friction and texture depth at 50km/h

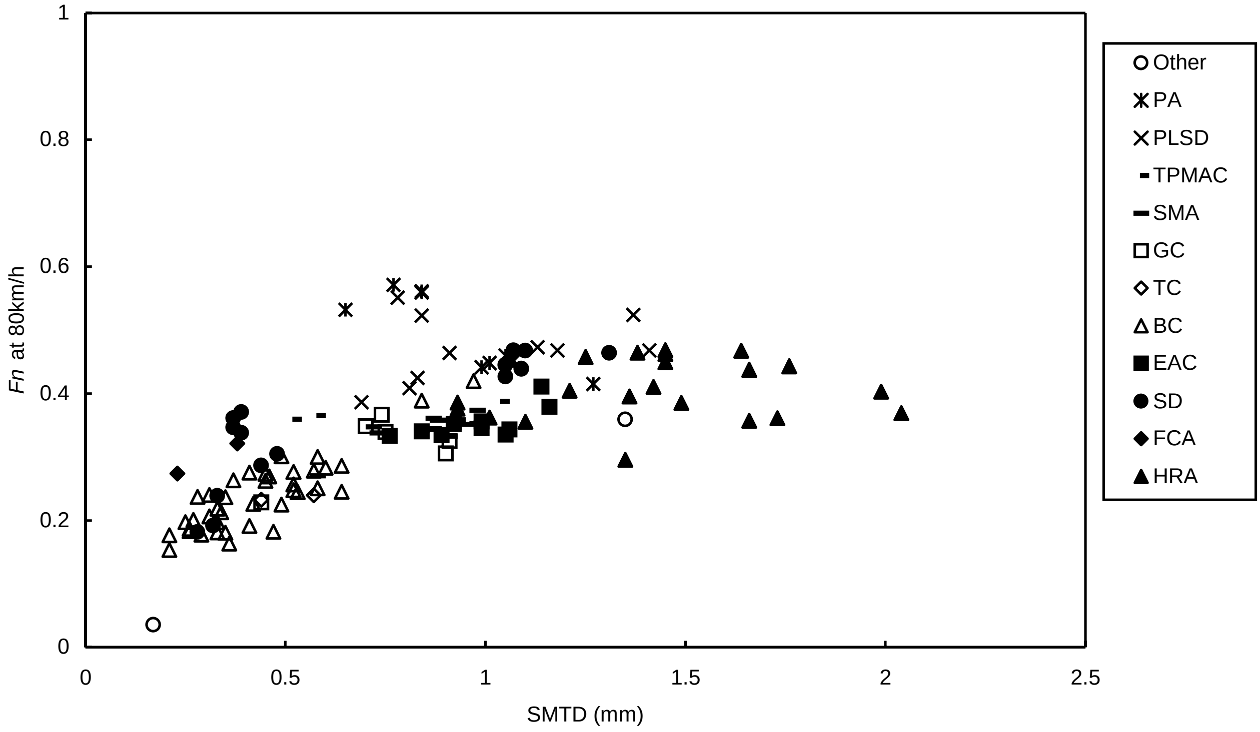


Figure 10 Relationship between locked–wheel friction and texture depth at 80km/h

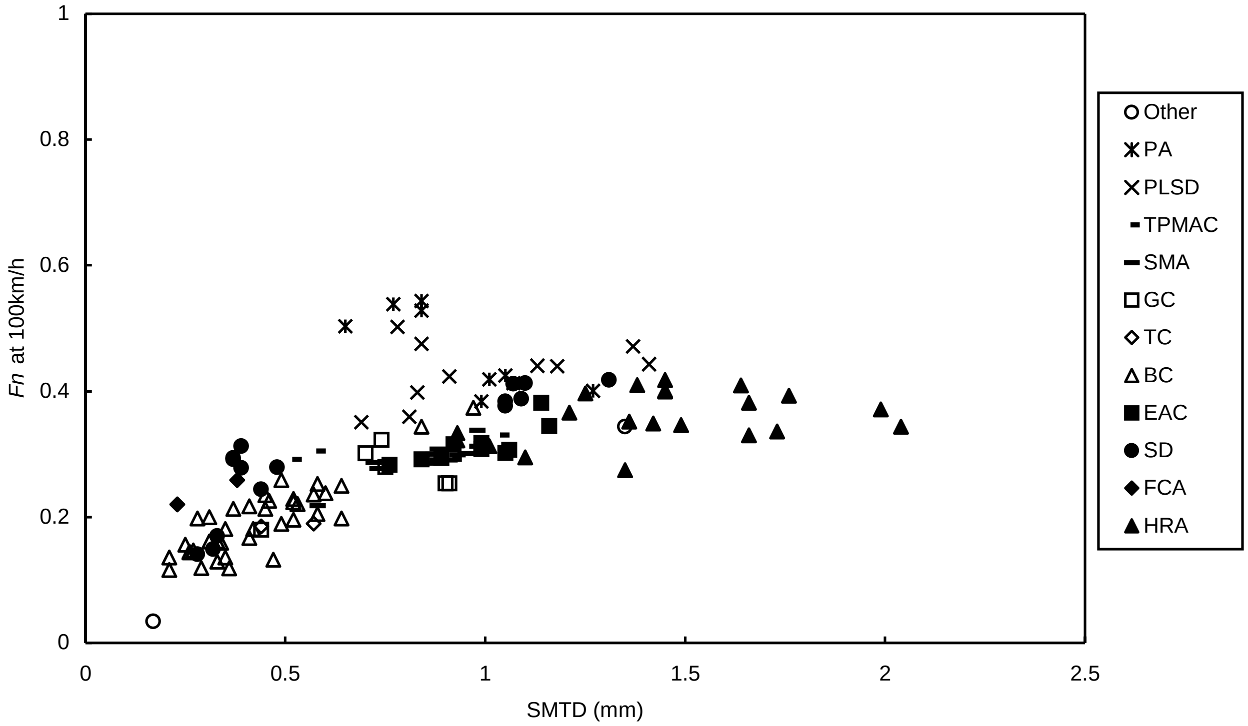


Figure 11 Relationship between locked–wheel friction and texture depth at 100km/h

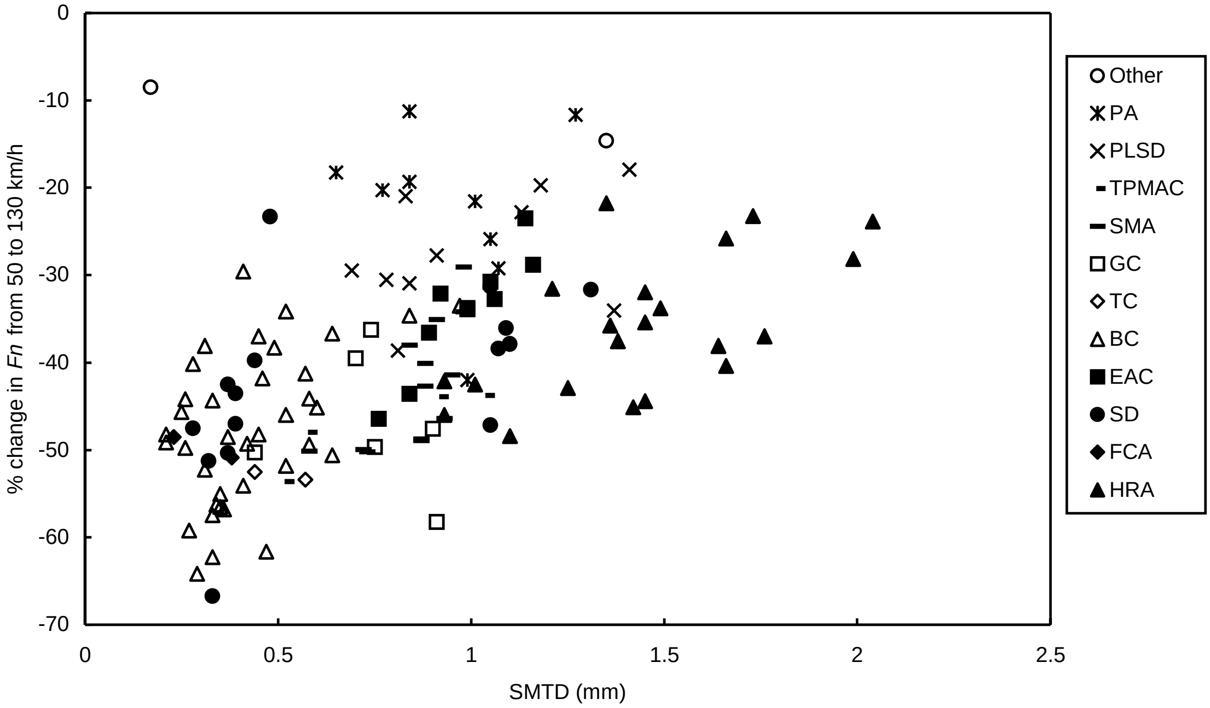


Figure 12 The effect of texture on the relative change in friction between 50 and 130km/h

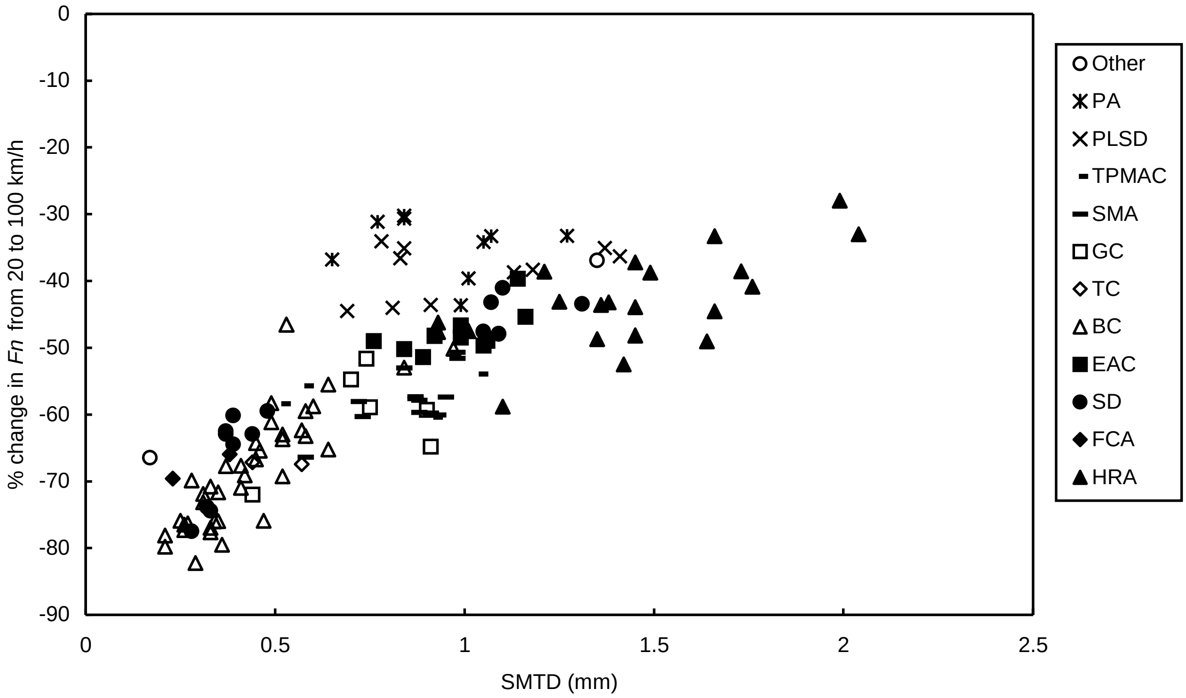


Figure 13 The effect of texture on the relative change in friction between 20 and 100km/h

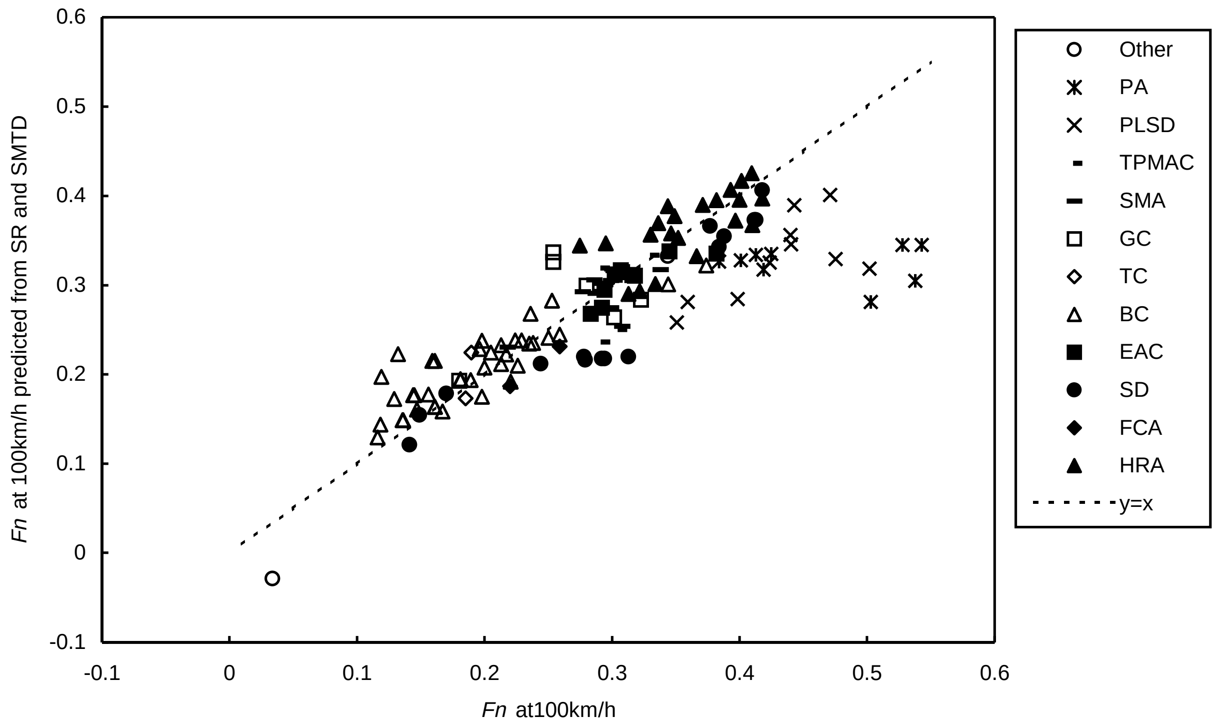


Figure 14 Comparison of Fn_{100} with values predicted from SR and SMTD

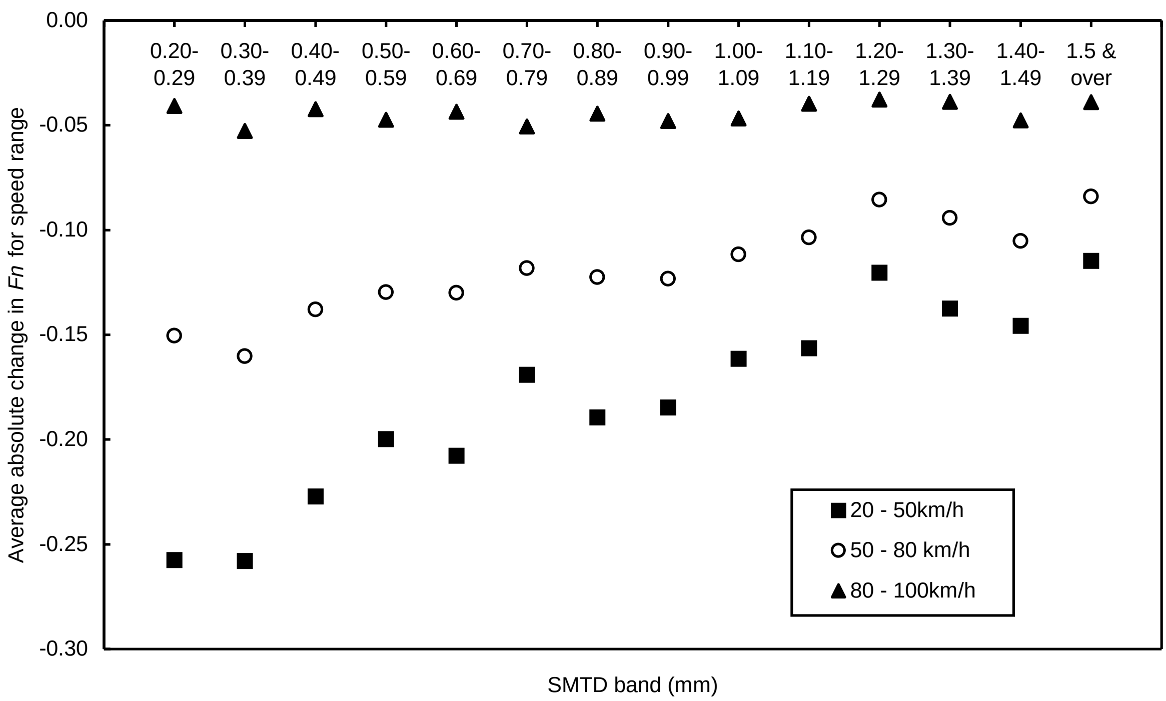


Figure 15 Effect of texture depth on absolute change in friction as speed is increased

from 80 to 100km/h. This reflects the quadratic nature of the friction/speed relationship (Figures 5 and 6). However, Figure 15 also shows clearly that the greatest fall occurs at low textures *and* at low speeds. This is a particularly important finding for urban roads, for which it has often been assumed that texture depth is relatively unimportant.

It should be borne in mind that Figure 15 shows the absolute change in friction between the speeds concerned. Providing that microtexture is good enough, the resultant friction at 50km/h, say, should still be adequate.

10.2 Porous materials

Most studies in this field have found that porous surfacings behave differently from impermeable surfacings and this work is no exception. Porous surfacings tended to retain their friction at high speed slightly better than other materials. This is shown most clearly in Figure 14. Here, the porous materials clearly had higher friction at 100km/h than the predictive model (which was based on the results from impermeable materials) suggested that they should, given their measured SR and SMTD.

It is possible that there are some different mechanisms involved in the way in which these materials interact with the tyre to generate friction. However, it is more likely that, whatever it is that SMTD measures on porous surfacings, this measure of texture depth does not adequately represent the texture. For example, such surfacings clearly have a greater drainage potential than SMTD (or sand patch) measurements of texture depth can quantify. It is likely, however, that older porous surfacings, in which the voids have closed up or become blocked, would behave in common with other types of material.

10.3 New forms of surfacing materials

The newer proprietary materials are usually placed in relatively thin layers and are often described as ‘thin surfacings’. There is naturally some interest in the way in which these surfacings perform in relation to conventional materials.

The sites in this study show that the paver-laid surface dressings (PLSD) performed similarly to porous asphalt. This might be expected, because material of this type has been found to have porous properties, although it is not as permeable as a purpose-designed porous asphalt.

The other types of material represented here, the TPMAC and SMA, performed broadly as expected from conventional materials with similar microtexture and sensor-measured texture depth.

10.4 Practical implications of findings

It was in recognition of the importance of skidding resistance to road safety that the Highways Agency commissioned this research. Underlying all studies of skidding resistance is the presumption that low levels of road/tyre friction could lead to increased accidents. The results of the work so far could therefore have important practical implications for specifications for surfacings and for their in-service requirements.

It is important to bear in mind that it is rare for low friction actually to cause an accident. Rather, this becomes an important factor when some other event causes a driver to brake or suddenly change course, or when an error of judgement leads to excessive speed on a bend or corner. It is important for a road to have adequate friction, but rather than set definite levels friction should be related to the risk of skidding at a site.

This was the approach taken in the UK Skidding Standards, which set investigatory levels for in-service roads based on SCRIM measurements related to accident risk on different categories of site. The effect of losing friction with speed is taken into account by specifying an appropriate level of polishing resistance for surfacing aggregates, together with minimum levels of texture depth for new surfacings. These are then designed so that they can be expected to maintain adequate texture throughout their service lives.

10.4.1 The issue of in-service texture depth

In Section 9.1 it was observed that, as speed increases, low-textured surfacings lose friction at a faster rate than high-textured surfaces and that this effect becomes more noticeable at textures below about 0.7mm SMTD. Work at TRL in the 1980s, reported in RR296 (Roe, Webster and West, 1991), studied the relationship between texture depth and accidents, concentrating mainly on high-speed roads. It was found that accident risk appeared to increase at textures below about 0.7mm SMTD, a similar level to that at which the effect of texture on high-speed friction becomes more noticeable in the present study.

At the same time as the work in RR296 was being carried out, the Skidding Standards were being developed. These were based on a national skidding-resistance survey (with SCRIM) which showed a link between SCRIM measurements and accident risk when the type of site was taken into account (Rogers and Gargett, 1991). The greatest increase in accidents associated with low SCRIM measurements occurred on high-risk sites (approaches to urban traffic lights, for example), whereas on low-risk sites (mainline motorways or dual carriageways) there was little increased risk in accidents at lower SCRIM levels. These findings led to the introduction of the investigatory levels for low-speed skidding resistance which vary with the accident risk of the site, but no account was taken of in-service texture depth.

At the time at which these studies were being made, the majority of low accident-risk sites would have been surfaced with hot-rolled asphalt with pre-coated chippings to provide texture depth. As a result, most would have had relatively high textures. Similarly, high-risk sites (many of which were by their nature on urban roads), would not necessarily have had high texture depths because, at that time, this factor was often disregarded in such situations. It is possible that the sites providing the basis for the Skidding Standards were unknowingly influenced by the presence, or absence, of texture depth. One reason why the lower SCRIM values proved appropriate on low-risk sites was that those had a high enough texture depth to limit the extent to which friction falls with speed. Conversely, higher SCRIM values would be needed at the high-risk sites to compensate for their lower textures. It may be, therefore, that the Skidding Standards have already, to some extent, taken account of texture depth and that this is one reason why, at the time of writing, wet skidding accidents are not necessarily found to be a problem on low-risk sites with low in-service texture.

Section 9.3 showed that it is possible to develop a model to predict *Fn* at 100km/h from SCRIM and SMTD measurements. Early attempts have indicated that it should also be possible to develop models for other speeds.

Using this technique it would be possible to re-analyse the database used for the RR296 studies and consider whether combining measurements of low-speed friction with texture depth to estimate friction at different speeds for the accident sites provides a better link with accident risk than texture depth alone. A development of this approach could provide a way forward for taking in-service texture depth into account in future standards.

10.4.2 Texture requirements for newly-laid surfacings

At present, newly-laid surfacings are required to have a minimum texture depth and it is assumed that the surfacing design will ensure that the material will provide adequate texture depth in service. Recent specifications for surface dressing provide for a texture depth requirement after two years rather than at new, but the basic philosophy is the same. It is important that the initial texture of a surfacing is adequate to take into account expected wear without being so high as to generate other problems, such as excessive noise or tyre wear.

Current standards set lower levels of texture depth for new transversely-textured concrete surfacings than for random textured asphalt surfacings. This was the result of the earlier work which was interpreted as showing different performance for the two types of texture. However, the present work has shown that, using the PFT (which has a larger test tyre and more closely-controlled wetting), there is no difference in performance between transverse and random textures at low texture depths. There may be a concern that transverse-textured surfacings built to the current standards could wear in service to texture depths which lead to an unacceptably large fall in friction at higher speeds. However, as indicated in the previous section, the relatively high skidding resistance at low speeds has some compensating effect. In addition, transverse textures are most often used on mainline dual carriageway, which would be classified as 'low risk' sites. For this reason the number of accident incidents are likely to be low, even though the results from the examples studied here showed low levels of friction at high speed.

Long experience has shown that rolled asphalt and pre-coated chippings laid to the current standard can be expected to maintain a texture depth above the level at which high-speed friction begins to fall more markedly throughout its life. However, as yet there has been insufficient experience of the newer surfacings, many of which are proprietary materials.

The results of this work suggest that the texture depth requirements for newly-constructed surfacings, particularly transverse textures, may need to be reconsidered in order to take into account wear by traffic.

10.4.3 The contribution of the tyre

The analysis and discussion has centred on the results from the PFT measurements. However, in reality, different vehicles use different tyres with different tread patterns and compounds, so the actual levels of friction experienced will inevitably vary from those measured with equipment such as the PFT. For this work, the object of the measurements has been to characterise the road surfacings and therefore a standardised procedure has been adopted.

It could be argued that the measurements for this study were unrealistic in that they represented the 'worst case' with a smooth tyre limited to 1mm nominal water depth. Most vehicles would have sufficient tread on their tyres to compensate, to some extent, for the lack of texture on the road in such situations. Also, increasing numbers of vehicles are fitted with anti-lock braking which enables them to take advantage of higher friction levels than in the locked-wheel situation.

The issue of low in-service texture depth cannot be dismissed on these grounds, however, because tyres near the minimum tread depth would be more akin to a smooth tyre than a new one. Also, if water depths were greater than 1mm, problems might nevertheless ensue.

10.5 Further work

There are a number of activities which are already in hand to take this work forward to a point where revised standards can be considered.

- *Improved predictive models and re-visiting the RR296 analysis*

  This work should verify whether it is practical to monitor the in-service friction level derived from measurements of low-speed skidding resistance and texture depth. It will also show whether it would be possible to consider taking texture into account by setting investigatory friction levels appropriate for the speed of traffic and accident risk at different categories of site.

- *Analysis of peak friction and ribbed tyre measurements*

  For most of the sites in the study, measurements have been made with a ribbed tyre. Also, the full braking cycle has been recorded which will provide peak-friction data on surfacings very similar to the locked-wheel results in most cases. Analysis of these results may provide a better understanding of how the worst-case locked-wheel measurements relate to these intermediate circumstances.

- *The effects of water depth and 'real' tyres*

  The study of the effect of water depth and tyre tread depth on road/tyre friction for normal-production car tyres is an important component of an international research project, supported by the European Commission, in which the Highways Agency are sponsoring TRL's contribution to the work.

In addition to the above activities, already in hand, there are two other aspects of the topic which have not been addressed by the present study but which should be considered as part of continuous assessment of the requirements for skidding resistance on in-service roads.

- *The role of texture depth on high-friction surfacings:*

  These materials, which often utilise calcined bauxite aggregate in small chipping sizes, are used increasingly at high-stress locations on higher-speed roads. They usually have very high friction at low speeds but there is some concern that, because they have relatively low texture depths, this may not be maintained at high speeds. It has not been possible to study them as part of this project because, on the network, they are located in places where high-speed measurements are impractical.

- *Early-life skidding resistance*

  Newly-laid asphalt surfacings frequently have a layer of binder coating the surface of the aggregate and blinding the microtexture, although they appear to comply with the skidding requirements. This is gradually worn away by traffic until the aggregate is exposed and the normal polishing processes begin. Some materials have relatively thick binder layers which can take some time to wear away. It is likely that different mechanisms could apply when surfacings are in this new condition, depending more upon the adhesive or viscous properties of the binder than the microtexture of the surface, and that they have different effects at different speeds.

11 Conclusions

The Pavement Friction Tester has been used to gather friction data for a wide range of surfacings, microtexture and texture depth levels. Some 2000 locked-wheel friction measurements with an ASTM smooth tyre on 133 sites have been analysed to date.

As expected, the results showed that friction falls with speed and it has been found that a quadratic model provides the best representation of the friction versus speed curves with an excellent fit (correlation coefficient better than 0.9 in 97% of cases). Generally, the lowest friction is reached by about 100km/h. The measurements have provided evidence that, as expected, the level of high-speed friction of a surfacing depends on the microtexture, which provides low-speed friction.

The research has confirmed that friction on low-textured surfaces falls more rapidly with speed than for high-textured surfaces but it has also shown, importantly, that texture depth has an impact on friction loss at slow speeds. Further, the results indicate that the effect of texture depth on loss of friction is similar for all impermeable materials and that the earlier distinction between transverse-textured and random-textured materials may be inappropriate.

The effect of texture depth on loss of friction is greatest below about 0.7mm SMTD. Above this level, increased texture has a relatively small effect.

An empirical equation could be developed which would allow high-speed friction to be reliably predicted from measurements of SCRIM Reading and SMTD for most surfacings, although some porous and negatively-textured materials may behave differently.

12 Acknowledgements

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Abstract

Current UK standards for skidding resistance and texture depth are based on studies carried out in the 1970s, which showed that low-speed skidding resistance depends upon the microtexture of the road surfacing, but as speed increases, the skidding resistance falls depending on the texture depth. In 1995, the Highways Agency commissioned further research in order to reassess the earlier work, particularly the influence of texture on the relationship between high- and low-speed skidding resistance, for the wide range of surfacings now used on UK trunk roads. A K J Law T1290 Pavement Friction Tester (PFT) was purchased by the Highways Agency, for this new study. The equipment has been used to make measurements of locked-wheel friction over a range of speeds from 20 to 130 km/h. Measurements have been made on more than 130 sites covering a wide range of types of surfacing, levels of texture and skidding resistance. The report presents the results of the first phase of analysis, which show clearly the loss of friction with increasing speed and confirm that this is more marked for surfacings with low texture depth. Significant findings were that texture has a greater impact on loss of friction at lower speeds than previously thought and that the effect is similar for both random-textured and transverse-textured impermeable surfacings.

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