Innovation in High Speed Friction Measurement

Project Summary Report

AECOM in partnership with Ulster University

Version 2.0
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Executive Summary

This project was commissioned by Highways England to investigate the method of friction measurement that is used to manage the accident risk of skidding accidents on the Strategic Road Network (SRN). The aim is to determine whether the current method is appropriate, or if a new method is required to measure skidding risk at high speed, at network level. Such a device would have to be reproducible at a reasonable price, suitably portable, recyclable, and most importantly, safe to use on the highway network with traffic at traffic speed.

A review of friction measurement around the world along with possible methods that could be developed to measure high speed friction was undertaken, along with a review of the fundamental properties of pavement surface friction and the tyre pavement interaction and methods that are used to understand this. The desk study identified potential aspects worthy of further investigation which were pursued as part of this project. These include development of a non-contact method to measure tyre temperature, the tyre envelopment of the road surface and 2d and 3d modelling of the road surface.

The principle of tyre temperature to be used as a non-contact method of measuring tyre road interaction at high speed was investigated. This non-contact method would mitigate current problems with excessive wear and damage to the friction measuring tyres currently used. If proven, this principle could be used as a surrogate indicator of tyre / road surface related properties such as skid resistance, noise and rolling resistance. The study successfully identified a suitable market ready bolt on device that measures tyre surface temperature and demonstrated a correlation with temperature and speed on a thin surface course and a hot rolled asphalt section of road.

The tyre/road surface texture interaction known as draping, enveloping or embedment was investigated in the laboratory. Two simple test rigs were developed; one to use the small diameter ASTM 1844 friction measuring tyre and a larger rig to assess the larger diameter tyres used by friction measuring devices such as those used to measure a sideways force. This larger rig is able to assess the treaded tyres fitted to cars and vans used on the roads around the world. These rigs were used to observe how a tyre deforms into the space between simulated aggregate particles. Predictable relationships were found between the amount of deformation / embedment into the space and factors such as load and gap spacing. These relationships apply to a space between two parallel plates. They are two dimensional and do not reflect the extremely complex 3-dimensional surface of a typical road surface.

The small rig was also used to study the contact patch of both new and worn ASTM tyres using XSensor pressure mapping. The tyre pressures and loading were analysed to see the behaviour of the tyre. The study showed worn tyre to have a larger contact area.

Different techniques were used to measure the texture and aggregate spacing of different asphalt samples. This was done in 2d and was then extended to 3d by creating a model using photographs. This gave an estimate of the characteristics of the different material types and can provide additional information in respect of water displacement. This includes the quantification of water for a given depth into a particular asphalt surface; analysis of the models show how this changes with depth. It offers information on channel connectivity which facilitates drainage and displacement if water under a tyre. It offers a new indicator of surface vulnerability to water related damage. This provides scope for consideration of the methods contribution to enveloping and durability studies.
1 Introduction

This project was commissioned by Highways England to investigate the method of friction measurement that is used to manage the accident risk of skidding accidents on the Strategic Road Network (SRN). The aim is to determine whether the current method is appropriate, or if a new method is required to measure skidding risk at high speed, at network level. Such a device would have to be reproducible at a reasonable price, suitably portable, recyclable, and most importantly, safe to use on the highway network with traffic at traffic speed.

Ulster University undertook a desk study to establish global best practice and research methods adopted to evaluate friction; followed by laboratory and field trials to investigate potential surrogates for friction measurement.

1.1 Purpose of document

This document is a compilation of the research reports developed for each work stage and summarises the work done to date and key research findings for the project as a whole. Further details are available in the individual work stage reports.

- Work stage 1: Desk study.
- Work stage 2: Review of Current Tyre/road Interface Modelling.
- Work stage 3a: Tyre temperature profiles / signatures.
- Work stage 3b: Estimate / measure tyre embedment into a road surface.
- Work stage 3c: Evaluation of 2D and 3D parameters.

1.2 Background

The SRN is a key English national asset requiring careful administration and maintenance; it comprises 1,865 miles of motorways and 2,571 miles of Class A trunk roads Highways England 2017). Although the SRN represents only 2.4% of roads in England it carries approximately one third of all traffic and two thirds of freight traffic. In 2014, 9% of reported road casualties were on the SRN (DfT, 2016).

The properties of road surfacing materials are extremely important for the safe use of the network. Skid resistance has been a priority with policies in place for many years. In 1930, Bradley and Allen (1930) asserted that the problem of skidding divides itself naturally into three parts each of which would have to be addressed separately by:

1. The Highway Engineer - to produce a road surface on which the wheels of vehicles can get a good grip at all speeds and under all weather conditions and the curves and contours of which are designed to be as safe as possible.
2. The Tyre Manufacturer - to supply tyres which will offer a resistance to slipping which is as high as possible and independent of the speed and surface conditions.
3. The Road-Vehicle Designer - to produce a vehicle of which the weight distribution, drive, and braking arrangements are best adapted to give safety under all conditions.

The provision of an adequately safe road network or problem of skidding cannot be solved by three separate stakeholders. Rather, there needs to be collaboration or at least consideration of what all the stakeholders have done and are doing. Likewise, research into other road surface properties, influenced by tyre/road interaction, such as noise generation and rolling resistance, which have become important recently, should also be considered.

1.3 Project Work Stages

The project was divided into 3 distinct work stages that are all interconnected and evolve from one to the other.
1.3.1 Work Stage 1 – Detailed desk study focusing on the definition of high speed friction

The methods of friction measurement around the world were considered along with possible methods that could be developed to measure high speed friction. The definition of high speed friction was at the current motorway speed limit and higher and concludes that the current skid measuring device used on the SRN is not appropriate due to the high rate of wear and other issues. This led to a review of current devices in use around the world but primarily in Europe as possible replacements but there was not something currently in use that is tried and tested that could perform this task. Then a matrix of different possible technologies and methods that could be developed was presented and was explored with a selection being seen to offer the greatest potential for success. This list led to generic requirements for a testing device that can deliver high speed friction measurement. These developed requirements were a direct input to the study presented in Work Stage 3(a) the laboratory testing and field trials of a thermal non-contact friction measuring device.

1.3.2 Work Stage 2 – Fundamental properties of pavement surface friction and the tyre pavement interaction

The previous work stage gave rise to questions about the fundamental properties of pavement surface friction and the tyre pavement interaction and methods that are used to understand this area. This work stage was focused on exploring the literature and current understanding that is available for these highly complex physical systems. The literature review moves through the surface texture and friction, laws of friction, tribology current laws and advances. This gave insight as to what makes one surface better than another and the laws used to understand this. The review then moved into tyre construction and the physical behaviour of tyres with its elastic, visco-elastic and hyper-elastic material properties. The review then concentrated on the interaction between tyres and pavement surfaces. This was explained under the titles of adhesion and hysteresis as the main components of tyre-pavement energy dissipation.

Tyre-pavement contact area and pressure was explored under the titles of tyre draping and deflection / embedment. These show that there are a number of phenomena taking place as a tyre traverses a pavement surface. These are happening and ending over a very short time scale making direct measurement impossible using current technology. The review then went on to explain the modelling techniques and studies that have tried to simulate this behaviour. These range from numerical methods like Finite element analysis to analytical models. Although these methods are powerful and with greater computer resources are becoming even more powerful they are always going to be simplifications of the real interaction. This is the weakest of these methods and why they are not explored further in this project. This review showed there is a need for greater understanding of the fundamental draping and embedment behaviour of tyres and how this influences tyre contact pressure. This need was addressed by the laboratory investigations described in Work Stage 3(b).

1.3.3 Work Stage 3(a) – Tyre temperature as a non-contact method of measuring tyre road interaction at high speed

This section considered whether the principle of tyre temperature could be used as a non-contact method of measuring tyre road interaction at high speed thus avoiding current problems with excessive wear and damage to the friction measuring tyres currently used. If proven, this principle could be used as a surrogate indicator of tyre / road surface related properties such as skid resistance, noise and rolling resistance. Work Stage 3(a) has the following findings:

- A test methodology was developed to investigate variables under controlled laboratory conditions.
- This methodology used the ULTRA rolling road apparatus, replicate test specimens and the ASTM 1844 friction measuring tyre.
- The main test variables were test specimen texture, speed, load, dry or wet, and rolling condition (free or offset).
• An equilibrium temperature is reached depending on the specific combination of test variables.
• It takes a period of time for the surface of the test tyre in contact with the test surface to reach an equilibrium temperature that is dependent on the combination of test variables.
• The application of water at the test tyre / test specimen interface causes an immediate and significant reduction in temperature (approximately 10 degrees in 1 second).
• Offsetting the test tyre at 2 degrees caused a significant increase in tyre surface temperature under free rolling conditions.
• A proof of principle bolt-on device was developed to investigate whether tyre temperature could be used at high speed as a measurement of tyre / road surface interaction.
• A free rolling tyre needs time to achieve a thermal equilibrium with its surrounding.

Tyre surface temperature may be used as a method to infer tyre and surface interaction.

1.3.4 Work Stage 3(b) – Tyre embedment into a road surface

Work Stage 3b investigated is it possible to estimate / measure tyre embedment into a road surface. This has been achieved by developing two devices to measure the embedment of different sized tyres for different gap spacing and loading. These devices are the TEA MK1 (smaller diameter tyres like GripTester friction measuring tyre) and TEA MK2 (for larger diameter tyres such as a car trailer tyre and sideways force tyre). These devices were used to investigate the principle of enveloping as identified by the ROSANNE project under controlled laboratory conditions. The devices consist of a varying gap support and loading arm so that different loading and gap spacing can be investigated.

Under static conditions and for the entire test conditions investigated, the main factor relating to tyre embedment or enveloping is gap space. For the ASTM friction tyre on the TEA MK1 device, there is a distinct trend in the data i.e. the amount of embedment decreases in a predictable linear relationship until a critical gap space of approximately 15 mm is reached. The amount of embedment then remains fairly constant as gap space is further decreased.

At the smaller gap spaces on the TEA MK2 device it would appear that the larger diameter sideways force tyre behaves in a similar manner to a treaded tyre. However, with increasing gap space there is more embedment (enveloping) for the sideways force tyre compared to the treaded tyre used in the reported investigations.

Tyre wear did not significantly affect the amount of deformation into the gap space for the two friction measuring tyres. This is interesting considering the significant difference in vertical pressure distribution within the contact patch shown by pressure mapping for new and worn tyres.

Similar variation in contact patch vertical pressure distribution is typical of treaded tyres with differing inflation pressures and degrees of tread wear. The relationship between tyre vertical stress distribution within the contact patch and whether it has a significant effect on measured skid resistance needs further investigation.

The tyre interface is predictable for pneumatic tyres used. There are linear or log relationships with very strong correlations between variables such as load, inflation pressure, contact area, length and width and degree of wear. This offers scope to develop intelligent tyres to measure their road interface. For example, the wedge of water that builds up at the front of the contact patch could be measured by the tyre as a change in contact length.
1.3.5 Work Stage 3(c) – 2d and 3d texture measurement modelling and water displacement

This stage dealt with the issue of 2d and 3d texture measurement modelling and water displacement the application of the UUTex3D method to this area. The complexity of measuring directly water displacement is explored and found to be too complex to measure directly due to the short duration of this process. Therefore, a method of inferring displacement based on using the UUTex3D method of measuring a pavement surface texture in 2d and 3d was presented. This includes the quantification of water for a given depth into a particular asphalt surface; analysis of the models show how this changes with depth. It offers information on channel connectivity which facilitates drainage and displacement if water under a tyre. It offers a new indicator of surface vulnerability to water related damage. This provides scope for consideration of the methods contribution to enveloping and durability studies.
2 High speed friction measurement and modelling review

A review of friction measurement around the world along with possible methods that could be developed to measure high speed friction was undertaken, along with a review of the fundamental properties of pavement surface friction and the tyre pavement interaction and methods that are used to understand this.

2.1 Factors affecting high speed friction measurement

In England, the measurement of road surface friction can be traced back to researchers such as Bradley and Allen (1930). They compared the relative slipperiness of road surfaces and determined factors which are conducive to the skidding of vehicles on such surfaces. The following sections describe the key principles and parameters for consideration.

2.1.1 High speed

This issue of high speed is a significant factor that impacts the methods considered in this research project. High-speed roads are defined in HD36/06 as those with an 85th percentile traffic speed exceeding 65 kph (40.39 mph). High speed within the context of the SRN means the legal speed limit of 70 mph (112.65 kph). However, traffic routinely exceeds the legal speed limit on the SRN. Therefore, for the purpose of this study, high-speed is not restricted to the maximum legal speed limit and will consider the ability to measure friction, or some related property of friction, at speeds of 80+ mph (128.75+ kph).

2.1.2 Friction

The term friction is typically used to represent the grip developed by a particular tyre on a particular road surface at a particular time and under given conditions. It is expressed as a coefficient of friction and is influenced by many parameters relating to the road, tyre, vehicle, ambient conditions and surface contaminants.

![Simplified diagram of forces on a tyre](Hall et al., 2009)

Various friction theories have been developed on the different components of rubber friction (Gabriel et al. 2010). These include but are not limited to Moore (1972) and more recently Persson (1999). There are several bodies of literature exploring and affirming the laws of friction such as Persson et al, (2000), Bowden and Tabor, (2001), van der Steen, (2007) and Gabriel et al, (2010). To see more detail on this area please consult Appendix A.
Friction between the tyre and road surface consists of two main components, both of which are related to speed.

1. Sliding resistance between tyre and road surface with its magnitude determined by the nature of the materials in contact.
2. Loss of energy caused by deformation (hysteresis) of the tyre. (DMRB 2006)

These two components are also understood as adhesion (2.1.5.1) and hysteresis (2.1.6.2) (Flintch et al., 2012). Van der Steen (2007) refers to these phenomena as rolling friction which is mainly due to energy dissipated as rubber is compressed and relaxed in the contact patch.

It has been accepted that there are three basic rubber friction forces generated by three different mechanisms that can arise when rubber products slide on harder materials in dry or wet conditions (Smith 2008). These have been summarised as:

- The combined adhesion between the rubber surface and the contacted surface.
- Resistance to bulk deformation in rubber when sliding on rough surfaces.
- Wear of the rubber product's surface by physical means (Kummer, 1966).

Smith (2008) adds a fourth basic friction force produced by sliding contact of a rubber product which he terms surface deformation resistance.

### 2.1.3 Contact area

Of particular importance is the area of contact within the tyre footprint which can be real or apparent. Persson (1999) notes that most surfaces exhibit roughness on many different length scales. Thus when a block is put on a substrate the actual contact area will not be the whole bottom surface of the block but the real contact area which is usually much smaller than the apparent contact area. The factors which influence the area of real contact include:

- Tyre inflation pressure
- Dynamic or static conditions
- Applied load
- Surface texture depth
- Properties of a given rubber compound
- Tyre tread design, depth and configuration
- Rubber embedment and displacement
- The catenary effect arising from aggregate spacing also known as tyre draping

According to Zbigniew (1991) the contact area is smaller in a dynamic tyre compared to that of a static tyre. Woodside et al. (1999) showed that an under inflated tyre combined with a constant load produces a larger contact area compared to that of a tyre with high inflation pressure and a constant load. This showed that the contact stress varies with the contact area, where the contact stress decreases as the contact area increases.

Lie (1992) established that when a small load is applied to an automotive tyre, the contact area takes the formation of an ellipse. It was also found that as the wheel load is increased at constant pressure, the contact area shape becomes increasingly elongated therefore closer to the shape of a rectangle. However these are overall plan contact areas and are not necessarily indicative of the true area of contact.

### 2.1.4 Surface texture

The DMRB (HD28/04) presents texture as a straightforward dichotomy of positive and negative as illustrated in Figure 2. Highway surface texture is associated with a range of performance indicators which are a function of the tyre/road interaction including, rolling resistance, skid resistance, grip, spray and response to contact stresses.
Millar (2013) argues that given trafficking it is more likely that highway surfacings will lie on a continuum across positive and negative textures. Whilst this may be true of asphalt surfaces in general, the majority of the SRN comprises proprietary thin surfacing which is negative texture.

The tyre interacts with the surfacing across a range of texture wavelengths each of which contribute to some tyre/road phenomenon as illustrated in Figure 3. According to the DMRB (2004) the level of wet road skid depends on two key characteristics of the surface, microtexture of the aggregate and its texture depth. At low speeds the main contributor to skid resistance is the aggregate microtexture and material fines. Macrotexture contributes to frictional resistance by deforming the tyre surface.

According to the DMRB, 2006 the friction coefficient at low speed depends mainly on the angularity of the asperities (<0.5mm) in the road surface (microtexture). Yurong et al. (2004) suggest that macrotexture has a more profound contribution to low speed frictional resistance than popularly considered. Yurong et al. (2004, p.308) show that the gap between sub contact areas of the macrotexture can significantly affect its frictional resistance noting that for the range of gap width between 2mm and 10mm the difference in measured frictional resistance could be as much as 10 British pendulum (BPN) points. The apparent dissonance suggests that some assumptions and established test methods require further investigation.

Macrotexture (0.5mm to 50mm) provides the hysteresis component of friction and allows for the rapid drainage of water from the pavement (Flintsch et al., 2003). Macrotexture reduces the potential for separation of tyre and pavement due to hydroplaning and for induced friction caused by hysteresis for vehicles travelling at high speeds (Hall et al., 2009). The true contact area will be influenced at all texture wavelengths.

From Figure 3 it is clear that this order of roughness is to be found only at the extreme end of the texture scale and it seems reasonable to conclude therefore that adhesion is unlikely to contribute to surface friction and hence skid resistance to any significant extent.
2.1.5 Skid resistance

The term skid resistance is typically used to describe the contribution that the road makes to tyre/road friction. Skid resistance is a measurement of friction obtained under specified standardised conditions and attempts to reduce the influence of parameters mentioned above, to isolate the contribution that the road surface provides to tyre/road friction. Although wet weather friction has been deemed a worse-case scenario, collision statistics indicate that approximately two thirds of collisions occur in dry conditions. It is clear therefore that there are other factors that merit consideration in addition to weather conditions.

According to Noyce et al. (2005), skid resistance is the friction force developed at the tyre-pavement contact area. It is re-stated that the accepted understanding is that there are two main mechanisms of skid resistance, adhesion (see 2.1.5.1) and hysteresis (see 2.1.6.2) which combine to give the sum of these mechanisms. The underpinning theory was developed by Kummer (1966) followed by Oliver et al. (2006), Smith (2008) and other researchers such as Masad (2009) (Figure 4).

![Figure 4 Schematic of adhesion and hysteresis (Masad et al., 2009)](image)

2.1.5.1 Adhesion

According to Hall et al. (2009) adhesion is the friction that results from the small-scale bonding/interlocking of the vehicle tyre rubber and the pavement as they come into contact with each other. It is a function of the interface shear strength and contact area. It is related to the molecular bond between the tyre and the road surface where the Van der Waals forces are able to ensure a stable interaction between the two materials. (Hall et al., 2009, Masad et al., 2009). The authors suggest that the microtexture of the road surface is a fundamental constituent in relation to adhesion.

According to Gabriel (2010), the mechanics of rubber friction were still subject to debate but it was still widely accepted that adhesion and hysteresis are the two principle factors contributing to friction. Choubane et al. (2004) suggested that the contact area between the two mediums is an important factor upon which adhesion depends. Historically, adhesion was deemed to account for the majority of the resistance force that occurred at a regular driving speed on a wet pavement surface (Hogervorst, 1974). Persson (2001) has cast doubt on the adhesive contribution to friction in any circumstances except where it can be shown that the rubber completely fills the substrate, as contaminants on the surface will affect the contact area. Given the nature of the in-situ tyre/road interface and its inevitable contaminants, Persson’s deductions appear well reasoned.
2.1.6 Tyre properties

Tyres are composed of numerous elements which contribute individually and collectively to its interaction with the highway surface. Figure 6 shows the elemental make up of a typical radial tyre. The tyre tread is created from a rubber compound which is arguably the most complex single element of the tyre. Tyre rubber compounds may comprise several polymers, vulcanising agents, accelerators, fillers and anti-degradants, plasticizers, softeners and tackifiers (Van der Steen, 2007). These enable the tyre to perform as required under various conditions.

Rubber displays elastic, viscoelastic and hyper-elastic characteristics.

- Elastic - able to recover to its unloaded state following removal of an applied load with no permanent deformation or dissipation.
- Viscoelastic - dissipates energy as heat when a load is applied and then removed. This phenomenon is illustrated in Figure 7.
- Hyper elastic - resists volumetric change when subjected to large strains, the material becomes harder to deform and approaches isotropy. The shear modulus becomes temperature dependant and the tyre becomes stiffer as the temperature of the rubber increases.
2.1.6.1 Tyre enveloping

There is some evidence showing that tyre deflection is an important variable governing the contact area at the interface. Various studies have examined how a tyre interacts with the texture of a road surface and drapes over it. Using geometrical analysis Browne et al., (1981) suggested that there would be no difficulties in establishing the relationship between contact area and tyre deflection in relation to aircraft tyres. For example if both applied load and tyre pressure are varied simultaneously in order to maintain constant tyre deflection, this will result in the contact area of the tyre being effectively constant.

Some aircraft tyres have little if any external tread and the shape of the contact area approximates to an ellipse. Such tyres are similar in surface texture to the ASTM friction tyre. New methods of highway surface recovery such as Millar (2013), Woodward et al. (2014), Boyle (2014) and McQuaid (2015) have allowed accurate recovery of the highway element of the interface. This has facilitated measurement of tyre draping and other associated phenomena to be measured for various combinations of tread configuration, inflation pressure and applied loading.

Hamet and Klein (2000) modelled how a tyre envelops different road surface textures (Figure 8). The modelling associated with the work of Hamet and Klein was considered too complex by Goubert (2016) who proposed a simplified algorithm.
Figure 9 shows Goubert’s simple enveloping algorithm, this 2d diagram illustrates enveloping and how aggregate particles embed into tyre rubber and how the tyre deforms into the space between particles.

Figure 9  Enveloping principle proposed by ROSANNE project

Figure 10 shows an example of enveloping for an asphalt test specimen. This has been created by painting an asphalt slab (305 x 305 x 50 mm) with blue paint and then subjecting it to simulated trafficking using the Road Test Machine (RTM). The removal of paint shows the tyre / asphalt envelope i.e. how the full-size treaded test tyre has interfaced with the macrotexture of the asphalt test specimen. For this type of asphalt, the tyre / asphalt interface essentially consists of isolated islands surrounded by blue paint denoting paths water may either be trapped or dispersed at high pressures.

Similar experiments have been conducted on Friction after Polishing (FAP) test specimens (Dunford, 2013) and Polished Stone Value (PSV) test specimens (Woodward et al., 2016). Woodward et al. (2016) reported enveloping to occur to a depth of approximately 0.4 mm. Both these test specimens are manufactured to test aggregate characteristics and are not representative of an asphalt surface so the paint wear pattern shown in Figure 11 is quite different to the contact with the texture shown in Figure 10.
Figure 11 Round FAP test specimen (Dunford, 2013) and rectangular PSV test specimens made with different aggregates (Woodward et al., 2016).

Contactless surface recovery has also facilitated measurement of a considerable range of areal pavement texture parameters that are aligned with a harmonised European standard. Work by Hamilton (2016) has demonstrated a clear catenary phenomena occurring at the tyre surface interface as shown in Figure 12.

Figure 12 3D Visualisation of the Catenary effect on idealised surface

Interface conditions will vary with load transfer as a vehicle rounds a corner or during acceleration and heavy braking therefore dynamic modelling enveloping is very complex. Consideration of the dynamic contact patch is fundamental to estimate / measure tyre embedment either with a contact or non-contact method of measurement at high speed.

2.1.6.2 Hysteresis

Hall et al. (2009) reports that hysteresis relates the amount of energy lost as a tyre moves over a road surface and deforms due to its interaction with the macrotexture. This relates to the stress-strain curve shown in Figure 7, known as a hysteresis loop, which shows that the material will not recover to its original shape after a stress is applied and removed. This property is important in the context of the tyre/road interface as surface asperities can create depressions within the tyre. The hysteresis mechanism under loading is illustrated in Figure 13 and for the static and moving conditions is shown in Figure 14.
Persson builds on the findings of Grosch that take into account that the sliding friction of rubber has the same temperature dependence as that of the complex elastic modulus (Van der Steen, 2007). Persson states that the friction force, under normal conditions, is related to the internal friction of the rubber therefore a hysteretic friction property.

Figure 13 Schematic of hysteresis (Haney, 2003)

2.2 Friction measurement

The traditional approach to friction measurement involves direct measurement of skid resistance under specified standardised conditions using some type of friction measuring tyre. Skid resistance can be measured at a discrete location, for instance at the site of an accident or as part of a large-scale routine highway network investigation or for specialist research purposes.

Each method is controlled by specific standard conditions chosen to reflect the practicalities of carrying out the test in relation to the complex reality of friction in the tyre/road interface. Typically the road surface is wetted and a quotient of the measured force and applied vertical load (friction coefficient) is recorded. The range of devices may be sub-divided into two main groups (Do and Roe, 2008):

- By longitudinal friction (measuring Longitudinal Friction Coefficient LFC).
- By transverse friction (measuring Transverse Force Coefficient SFC).

Longitudinal and transverse friction devices attempt to simulate the interaction of a braked tyre with the road surface in a longitudinal direction and as a tyre turns into a corner respectively. More detail on LFC and SFC can be found in Appendix B.

There are over twenty devices used in EU member countries to measure skid resistance, and although each test is standardised the EU does not have a harmonized policy regarding skid resistance. According to Nitsche and Spielhofer (2009), the LFC (used by 12 EU countries) is more common than the SFC (9 EU countries). The two main types of SFC device are the UK SCRIM and German SKM, followed by the GripTester. Some countries use a combination of devices based on different principles. There was no mention of a high speed policy of friction measurement in this European survey.
The Skid Resistance Tester (SRT) or pendulum is included in most policies as a local measurement device used to complement mobile skid resistance measurement devices, local investigations or as a research tool. However, this slow, spot device is not suitable for high speed measurement at network level.

Table 1 summarises the main characteristics of the 16 principal devices identified by Do and Roe (2008), it does not include research devices such as the Swedish VTI Skidometer BV 12. These details include: device name, measurement type, test tyre details, vertical load, slip ratio, typical operating speed range and water film thickness.

Table 1 Main characteristics of skid measurement devices (Do and Roe, 2008)

<table>
<thead>
<tr>
<th>Device</th>
<th>Measurement type</th>
<th>Test tyre</th>
<th>Vertical load (N)</th>
<th>Slip ratio (%)</th>
<th>Typical operating speed range (km/h)</th>
<th>Water film thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADHERA</td>
<td>LFC</td>
<td>PIARC</td>
<td>smooth</td>
<td>165 R15</td>
<td>3000</td>
<td>100 – 400</td>
</tr>
<tr>
<td>BYH1 SFT</td>
<td>LFC</td>
<td>Trelleborg</td>
<td>smooth</td>
<td>155 mm</td>
<td>1000</td>
<td>120 – 40</td>
</tr>
<tr>
<td>GRIPTESTER</td>
<td>LFC</td>
<td>ASTM</td>
<td>smooth</td>
<td>254 mm</td>
<td>1500</td>
<td>70 – 70</td>
</tr>
<tr>
<td>ROADSTAR</td>
<td>LFC</td>
<td>PIARC</td>
<td>smooth</td>
<td>165 R15</td>
<td>3000</td>
<td>100 – 400</td>
</tr>
<tr>
<td>ROAR OK</td>
<td>LFC</td>
<td>ASTM</td>
<td>smooth</td>
<td>155 mm</td>
<td>1500</td>
<td>80 – 80</td>
</tr>
<tr>
<td>ROAR NL</td>
<td>LFC</td>
<td>ASTM</td>
<td>smooth</td>
<td>155 mm</td>
<td>1500</td>
<td>80 – 80</td>
</tr>
<tr>
<td>RWS trailer</td>
<td>LFC</td>
<td>PIARC</td>
<td>smooth</td>
<td>165 R15</td>
<td>3000</td>
<td>100 – 400</td>
</tr>
<tr>
<td>SCRM</td>
<td>SFC</td>
<td>AVON</td>
<td>smooth</td>
<td>76/588 mm</td>
<td>1960</td>
<td>30 – 80</td>
</tr>
<tr>
<td>SKIDOMETER BV9</td>
<td>LFC</td>
<td>PIARC</td>
<td>smooth</td>
<td>165 R15</td>
<td>3000</td>
<td>100 – 400</td>
</tr>
<tr>
<td>SMK</td>
<td>SFC</td>
<td>AVON</td>
<td>smooth</td>
<td>76/588 mm</td>
<td>1960</td>
<td>30 – 80</td>
</tr>
<tr>
<td>SMR</td>
<td>LFC</td>
<td>PIARC</td>
<td>smooth</td>
<td>165 R15</td>
<td>3000</td>
<td>100 – 400</td>
</tr>
<tr>
<td>TRT</td>
<td>LFC</td>
<td>ASTM</td>
<td>smooth</td>
<td>165 R15</td>
<td>3000</td>
<td>100 – 400</td>
</tr>
<tr>
<td>IMAG</td>
<td>LFC</td>
<td>PIARC</td>
<td>smooth</td>
<td>165 R15</td>
<td>3000</td>
<td>100 – 400</td>
</tr>
<tr>
<td>OSCAR</td>
<td>LFC</td>
<td>ASTM</td>
<td>smooth</td>
<td>524-88</td>
<td>4826</td>
<td>140 – 140</td>
</tr>
<tr>
<td>PFT</td>
<td>LFC</td>
<td>ASTM</td>
<td>smooth</td>
<td>524-88</td>
<td>4826</td>
<td>140 – 140</td>
</tr>
<tr>
<td>ODDELOGRAPH</td>
<td>SFC</td>
<td>PIARC</td>
<td>smooth</td>
<td>27/3000</td>
<td>2374</td>
<td>80 – 80</td>
</tr>
</tbody>
</table>

The majority of devices are of the LFC type with only three being the SFC type, almost all use a smooth tyre. Vertical load and slip ratio vary so the actual values recorded can vary significantly for the same road surface.

All the devices with the exception of the ROADSTAR (60 kph) have a maximum operating speed greater than 65 kph. Only four of the devices have a maximum operating range that meets or exceeds 100 kph; ADHERA (120 kph), GripTester (100 kph), TRT (140 kph) and IMAG (140 kph). The PFT is capable of measuring up to 130 kph but its use in the UK is restricted to research.

2.2.1.1 Appropriateness for a high speed network

The interaction of the friction measuring tyre and the road surface is probably one of the key criteria influencing the choice of the most appropriate form of high speed friction measurement. At higher test speeds the tyre is subjected to greater stresses, especially for surfaces with greater macro-texture and to a lesser extent greater microtexture. Therefore, SFC type test is not appropriate for high speed measurement as the tyre is constantly under stress and susceptible to high speed blow outs.

Although there have been developments to improve the Sideway force Coefficient Routine Investigation Machine (SCRIM) (Appendix C) to achieve test speeds up to 80 kph (50 mph) this is significantly lower than typical motorway speeds. European standards demonstrate that the current iteration of SFC is applicable to measurement at lower speeds. The contact measurement speed is 17mph and the sideways force measured is not considered typical of that generated by braking from the speeds defined in this report. It is therefore concluded that the current sideways force devices should not be considered further in this project.

Different LFC devices allow test measurements ranging from constant fixed slip to simulated locked wheel braking events, so are more appropriate for high speed measurement. However
the four devices with an operating range at or above 100 kph all have smooth tyres. Direct measurement using a smooth friction tyre is not a suitable means of measuring high speed friction at network level as it is this interaction between a treaded tyre and road surface texture at different scales that is the property that should be measured. It also does not consider issues related to the wear of treaded tyres that will influence tyre/road interface.

In addition, prolonged testing under more extreme conditions caused by higher speeds may cause changes in the properties of the tyre rubber during testing which can in turn influence the measured data.

Almost all skid resistance testing is carried out under wet conditions, and there are logistical problems in carrying a sufficient volume of water to create the necessary water films. The requirement to carry water limits the lane miles measured per day so there are challenges to covering the SRN more than once a year with the limited number of devices available.

2.3 High speed friction measurement

There is little evidence of any country operating high speed friction measurement on their road network. Higher speed testing is carried out on runway surfaces. However, these devices are typically designed to operate in straight lines.

The newly upgraded and redesigned RT3® Curve roadway continuous friction tester (Halliday Technology Inc., 2016) is claimed to measure both roads and runways at speeds up to 70 mph (Figure 15). The device was released in North America towards the end of 2016. It operates on the principle of measuring the interaction of a tyre offset at an angle of 1.5° with the road surface.

![Figure 15 The RT3® Curve continuous friction tester.](image)

The RT3® Curve has 4 wheels, the 2 inner wheels are for transporting the device. The two outer wheels are used for tyre/road measurement purposes. They can be either smooth or treaded. The width of the measuring tyre spacing can be adjusted to accommodate the width of wheel tracks. Either or both measurement wheels give a continuous measurement of friction that is geo-referenced.

The device is fitted to the back of tow truck that carries water for wet testing and may be operated in dry conditions to assess other tyre / road surface interface issues such as the detrimental effect of contaminants or dry weather polishing. The legal requirement within the UK for a towed trailer is that a vehicle has a maximum speed of 60mph. This restricts the measurement of high speed friction with this device on the SRN.
2.4 Potential alternative direct or indirect measurement of high speed friction

There is a range of possibilities to directly or indirectly measure high speed friction. These range from laboratory testing to developing a friction device that uses either direct or indirect methods. A selection of these proposals is presented in the following sections, for the complete list please see Appendix D.

2.4.1 Laboratory testing methods

The main laboratory methods for predicting skid resistance are:

- Polished Stone Value (PSV) – a pendulum test for 10/6.3mm sized aggregate only
- Friction After Polishing (FAP) – a test for asphalt mixes utilising cores. A speed profile is measured during the friction measurement part of the FAP test. This profile could be re-evaluated to look at the higher speed measurements recorded during test.
- Road Test Machine (RTM) – a pendulum test for asphalt mixes. The RTM is a slow speed method used to measure changes in friction. The advantage of this method is the use of a 305 x 305 mm slab.

2.4.2 Development of a tyre based friction tester

The route of developing yet another friction tester with a friction measuring tyre is one that would probably result in the same limitations associated with many of the existing devices. This would necessitate a low slip condition to take measurements rather than the traditional peak or almost peak friction value.

The proportional relationship between the slip ratio and the frictional behaviour of a tyre under low slip conditions illustrate that a system may be used at high speed with low slip ratio (<5%) in order to deliver the measurements required without rapidly damaging the tyre carcass. This may not be feasible with the added complications arising from the heat generation of such testing. However, this aspect of heat generation may prove a viable indirect indicator of road surface friction.

2.4.2.1 The accelerated tyre method

The legal requirement within the UK for a towed trailer is that a vehicle has a maximum speed of 60mph. This limits the measurement of high speed friction. A possible method to circumvent this restriction is to accelerate the testing tyre prior to contact with the road surface. Measurements would be recorded from the power requirements on the electric motor driving the test axle.

The ULTRA apparatus in Ulster University could be used to simulate a rolling road to test a tyre driven using an electrical motor. An electrical pulse generated by the tyre dropping onto the rolling road could be related to the tyre surface interaction.

2.4.3 Re-evaluation of 2D and 3D road surface parameters

2D and 3D profile data has been used to investigate road surface textures at different scales. The main problem with this type of data is working with large datasets and extracting meaningful parameters from the measured 2D or 3D profile. Work by Dunford (2014), Millar (2014) and McQuaid (2015) highlight that not all of the measured data is relevant.

Analysis to show parameters such as contact area, surface volume and tyre draping would be feasible and allow indirect non-contact predictions of high speed friction. Development of such systems would need laboratory verification using a rolling road to prototype a suitable device and if proven reliable retrofitted to a suitable vehicle for high speed testing.
2.4.4 Water footprint / displacement method

The contact area between the tyre and the road surface is impacted by the development of water film on the tyre during rolling interaction. As the degree of hydroplaning increases the tyre contact decreases. The interaction with the surface will reduce as the water film thickness increases to a point where the tyre is only interacting with the water on the surface. The measurement of this water layer that causes full hydroplaning at high speed may then be related to the friction characteristics.

Water displacement is affected by the road surface texture, tyre tread water film thickness and speed. It would take a tyre with a diameter similar to a sideways force tyre 0.0003 seconds to traverse a 10 mm aggregate particle at a speed of 120 kph, the time taken will reduce at higher speeds.

The Volumetric Patch Technique is a means of estimating the mean texture depth (MTD) or macrotexture of an asphalt surfacing. Macrotexture contributes to frictional resistance by deforming the tyre surface. It has also been the practice in the UK for many years to ensure that there are interconnecting drainage paths within the surface over which the tyre runs to help disperse water and improve skidding resistance, particularly at high speeds (HD28/15 2015). Millar (2013) found that MTD alone is not necessarily a good indicator of a pavement's liability to retain water or efficiency of water displacement.

Figure 16 shows a plot of a Risk Index (RI) against MTD for the range of surfacings identified. The index was based on passing a 40 mm tread block over depth threshold models of each surfacing type. Thresholds represent horizontal planes set at 0.5 mm intervals into the model from the highest elevation.

![Figure 16 Risk Index v Mean Texture Depth for various asphalt surfacings (Millar, 2013)](image)

In spite of the similarity of many of the surfacings no clear correlation could be established between the MTD and RI. Although occasionally strong correlations are obtained for smaller groups of asphalt surfacings there are no clear causal reasons within the groups to suggest why this is so. Therefore initial investigation concluded that neither MTD nor surfacing material type are useful indicators of water entrapment.

Figure 17 shows the development of texture for a selection of surfaces indicated in Figure 16. The percentage of texture volume shows a curvilinear increase from approximately 1 mm to 11 mm into the depth of the surface. Similar trends were found for all of the remaining modelled surfaces in the dataset irrespective of surfing material.
Although a third order polynomial was found to be the best fit to the data and gave strong $R^2$ correlations of 0.99 a linear correlation for this data set also gave a strong $R^2$ correlation of 0.98. Figure 17 shows that for low textured surfaces the volume develops at a greater rate compared to the higher textured surfaces such as surface dressings or chipseals and hence will reach saturation more quickly. This is not necessarily an indicator of the amount of water that a vehicle travelling will have to displace as the drainage characteristics are also controlled by channel connectivity.

Findings confirm that the volumetric capacity, the ability to drain effectively or liability to breakdown due to water and freeze-thaw damage of a highway surfacing may be estimated using non-contact methods. This makes it possible to rank the surfaces according to their capacity to accommodate and displace water (Millar, 2013).

2.5 Modelling the tyre/road interface

In broad terms a model may be described as a construct that facilitates the investigation of the properties of a system. Within the context of the tyre road surface interface they should also allow prediction of future behaviours should one or more variables be modified. Ideally models should be verifiable from data derived from the actual systems to which they relate.

2.5.1 Complexity of the tyre/road interface

It has been recognised for some time that the tyre/road interface is unquestionably complex. For example Ammon (1992), reports that the properties of real roads along the lateral axis cannot not be adequately explained with the classic model of the isotropic road. Implicitly this is attributable to the complexity and variability of the highway surface. More recently Ivanov (2010) observes that for the most part, tyre–surface friction and rolling resistance are the deciding factors in tyre dynamics models and identifies some forty four separate parameters which impact on the tyre-surface interface as shown in Table 2.

Given the complexity and fluidity of the tyre/road interface it is not surprising that numerous models have been developed over many years of highway research in an attempt to better understand the dynamic tyre/road interface.
Table 2 Parameters impacting on the tyre-surface interface, (Ivanov et al., 2010)

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A )</td>
<td>albedo (%)</td>
</tr>
<tr>
<td>( A_t )</td>
<td>tyre–surface contact area (( \text{m}^2 ))</td>
</tr>
<tr>
<td>( C )</td>
<td>cohesive strength of soil (Pa)</td>
</tr>
<tr>
<td>( c_1 )</td>
<td>coefficients of membership functions various</td>
</tr>
<tr>
<td>( c_{el} )</td>
<td>longitudinal tyre stiffness (N/m/rad)</td>
</tr>
<tr>
<td>( d )</td>
<td>granulometry (( \text{mm} ))</td>
</tr>
<tr>
<td>( f_r )</td>
<td>rolling resistance coefficient (–)</td>
</tr>
<tr>
<td>( f_{ref} )</td>
<td>reference value of rolling resistance coefficient (–)</td>
</tr>
<tr>
<td>( F_d )</td>
<td>longitudinal aerodynamic resistance force (N)</td>
</tr>
<tr>
<td>( F_y )</td>
<td>tyre rolling resistance force (N)</td>
</tr>
<tr>
<td>( F_x )</td>
<td>tyre longitudinal force (N)</td>
</tr>
<tr>
<td>( F_z )</td>
<td>normal wheel load (N)</td>
</tr>
<tr>
<td>( i )</td>
<td>precipitation intensity (snow, rain) (mm/min)</td>
</tr>
<tr>
<td>( J_\omega )</td>
<td>moment of wheel inertia (kg ( \text{m}^2 ))</td>
</tr>
<tr>
<td>( k_{el} )</td>
<td>longitudinal tyre damping coefficient (Nm s/mrad)</td>
</tr>
<tr>
<td>( m_v )</td>
<td>vehicle mass (kg)</td>
</tr>
<tr>
<td>( M )</td>
<td>the average of distribution (n/a)</td>
</tr>
<tr>
<td>( M_{br} )</td>
<td>brake moment (Nm)</td>
</tr>
<tr>
<td>( p )</td>
<td>tyre inflation pressure (kPa)</td>
</tr>
<tr>
<td>( q )</td>
<td>penetration resistance (kPa)</td>
</tr>
<tr>
<td>( r_w )</td>
<td>tyre effective radius (m)</td>
</tr>
<tr>
<td>( s )</td>
<td>slip (–)</td>
</tr>
<tr>
<td>( T_c )</td>
<td>surface contact temperature (( ^\circ \text{C} ))</td>
</tr>
<tr>
<td>( T_e )</td>
<td>environmental temperature (( ^\circ \text{C} ))</td>
</tr>
<tr>
<td>( v )</td>
<td>linear vehicle velocity (m/s)</td>
</tr>
<tr>
<td>( w )</td>
<td>bulk soil moisture (%)</td>
</tr>
<tr>
<td>( w_0 )</td>
<td>optimal soil moisture (%)</td>
</tr>
<tr>
<td>( \delta_z )</td>
<td>variation of rolling resistance coefficient (–)</td>
</tr>
<tr>
<td>( \delta_a )</td>
<td>variation of traction ratio (–)</td>
</tr>
<tr>
<td>( \phi )</td>
<td>angle of internal friction or wheel rotation angle (( ^\circ )) (rad)</td>
</tr>
<tr>
<td>( \kappa )</td>
<td>surface microprofile (mm)</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>surface macroprofile (mm)</td>
</tr>
<tr>
<td>( \mu )</td>
<td>actual coefficient of tyre-road friction (–)</td>
</tr>
<tr>
<td>( \mu_{syn} )</td>
<td>traction ratio (–)</td>
</tr>
<tr>
<td>( \mu_{f} )</td>
<td>environmental friction coefficient (–)</td>
</tr>
<tr>
<td>( \mu_{max} )</td>
<td>maximum of tyre–road friction (–)</td>
</tr>
<tr>
<td>( \mu_{prim} )</td>
<td>primary friction coefficient (–)</td>
</tr>
<tr>
<td>( \mu_t )</td>
<td>thrust coefficient (–)</td>
</tr>
<tr>
<td>( \rho )</td>
<td>environmental moisture (%)</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>variance (n/a)</td>
</tr>
<tr>
<td>( \tau )</td>
<td>cohesion (kPa)</td>
</tr>
<tr>
<td>( \omega )</td>
<td>wheel rotational velocity (rad/s)</td>
</tr>
</tbody>
</table>

2.6 Numerical and analytical modelling in highway interface applications

Application of numerical modelling has been established across numerous and diverse disciplines including mechanical and structural engineering and biomechanics. Its origin and history are detailed by Gupta (1996) which introduces the area as

The method of analysis in which the field equations of mathematical physics are approximated over simple regions (triangles, quadrilaterals, tetrahedrons, etc).

2.6.1 Validity of FE models in interfacial phenomena

In the context of the tyre/road interface, the extent to which FE models resonate with the real world requires verification from observed or measured data. In Gabriel (2010) Finite Element Analysis is used to validate experiments. This may not be unreasonable within the confines of the experimental regime presented but the extent to which the findings may be extrapolated to the dynamic tyre/road interface is uncertain as the experimental set up (configuration 2) is not grounded in reality.

2.6.2 \textsc{Finite} \_\textsc{em}: pavement and material response

Fang et al., (2007) citing De Beer et al., (1997) observes that the tyre footprint which is of significant importance to tyre/road interaction is not a rectangular shape but composed of several areas determined by the tyre tread shapes, inflation pressure and axle load. That the tyre footprint is not rectangular was first demonstrated by Siegfried in 1993 and confirmed by De Beer et al., (1996). The variation in contact patch with inflation pressure has been confirmed by Woodward et al., (2011) using pressure pad technology.

2.6.3 Profiling and texture modelling

Wang et al. (2011) explores the potential of finite element (FE) models to simulate tyre-pavement interactions and highlights the challenges facing numerical modellers in this field.
Fernando (2006) presents a report on estimation of contact stresses. It acknowledges implicitly that historical assumptions regarding tyre pressure are unnecessarily simplistic and presents a four aspect investigation of the tyre contact stresses including application of FINITE_EM. Stresses were measured using the stress in motion (SIM) apparatus shown in Figure 18 which broadly reflects the findings of De Beer (1996).

Figure 18 SIM Mk IV Pad Used for Tyre Contact Stress Measurements, (Fernando, 2006)

Fernando (2006) and Siddharthan et al., (2002) estimate contact stresses at the contact surface but they are concerned with pavement response and not the immediate impact of those stresses on the bearing surface. Siddharthan et al., (2002) note that the difference in pavement responses computed with uniform (conventional assumption) and non-uniform contact stress distributions could vary between 6% and 30%. It therefore logically follows that the predicted surface frictional performance would vary considerably depending on what assumptions are applied.

Although not in the context of surface friction significant progress in the inclusion of more of the interfacial details of the tyre/road interface has been demonstrated by Anderson and Kropp, (2008) who note that previously, including scales on the order of micrometres have been neglected in previous tyre/road interaction models. No explicit measure of computational efficiency is offered and appears pessimistic as compared to photogrammetry in light of Matthews (2008), citing an attainable accuracy of 0.025 microns for significantly sized archaeological artefacts. It is also recognised that computational efficiency has increased considerably since the observation of Anderson and Kropp (2008).
Whilst other studies such as Hofstetter et al., (2006) and Ghoreishy, (2006) apply the \textit{FINITE\_EM} to tyre and tread response, Andersson and Kropp (2008) appear to come closest in discretisation of the actual contact geometry. Figure 19 for example shows a detail road scan; this is compared with a sampled version in Figure 20.

The coarse configuration shown by the discretisation is acknowledged by Andersson and Kropp, (2008) noting that it is not feasible to use the detailed surface geometry directly in contact models due to the vast number of samples leading to very high computational cost.

High computational cost is often cited as a reason why certain kinds of analyses are impracticable but it is not always clear what is meant. Liu et al. (2003) offers some insight noting that in the dynamic finite element simulation analysis, a total of about 490000 time increments were involved. The central processing unit time taken per computer run was about 10h. Given the date of this study and the development of newer and faster processors this impairment is likely to become less significant in numerical simulations.

Contextual studies relating to friction testing have been conducted by Purushothaman et al. (1998) and more recently Yurong et al. (2003). Much of Purushothaman et al. (1988a) is given to design, development and verification of a Variable Speed Pendulum Friction Tester (VSPFT). The research observes that a limitation of the British pendulum tester is that it can measure the
coefficient of friction only at its operating speed of 10km/h, considerably lower than the motorway speeds cited in this review. The FINITE_EM used to verify the experiment is detailed in other work including Purushothaman (1987). Purushothaman et al. (1988) is concerned with the hysteretic component of friction.

The findings of Liu et al. (2003) in the development of a 3D FINITE_EM for the British pendulum test appear impressive asserting that the examples presented in the paper demonstrate that a British pendulum tester is no longer required in order to estimate a skid resistance provided a straightforward static friction test is carried out. This would provide the data required to define the friction function for the model. Once again, something has to be measured in order to validate the findings of the finite element model.

In spite of the ambitious claims of Liu et al. (2003), Pin (2005) asserts, as a major limitation of the model of Liu et al. (2003) that it could not analyse complex textured surfaces with non-symmetric pattern. Given the random or orientated nature of highway surfacings this limitation would appear to be critical. Pin (2005) presents what is claimed to be an improvement of the model by Liu (2003) considering a wider range of surfaces including asphalt concrete though the aggregate specifications are not given. In any case, the main and perhaps only contribution to friction for vehicles moving at motorway speeds is hysteretic and a function of the macrotexture.

2.6.4 FINITE_EM and stress distribution in the contact patch

Ziefle and Nackenhorst (2008) note that the local reactions in the finite contact patch, even under high speed conditions, are essential for safety, comfort etc. The paper asserts a mathematically consistent update algorithm for internal variables that represent the inelastic material history together with a novel approach for the treatment of tractive rolling contact.

Figure 21 presents a normal stress distribution under a free rolling wheel from which the contact patch may be inferred. The distribution implies an elliptical contact patch approximately 35mm wide by approximately 16mm in length showing elevated stresses at the margins.
As the Grosch wheel is a solid rubber wheel it lacks correspondence with the impact of a pneumatic tyre on a real surface and its apparent stress distribution more closely resembles that of an underinflated tyre. However the authors do not claim to simulate in-situ conditions and state that

“As an explicit scheme has been suggested for the computation of rolling contact problems of inelastic bodies, known as Fractional-Step-method from other established ALE-applications, because a fully implicit algorithm seems to be not computable for real life problems yet”. (Ziefle and Nackenhorst, 2008, p.353)

According to Pinnington (2009) the aim in tyre and road surface design is slowly becoming the provision of adequate friction while minimising negative contributions. Pinnington (2001) provides a broad summary of the interactions at the tyre/road interface whilst acknowledging that there is not yet a single surface model for all interactions.

2.7 Analytical and empirical tyre/road friction models

Wang et al. (2006) note that significant research efforts had been put into tyre/road friction modelling during the last 40 years. It seems clear therefore that given the continued development of models and modelling techniques that there remains much work to be done. According to Wang tyre/road friction is hard to analyse especially for three reasons:

1. The friction force is affected by deformations, adhesion and tearing (wear) with deformation friction providing most of the friction force. Wang et al. (2006) suggest that these forces are highly dependent on sliding velocity and tyre surface temperature.
2. Most empirical tyre/road friction formulas are hard to explain by physical laws
3. An appropriate tyre/road friction model should be easy to employ in vehicle control systems.

The third is an important point as it suggests that evaluation of the tyre/road friction phenomena should be in quasi-real time within the vehicle itself. A synopsis of a range of longitudinal tyre/road friction models is given in Table 3 (Wang et al., 2006).

Table 3 Synopsis of longitudinal tyre/road friction models

<table>
<thead>
<tr>
<th>Year</th>
<th>Model Name</th>
<th>Model Properties</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>2. Has some revised formula</td>
</tr>
<tr>
<td>1994</td>
<td>Rill Model</td>
<td>Semi-Empirical</td>
<td>Easy to identify</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2. Has lost of revised formula</td>
</tr>
<tr>
<td>1977</td>
<td>Dahl Model</td>
<td>Analytical</td>
<td>3. Can employ different factors</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1. Can describe Coulomb friction.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2. Can produces smooth transition around zero velocity</td>
</tr>
<tr>
<td>1991</td>
<td>Bliman-Sorine Model</td>
<td>Analytical</td>
<td>Can capture the Stribeck effect in addition to Dahl model</td>
</tr>
<tr>
<td>1995</td>
<td>LuGre Model</td>
<td>Analytical</td>
<td>Can combine pre-sliding &amp; sliding in addition to Bliman-Sorine Model</td>
</tr>
</tbody>
</table>
A representative range of lateral tyre/road friction models is shown in Table 4. A range of integrated tyre/friction models have been developed such as Stephant et al., (2002), and Galvert and Svendenius (2003) which present empirical and semi-empirical models. By comparison analytical integrated models have received less attention (Wang 2006).

<table>
<thead>
<tr>
<th>Year</th>
<th>Model Name</th>
<th>Model Properties</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>1987</td>
<td>Magic Formula</td>
<td>Semi-Empirical</td>
<td>Can accurately fit curves</td>
</tr>
<tr>
<td></td>
<td>Bicycle Model</td>
<td>Analytical</td>
<td>Does not reflect tire/road friction force directly</td>
</tr>
</tbody>
</table>

Inevitably the models are based on reasoned assumptions and simplifications from which significant errors may accrue.

### 2.8 Summary of findings

There is no explicit definition of high speed friction in the literature within the context of the SRN. Generic requirements for high speed friction measurement suggest a device that can be used at speeds in excess of 70 mph. The most appropriate aspects of friction for high speed roads such as the SRN are factors related to the tyre / road surface interface during high speed braking events.

There is no friction measuring device in common use at network level that can be used to measure high speed friction of the English SRN. The longitudinal force test is generally capable of higher speeds than the sideways force method; however the current devices for both methods employ a test tyre that is susceptible to damage or blow out if speeds are to be increased. The new American RT3® CURVE device claims to measure continuously at 70 mph and should be further investigated as a possible device for the English SRN. However, as it is a towed device the speed at which it can be used is restricted to the legal speed limit for towing vehicles (60 mph). Therefore, it is appropriate to consider measuring or modelling another property related to friction or some form of non-contact assessment.

The dynamic tyre/road interface is one of considerable complexity and not fully understood at motorway speeds. The traditional understanding of the adhesion/hysteresis mechanism is not universally accepted by researchers with some arguing convincingly that the apparent adhesion component should be ignored. It follows therefore that any model based on the traditional assumptions will be limited by definition. However this finding is based on laboratory testing at low speed under idealised conditions.

Numerous empirical, semi empirical and numerical models have been developed over many years each of which has its own limitations. It is clear therefore that there is no universally accepted model or method of modelling which is valid under all circumstances. Models require simplifications and assumptions in order to mitigate the array of variables comprising the dynamic tyre/road interface. Therefore the models are removed to a greater or lesser extent from the scenario being modelled.

Models or modelling outputs require validation against a measureable scenario which tends to be a laboratory or idealised field test. It is unclear therefore to what extent modelling outputs may be extrapolated to real highway conditions under high speed. The continuing development of models and modelling methods confirms that understanding the dynamic tyre/road interface remains a challenging area of research.
Future development of friction measuring devices should so far as is reasonably possible be based on in-situ highway conditions. That is, it should be capable of measurement at motorway speed without contravention of statutory health and safety legislation; it should measure with treaded tyres under realistic loads. The move from the traditional approach of measurement, which has not fundamentally changed for the last eighty five years, opens up many possibilities. These might include prediction of friction using non-contact measurement of road surface properties, extraction and evaluation of data from the vehicle or its tyres to using large datasets from orbiting satellite that measure all parts of the earth’s surface every few days. In addition, the recommendation from the ROSANNE project of a simplified principle of enveloping should be considered in any future investigation.

Consideration should be given to measurement of friction demand in quasi real time by the vehicles that actually use the SRN. This would require the development of smart sensor based tyre technology which measures friction demand using in situ parameters as surrogates. This has potential advantages including:

- measurement would be continuous in quasi real time under actual in situ conditions and not merely seasonal.
- vehicle response could be updated in real time

Friction measuring device outputs would not be required except as an indicator of a minimal standard of the highway surfacing. Factors contributing to a potential reduction in skid resistance can be linked to the car and its driver from weather forecasts warning the driver or car. This would also give better understanding of the impact of seasonal, daily and other short term changes.

The themes explored and the areas exposed in the literature have led to the creation of a detailed laboratory and field testing programme. This programme has three distinct objectives:

- A method of assessing road pavement skid resistance using a non-contact measuring method consisting of laboratory and field trials.
- A fundamental assessment of tyre-pavement enveloping using specially developed laboratory devices and contact pressure measurement.
- Measurement of pavement texture using 2d, 3d pavement surface texture modelling and application to water displacement.
3 Development of a non-contact measuring method

This section summarises the investigation into using tyre temperature as a proxy for tyre road friction at high speed. This method would avoid current problems with excessive wear and damage to the friction measuring tyres currently used. If proven, this principle could be used as a surrogate indicator of tyre / road surface related properties such as skid resistance, noise and rolling resistance. This investigation was conducted in two parts:

1. Laboratory – to consider tyre temperature / road surface texture interaction.
2. In situ – development of a bolt on device to produce a thermal signature of roads.

3.1 Laboratory testing

The ULTRA rolling road apparatus was used with replicate test specimens and the ASTM 1844 friction measuring tyre (used on the GripTester device) A forward looking infrared (FLIR) thermal camera was used to measure test tyre temperature. The main test variables considered include surface texture, vertical load, test speed, whether the interface was dry or wet and rolling condition (free or offset).

3.1.1 The ULTRA rolling road apparatus

The ULTRA rolling road apparatus (Figure 22) consists of a 1.12 m diameter drum. Drum rotation speed is electronically controlled up to a limit of 300 rpm or an equivalent road speed of 64.3 kph.

Figure 22 The ULTRA rolling road apparatus.

Fifteen curved test specimens are fitted to the inside face of the drum to form a continuous test surface, that the test tyre runs on. The lateral slip angle of the test tyre can be adjusted to simulate an offset slip similar to the principle of a sideways force device. Offset running can result in significant wear of the tyre surface. Due to the diameter of the drum, the test tyre is
limited in size to something similar to a go-kart tyre. Therefore, the ASTM 1844 measuring friction tyre was chosen for this investigation.

The ULTRA apparatus is typically run under dry free rolling conditions. The ULTRA was modified to investigate the effect of water on the test tyre surface interface during testing. This involved directing water immediately in front of the test tyre / test surface interface at rates comparable to those used during GripTester testing. This gives theoretical water depths of 0.25, 0.5 and 1 mm. Figure 23 shows the system used to feed water immediately in front of the test tyre.

![Figure 23 System to feed water directly in front of test tyre.](image)

Two thermocouples were used to monitor water supply temperature at point of delivery and ambient air temperature local to the wet testing.

3.1.1.1 ULTRA test specimen manufacture

The 15 test specimens that line the inside face of the ULTRA are replicates of asphalt made with Fosroc Nitomortar PE Catalysed Filler mortar. A replicate is made by pouring a hot melt vinyl compound (Vinamold) over the asphalt, either on the road surface or a laboratory manufactured slab. The Vinamold cools quickly and within a few minutes can be carefully peeled off the surface. This provides an invert copy of the surface texture which is used to line the ULTRA specimen mould. Figure 24 shows Vinamold coating an SMA slab with the selected area cut out for preparation of ULTRA test specimens.

![Figure 24 Vinamold coating SMA slab.](image)

The selected piece of Vinamold is placed in the bottom of the ULTRA specimen mould as shown in Figure 25. Nitomortar is poured to fill the ULTRA specimen mould. A curved backing plate is fixed onto the mould. The Nitomortar is allowed to set for 24 hours, then the mould is disassembled and the curved ULTRA test specimen removed.

The process is repeated for the 15 test specimens required for the ULTRA apparatus. The same Vinamold replicate can be used to make all fifteen test specimens, ensuring the tyre is interacting with a consistent test specimen surface. Figure 25 shows a completed ULTRA test specimen.
Figure 24  Vinamold on SMA, cut out section used to prepare ULTRA test specimens

Figure 25  ULTRA specimen mould and completed specimen on the left
3.1.2 ULTRA rolling road thermal method development

A method to investigate the thermal characteristics of the ASTM 1844 friction measurement tyre running on the ULTRA apparatus rolling road was developed. This involved the following stages:

- Selection of test speeds.
- Selection of test loading conditions.
- Selection of FLIR camera position for image capture.
- Selection of optimal friction tyre measurement location.

3.1.2.1 Selection of test speeds

The speeds were 20 kph for slow speed measurement, 50 kph to simulate standard GripTester device test conditions and 65 kph as it is the maximum rotational speed of the device.

3.1.2.2 Selection of test loading conditions

The test tyre is mounted on a stub axle fitted to a mounting carriage. Vertical load on the test tyre is altered by adding weights to the mounting carriage. The static vertical load of the test tyre is determined using a load cell placed under the test tyre. Three standard loading conditions were selected and are shown in Table 5.

<table>
<thead>
<tr>
<th>Load condition</th>
<th>Description</th>
<th>Load under test tyre (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Weight of mounting carriage and test tyre resting on the test specimen surface.</td>
<td>0.22</td>
</tr>
<tr>
<td>B</td>
<td>As above with addition of a system for holding weights, plus 1 x 10 kg weight.</td>
<td>0.50</td>
</tr>
<tr>
<td>C</td>
<td>As above with total of 3 x 10 kg weights.</td>
<td>0.73</td>
</tr>
</tbody>
</table>

3.1.2.3 Selection of FLIR camera position for image capture

Tests were performed to optimise the position of the FLIR camera to avoid possible damage and the adverse effects of spray during wet testing. The FLIR camera has a 22° lens designed for longer range image capture and a minimum working distance of 0.3m. The optimum position was determined to be 0.5m from the test tyre and 0.4m above ground-level (Figure 26).

For investigation of the test tyre / test surface, the camera was oriented 10° from parallel to the orientation of the test tyre. Measurements were taken as the tyre lifted from the test surface during rolling conditions.
3.1.2.4 Selection of optimal friction tyre measurement location

Figure 27 and Figure 28 show thermal images of the test tyre sidewall during dry free rolling test conditions. Figure 27 shows heat generation within the bearings of the stub axle, reflected off the wheel assembly of the test tyre. A plastic cover was manufactured to cover the stub axle and bearings and so avoid contamination of the test tyre thermal data (Figure 27).

The FLIR Researcher software has an area average measurement tool. This allows pixels within a specified area to be manually selected on the thermal image and the average temperature calculated. Two scenarios were evaluated i.e. four area averages and three area averages shown in Figure 28 and Figure 29 respectively.
Figure 28 Thermal image of test tyre with four areas averaged

Figure 28 shows four equally sized 15 x 15 mm areas located across the test tyre with the FLIR camera operated at a distance of 0.5 m. Comparison of average temperature for the two central areas found them to be similar. The two areas at the outside edges of the test tyre were affected by heat generated by the shoulder of the tyre flexing under the load applied. Figure 29 shows three defined areas across the width of the test tyre. The central rectangle is 30 x 15 mm in size and referred to as Area 2. Ambient temperature is recorded at Area 4.

Figure 29 Thermal image of test tyre with three areas averaged
Figure 30 shows an example of the average temperature against time recorded in Area 2, under dry free rolling conditions.

![Figure 30 Typical area average thermal data from Area 2 (central 30 mm wide rectangle)](image)

Four distinct regions can be identified from the thermal plot (Figure 31) captured under dry free rolling test conditions. An explanation of what happens within each region is given in Table 6.

![Figure 31 The four thermal zones under dry free rolling test conditions](image)
Table 6 Dry free rolling thermal regions

<table>
<thead>
<tr>
<th>Free Rolling Region</th>
<th>What is happening during the test</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRR1</td>
<td>Drum speed increases to set value and remains constant. Temperature being recorded in Area 2 increases from ambient to an equilibrium value depending on test conditions.</td>
</tr>
<tr>
<td>FRR2</td>
<td>Drum rotating at constant speed. Test tyre / test surface under equilibrium conditions.</td>
</tr>
<tr>
<td>FRR3</td>
<td>Drive motor is switched off and drum comes to a halt. Spike in measured temperature as the test tyre becomes stationary.</td>
</tr>
<tr>
<td>FRR4</td>
<td>Test tyre cools slowly to ambient room temperature.</td>
</tr>
</tbody>
</table>

Region FFR2 represents an equilibrium condition during which there may be only a further small increase in temperature. With respect to this investigation, FFR2 was selected to best simulate a vehicle travelling along a road at constant speed and any change in tyre temperature reflect interaction with a change in interface condition.

3.1.2.5 ULTRA rolling road thermal test protocol

The following test protocol was developed from the initial testing and subsequently used for dry free rolling investigations:

- Fix a set of 15 test specimens to the inside face of the ULTRA to create a test surface.
- Fit sacrificial tyre to condition the test surface.
- Run drum at 300 rpm for 30 minutes to bed in specimens and remove any roughness.
- Check fixing of test specimens
- Fit and check test tyre for physical damage and inflation pressure.
- Set up and synchronise FLIR thermal camera with the control computer.
- Focus thermal camera set using a high emissivity surface against the area of interest on the friction tyre. FLIR camera runs continuously throughout the test.
- Check charge of the ULTRA pneumatic control system and safety brake disengaged.
- ULTRA 3-phase power supply energised.
- ULTRA room closed to ensure safe remote operation.
- Lower test tyre into contact with the test surface using pneumatics.
- Bring drum rotation up to the required speed with the electronic controller.
- Check the combination of test factors investigated.
- Run ULTRA for 20 minutes to achieve equilibrium conditions.
- Switched off motor and record time taken for the drum to come to a complete stop.
- Monitor tyre wear before and after testing.

3.1.3 Dry free rolling laboratory investigation

This section details the laboratory investigation of the thermal characteristics of an ASTM 1844 friction measuring tyre in dry free rolling conditions with four different types of test surface. The test conditions are summarised in Table 7 and the four test surfaces are detailed in Table 8.

Table 7 Summary of test conditions

<table>
<thead>
<tr>
<th>Test tyre</th>
<th>Almost new ASTM 1844 friction measurement tyre, inflation pressure 20 psi (138 kPa).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test surface</td>
<td>Smooth steel, 6MA, 8SMA, 14SMA</td>
</tr>
<tr>
<td>Load (kN)</td>
<td>0.22, 0.5, 0.73</td>
</tr>
<tr>
<td>Test speed (kph)</td>
<td>20, 50, 65</td>
</tr>
<tr>
<td>Ambient temperature (°C)</td>
<td>16 to 32</td>
</tr>
</tbody>
</table>
Table 8 Test specimens investigated for free rolling thermal characteristics

<table>
<thead>
<tr>
<th>Test Specimen Texture</th>
<th>Source of test specimen replicate</th>
<th>Texture depth (mm)</th>
<th>Type of texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULTRA apparatus drum inside face</td>
<td>N/A</td>
<td>0</td>
<td>None Smooth steel</td>
</tr>
<tr>
<td>6 MA</td>
<td>RTM test specimen after 60,000 wheel passes</td>
<td>0.93</td>
<td>Positive</td>
</tr>
<tr>
<td>8 SMA</td>
<td>RTM test specimen after 75,000 wheel passes</td>
<td>0.42</td>
<td>Negative</td>
</tr>
<tr>
<td>14 SMA</td>
<td>RTM test specimen after 2000 wheel passes</td>
<td>1.59</td>
<td>Negative</td>
</tr>
</tbody>
</table>

The smooth steel surface was assumed to have almost no macrotexture. The 6 MA was a replicate of a 6 mm Microasphalt (MA) RTM test specimen (305 x 305 x 50 mm) that had received 60,000 wheel passes of simulated trafficking. The asphalt test specimen had a positive texture with a macrotexture of 0.93 mm measured using the volumetric sand patch technique. The 8 SMA was a replicate of an 8 mm Stone Mastic Asphalt (SMA) test specimen (305 x 305 x 50 mm) that had received 75,000 wheel passes of simulated trafficking. This had a negative texture with a macrotexture of 0.42 mm. The 14 SMA was a replicate of a 14mm SMA test specimen (305 x 305 x 50 mm) that had received 2,000 wheel passes of simulated trafficking. This had a negative texture with a macrotexture of 1.59 mm.

The majority of experiments were undertaken at ambient room temperatures of 20°C +/- 2°C. The effect of load and speed on equilibrium temperature was investigated for the four test surfaces.

3.1.3.1 Effect of load during dry rolling

Figure 32 to Figure 35 show the relationships between equilibrium temperature and load for the smooth steel, 6 MA, 8 SMA and 14 SMA test surfaces respectively. Comparison of the plots shows good relationship between load and equilibrium temperature. An increase in load causes equilibrium temperature to increase for all test surfaces and test speeds.

The smooth steel surface has the lowest equilibrium temperatures of the surfaces assessed. This can be explained by it having the least interaction and the thermal conductivity of steel is 54 W/mK which is a magnitude greater than Nitomortar with 1 W/mK. Therefore, the heat generated within the tyre is more easily dissipated to the steel surface while the apparatus is in operation. The increase in tyre temperatures in FRR3 (as the ULTRA stops) was significantly higher for the steel drum than the Nitomortar surfaces.
Figure 32 Equilibrium temperature and load for smooth steel surface

Figure 33 Equilibrium temperature and load for 6MA.

Figure 34 Equilibrium temperature and load for 8SMA.
The highest equilibrium temperatures recorded during the test conditions were on the 6MA replicate texture (Figure 33). Figure 34 and Figure 35 show similar relationships for both the negatively textured 8SMA and 14SMA test surfaces.

Figure 35 Equilibrium temperature and load for 14SMA.

The linear relationships are summarised in Table 9 and show good prediction of equilibrium temperature based on load.

Table 9 Linear regressions for equilibrium temperature and load.

<table>
<thead>
<tr>
<th>Surface type</th>
<th>Test speed</th>
<th>Equation</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth steel</td>
<td>20</td>
<td>y = 5.2764x + 19.36</td>
<td>0.9948</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>y = 5.4911x + 22.146</td>
<td>0.7988</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>y = 4.767x + 22.883</td>
<td>0.9935</td>
</tr>
<tr>
<td>6MA</td>
<td>20</td>
<td>y = 9.2665x + 26.355</td>
<td>0.9965</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>y = 15.926x + 29.316</td>
<td>0.9985</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>y = 16.917x + 31.267</td>
<td>0.9980</td>
</tr>
<tr>
<td>8SMA</td>
<td>20</td>
<td>y = 7.9331x + 24.666</td>
<td>0.9614</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>y = 13.114x + 28.061</td>
<td>0.9991</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>y = 9.4711x + 31.756</td>
<td>0.9879</td>
</tr>
<tr>
<td>14SMA</td>
<td>20</td>
<td>y = 5.0304x + 26.869</td>
<td>0.8725</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>y = 8.5018x + 30.841</td>
<td>0.9662</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>y = 10.661x + 31.297</td>
<td>0.9995</td>
</tr>
</tbody>
</table>

3.1.3.2 Effect of speed during dry rolling

Figure 36 to Figure 39 show the relationships between equilibrium temperature and speed for the smooth steel, 6MA, 8SMA and 14SMA test surfaces respectively. Explanation of the data is comparable to that described for the load and equilibrium data. The issue of thermal conductivity may account for the lower equilibrium temperatures measured for the steel surface and highest speed tests.
Figure 36  Equilibrium temperature and speed for smooth steel surface.

Figure 37  Equilibrium temperature and speed for 6MA.

Figure 38  Equilibrium temperature and speed for 8SMA.
Figure 39 Equilibrium temperature and speed for 14SMA.

Linear relationships were found for all test conditions and are summarised in Table 10. The results show good prediction of equilibrium temperature based on speed.

Table 10 Linear relationships for equilibrium temperature and speed.

<table>
<thead>
<tr>
<th>Surface type</th>
<th>Speed</th>
<th>Equation</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth steel</td>
<td>20</td>
<td>( y = 0.0836x + 19.066 )</td>
<td>0.8685</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>( y = 0.0883x + 20.09 )</td>
<td>0.8921</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>( y = 0.0603x + 22.345 )</td>
<td>0.6066</td>
</tr>
<tr>
<td>6MA</td>
<td>20</td>
<td>( y = 0.1528x + 25.263 )</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>( y = 0.19x + 27.411 )</td>
<td>0.9985</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>( y = 0.2456x + 28.274 )</td>
<td>0.9941</td>
</tr>
<tr>
<td>8SMA</td>
<td>20</td>
<td>( y = 0.1657x + 22.843 )</td>
<td>0.9991</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>( y = 0.1724x + 25.71 )</td>
<td>0.9985</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>( y = 0.1938x + 26.745 )</td>
<td>0.9407</td>
</tr>
<tr>
<td>14SMA</td>
<td>20</td>
<td>( y = 0.137x + 25.143 )</td>
<td>0.9795</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>( y = 0.1577x + 27.011 )</td>
<td>0.9736</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>( y = 0.2019x + 26.314 )</td>
<td>0.9946</td>
</tr>
</tbody>
</table>

3.1.3.3 Dry rolling results

The investigation showed good prediction of equilibrium temperature is achievable from load or speed data. Equilibrium data averaged from the FFR2 region (10 to 15 minutes into the test) for both load and speed are shown in Table 11. The majority of experiments were undertaken at ambient room temperature of 20°C +/- 2°C. The effect of load and speed on equilibrium temperature was investigated for the four test surfaces.
Table 11 Summary of equilibrium temperature data for the FFR2 region of Area 2

<table>
<thead>
<tr>
<th>Test speed (kph)</th>
<th>Test load (kN)</th>
<th>Equilibrium temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Drum</td>
<td>6MA</td>
</tr>
<tr>
<td>20</td>
<td>0.22</td>
<td>20.5</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>22.1</td>
</tr>
<tr>
<td></td>
<td>0.73</td>
<td>23.2</td>
</tr>
<tr>
<td>50</td>
<td>0.22</td>
<td>24.1</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>23.7</td>
</tr>
<tr>
<td></td>
<td>0.73</td>
<td>26.6</td>
</tr>
<tr>
<td>65</td>
<td>0.22</td>
<td>23.9</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>26.3</td>
</tr>
<tr>
<td></td>
<td>0.73</td>
<td>25.4</td>
</tr>
</tbody>
</table>

3.1.4 Wet free rolling laboratory investigation

Testing was carried out to investigate the effect of water at the test tyre / test surface interface during free rolling conditions. Thermal data was used to investigate how quickly the temperature decreased once water was applied to the interface. Three test surfaces were used: 6MA, 8SMA and 14SMA, with three loads at a test speed of 50 kph. The water temperature ranged from 9.5 to 10.5 °C and the ambient room temperature ranged from 17.0 to 19.7 °C.

The test tyre was brought up to equilibrium temperature and then water was applied immediately in front of the test tyre / test surface contact area. This application method is similar to how water is applied for most types of friction measurement such as GripTester and sideways force devices. The water flow was turned off and a second equilibrium temperature reached then the power to the motor was cut so the drum slows to a halt and the tyre starts to cool back to ambient. Figure 40 shows four distinct periods during the test;

1. Initial tyre warming up to a dry equilibrium temperature
2. Tyre drenching - water with a recorded temperature of 12°C was applied in front of the contact area and an almost immediate drop in temperature is recorded. In most cases it took less than 1 second to drop 10°C from its dry free rolling equilibrium temperature. The thermal camera recorded a similar temperature to the water temperature.
3. Secondary increase in tyre temperature occurs once the water flow is turned off. An increase of 10°C within 2 minutes was recorded. The new equilibrium temperature is less than the original totally dry interface condition. It is proposed that water is still trapped in the surface texture of the rolling road test surface and helping to cool the interface yielding a wet equilibrium. The 14SMA surface remained cooler for longer compared to the 6MA.
4. Tyre cooling at the end of the test showed a gradual drop in temperature.

The effect of water allocation rate was investigated. Figure 41 plots Area 2 temperature data for a test in which water application was increased in a series of steps. Testing started dry, then water was applied at 0.54 l/min. Water was stopped and the temperature increased as the interface started to dry. Water was then applied at 3.6 l/min and so on. Water temperature remained constant. Extended wet testing found the FLIR camera measured temperature to remain fairly constant.
Figure 40 Test tyre condition during a wet free rolling test.

Figure 41 shows a small stepped decrease in ambient air temperature, probably due to the increase in moisture in the air. There was a significantly greater decrease in Area 2 temperature with respect to water allocation rate.

Figure 41 Effect of water application rate.
Figure 42 shows the equilibrium temperatures for this experiment, illustrating the significant drop in temperature between dry and wet free rolling conditions. It also shows a linear decrease in equilibrium temperature with increasing application of water to the interface.

![Figure 42 Difference between dry and increasing amounts of water at the interface.](image)

The test protocol developed showed linear relationships between variables. Wet testing found an immediate cooling effect on test tyre surface temperature once wetted during dry free rolling conditions. Sideways angled testing found a significant increase in interface temperature. The FLIR camera was compared with a single spot ruggedized sensor and found to give comparable results in the laboratory.

### 3.1.5 Rolling resistance testing

A roll down test was used to determine the rolling resistance of each test surface under dry conditions. The experiments were carried out at 65 kph under the three loading conditions. The inflation pressure of the ASTM 1844 test tyre was 20 psi.

Testing consisted of running the ULTRA rolling road at 65 kph for 20 minutes to ensure the test tyre was at equilibrium temperature. The power to the drive motor was switched off. The time for the ULTRA drum to stop rotating was recorded as a measure of rolling resistance. A shorter time is indicative of greater rolling resistance i.e. greater interaction between the test tyre and the test surface.

The time to stop data is given in Table 12 and plotted in Figure 43. This shows good linear relationships between load, time to stop and test surface. The effect of surface texture was most pronounced at the lowest load. At the greatest load, the times to stop were almost identical.

<table>
<thead>
<tr>
<th>Load (kN)</th>
<th>6MA</th>
<th>8SMA</th>
<th>14SMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.22</td>
<td>225</td>
<td>250</td>
<td>229</td>
</tr>
<tr>
<td>0.5</td>
<td>176</td>
<td>205</td>
<td>192</td>
</tr>
<tr>
<td>0.73</td>
<td>157</td>
<td>161</td>
<td>159</td>
</tr>
</tbody>
</table>

The 6MA replicate shows the greatest rolling resistance and 8SMA the least with a 0.22kN load applied. However the difference between rolling resistance is reduced as the applied load increases.
As the ULTRA rolling road apparatus came to a halt in the faster, heavier load experiments, an interesting phenomenon was observed in the thermal video. An example is shown in Figure 44. This shows the texture of the 14SMA test surface caught in the thermal image of the test tyre.

It represents thermal conduction from the still hot test tyre into the texture of the test surface. It provides evidence of how energy is transferred from a moving vehicle to the road. This phenomenon could only be discerned at very low test speeds due to the limitations of the FLIR SC640 thermal camera. High speed thermography could be used to determine this interaction between tyre and road surface.
3.2 In situ testing

Following the successful proof of concept in the laboratory investigation further development to field testing was conducted. The following sections outline the development and field testing of a bolt-on device that could be fitted to a vehicle to measure tyre temperature in situ.

3.2.1 Laboratory development of an in situ test method

The laboratory investigations using the FLIR thermal camera had shown good correlation between variables thought to influence tyre temperature. The FLIR camera was not sufficiently hardy for operation in the field; the lens was particularly delicate and susceptible to damage from detritus thrown up during testing. This resulted in a search for suitable bolt-on devices. The system chosen was simple yet powerful. It consisted of two elements i.e. a single point infra-red temperature sensor and a GPS data logger. Both devices have been developed for motorsport application and are robust.

The temperature sensor chosen is a Texense INF (V/T) 150°C (details are available at www.texense.com). This sensor was developed for the non-contact measurement of tyre temperature in motorsport. It has a measurement range of 0 to 150°C with a response time of 50 ms. At a distance of 50 mm the spot measurement is 12.5 mm diameter. The signal from the sensor was logged up to 100 times a second at high level accuracy.

Figure 45 shows the main elements of the bolt-on device i.e. the Texense sensor, the Racelogic mini input module and the Racelogic GPS data logger. This was trialled in the laboratory along-side the FLIR thermal camera. The Texense sensor is shown in Figure 46 located to the back of the test tyre so as not to interfere with the FLIR thermal camera.

Figure 45 Main elements of the bolt-on device

A series of test runs were conducted to compare test tyre temperature data recorded by each device. A summary of equilibrium temperatures at test speeds of 50 and 65 kph is shown in Table 13. The equilibrium temperatures are slightly different because the sensors are being exposed to different amounts of thermal energy. The FLIR sensor may have been influenced by the additional reflected and ambient infrared sources. The Texense sensor is located approximately 50 mm to the test tyre and is less influenced by thermal sources other than the tyre. Figure 46 shows the Texense position for testing, experimentation at 50 and 65 kph found that the measured test tyre temperature was not affected by sensor location.
Table 13 Comparison of FLIR and Texense equilibrium data.

<table>
<thead>
<tr>
<th>Test speed (kph)</th>
<th>FLIR thermal camera</th>
<th>Texense sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>30.1, 29.1</td>
<td>29.6, 29.1</td>
</tr>
<tr>
<td>65</td>
<td>31.5, 32.9</td>
<td>29.9, 30.3, 31.0</td>
</tr>
</tbody>
</table>

The data from both sensors under free rolling conditions and with the test tyre offset at 2° are plotted in Figure 47. The test surface was 8SMA replicate, the test speed was 50 kph and load was 0.22 kN.

Figure 47 Offset test tyre compared to free rolling conditions.
The equilibrium temperature for free rolling conditions was 29.1 for both sensors. The comparable average equilibrium temperatures with a 2° offset test tyre were 44.4 and 42.9 for the FLIR and Texense sensors respectively. Figure 47 also shows the offset test tyre reaches equilibrium temperature much quicker than the free rolling tyre. There was more test tyre wear during offset testing and so this possible modification to the bolt-on test method is not recommended.

### 3.2.2 Field trial of in situ test method

The Texense sensor was installed onto a GripTester. The chain was removed from the GripTester to represent free rolling conditions similar to the laboratory investigations. A mounting was fabricated to locate the sensor approximately 50 mm behind the ASTM friction tyre. A guard was fabricated to protect the sensor from detritus thrown up by the tyre. The data logger GPS receiver was centrally located on the GripTester and data was logged at 100 Hz.

A series of road trials was initiated to determine whether it offered a possible means of recording a thermal signature for a road surface indicative of texture related properties such as skid resistance. This proved interesting and confirmed laboratory observations.

The trial site is a 15 km length of dual carriageway surfaced with a 14 mm TSCS which is approximately 1 year old. The trial site consists of a 1 km section leading into a roundabout followed by 14 km of TSCS and finishing at another roundabout. Figure 48 and Figure 49 show plots of test speed and voltage from the Texense sensor with distance travelled, and a selection of variables that can be displayed on the y-axis.

Figure 48 shows test speed increasing during the first 1 km and then slowing for the roundabout, the tyre temperature gradually increases then spikes at km 1 with the deceleration for the roundabout. The tyre cools a little after the roundabout and then resumes its gradual increase in temperature towards equilibrium. It takes about 5 km the test tyre to reach equilibrium temperature under free rolling conditions. The test speed is maintained between 75 and 85 kph for the remaining 14 km. The spike in the voltage data at km 11 is located at a slip road entering the carriageway. The spike may be showing how this is affecting the development of early life skid resistance at this location. The equilibrium temperature is regained almost instantly and maintained until slowing down for the roundabout at km 15 where a third spike in temperature is observed.

![Figure 48 Screenshot showing data for 15 km of 14 mm TSCS](image-url)
Figure 49 also shows the gradual increase in temperature up to equilibrium, interrupted by a spike in temperature associated with braking for the roundabout. Equilibrium temperature is reached after 5 km.

![Figure 49 Test data showing effect of speed reduction for a roundabout and distance taken to reach equilibrium](image)

Figure 49 Test data showing effect of speed reduction for a roundabout and distance taken to reach equilibrium

Figure 50 shows data plots relating to a 1.5 km section of hot rolled asphalt located between two roundabouts as shown in the location map. In this example, the test tyre has been running at equilibrium temperature before encountering this section of road. This data illustrates a relationship between speed and temperature i.e. as speed increases to 80 kph tyre temperature decreases to an equilibrium condition. Slowing for the second roundabout the tyre temperature increases.

![Figure 50 Screenshot showing data for 1.5 km of hot rolled asphalt](image)

Figure 50 Screenshot showing data for 1.5 km of hot rolled asphalt
The road trials were carried out in dry conditions the test sections were mostly dry with some short wet or damp sections. The tyre thermal data was found to be sensitive to in-situ circumstances such as sun / shadow and the presence of moisture / water on the road surface. This agrees with laboratory investigations that showed the presence of water at the interface to have a significant influence in cooling the tyre surface, going from bright sun to shade had a small influence.

Dirt thrown up by the tyre during testing proved to be an issue necessitating cleaning of the sensor on a regular basis. Despite these issues, the road trials found that the bolt-on device offered a method of evaluating the high speed tyre / road surface texture interface based on a thermal signature.

The proof of principle device used relatively cheap and commonly available off-the-shelf components. It has multiple inputs that are all geo-referenced so can be adapted. A MK2 bolt on device could include video capture and multiple sensors to measure air, road surface and tyre surface temperature. IMU could be used to relate accelerating, braking and turning influences.

3.3 Results

Work Stage 3a considered whether the principle of tyre temperature could be used as a non-contact method of measuring tyre road interaction at high speed thus avoiding current problems with excessive wear and damage to the friction measuring tyres currently used. If proven, this principle could be used as a surrogate indicator of tyre / road surface related properties such as skid resistance, noise and rolling resistance. Work Stage 3a has the following findings:

- A test methodology was developed to investigate variables under controlled laboratory conditions using the ULTRA rolling road apparatus, replicate test specimens and the ASTM 1844 friction measuring tyre.
- The main test variables were test specimen texture, speed, load, dry or wet, and rolling condition (free or offset).
- An equilibrium temperature is reached depending on the specific combination of test variables.
- It takes a period of time for the surface of the test tyre in contact with the test surface to reach an equilibrium temperature that is dependent on the combination of test variables.
- The application of water at the test tyre / test specimen interface causes an immediate and significant reduction in temperature (approximately 10 degrees in 1 second).
- Offsetting the test tyre at 2 degrees caused a significant increase in tyre surface temperature under free rolling conditions.
- A proof of principle bolt-on device was developed to investigate whether tyre temperature could be used at high speed as a measurement of tyre / road surface interaction.
- A free rolling tyre needs time to achieve a thermal equilibrium with its surrounding.
- Tyre surface temperature may be used as a method to infer tyre and surface interaction.
4 Assessment of tyre-pavement enveloping

The 2d contact patch of tyres with a smooth surface and 3d contact patch with textured surfacings were considered to assess whether road surface texture classification is still valid. Two test apparatus were developed

1. The Tyre Embedment Apparatus Mark 1 (TEA MK1) was designed to investigate the small diameter ASTM friction tyre used in the GripTester which rotates about 17 times at 50 kph
2. The Tyre Embedment Apparatus Mark 2 (TEA MK2) was designed to investigate larger diameter sideways force friction tyre and tyres fitted to cars and vans which rotate about 7 times at 50 kph

To simplify matters, enveloping was considered to be the amount of tyre embedment or deformation that may occur into the space between coarse aggregate particles as a result of surface macrotexture or the grooves associated with runways.

Factors considered include gap size (simulated distance between aggregate particles, or groove width), wear of the aggregate particle or groove edge, vertical load, tyre inflation pressure and tyre wear. The influence of aggregate particles penetrating into the rubber was not considered in this investigation because most asphalt materials used in the English SRN are negative texture. The influence of positive texture could be investigated in future research.

An idealised macrotexture was simulated using two steel plates which could be moved apart to create a gap of known width. This ranged from approximately 6 mm to a maximum of 150 mm for both devices. Testing was carried out in a dry static condition. During a test the test tyre is lowered onto this gap between two plates and the amount of tyre embedment or deformation into the gap spacing is measured i.e. a simple indication of enveloping.

The contact patch of friction measuring and treaded tyres was measured using pressure mapping on a smooth surface. This allows factors such as tyre wear, inflation pressure, vertical load, contact area, contact length and contact width to be measured. With respect to high speed friction measurement it was considered important that the two main types of friction measuring tyre used in the UK should be central to the investigation. Table 14 details the two types of friction measuring tyre investigated.

<table>
<thead>
<tr>
<th>Friction device</th>
<th>Test wheel</th>
<th>Diameter</th>
<th>Inflation pressure</th>
<th>Static wheel load</th>
</tr>
</thead>
<tbody>
<tr>
<td>GripTester</td>
<td>Smooth ASTM-tire</td>
<td>254 mm</td>
<td>0.14 MPa (20.3 psi)</td>
<td>250 ± 20 N</td>
</tr>
<tr>
<td>Sideways force (British)</td>
<td>Smooth tyre</td>
<td>669 mm</td>
<td>0.35 MPa (50.7 psi)</td>
<td>2000 ± 80 N</td>
</tr>
</tbody>
</table>

4.1 Development of the TEA MK1

The TEA MK1 apparatus was developed to investigate the small diameter ASTM tyre fitted to the GripTester. The TEA MK1 apparatus consists of 2 main elements:

- A modified wheel tracking machine fitted with an ASTM friction measuring tyre.
- A variable gap device.

The modified wheel tracking machine (MWTM) used in the TEA MK1 is based on a Wessex wheel tracker typically used for permanent deformation testing. The environmental chamber has been removed and the arm modified to hold an ASTM friction tyre.
Figure 51 shows a loaded ASTM friction measuring tyre sitting across a gap spacing with the depth of embedment / deformation into the space between two edge plates being measured.

![The TEA MK1 apparatus.](image)

The variable gap device (VGD) is shown in Figure 52. The VGD was designed to simulate the space or gap width into which a tyre may embed or deform. This relates to the macrotexture of an asphalt surface or the grooves cut in a runway surface.

The VGD consists of simple metal frame with 4 legs. Slots on the top-side of the frame allow gap width to be varied between plates with different types of edge profile.

![The TEA MK1 Variable GAP Device (VGD) fitted with straight edge plates.](image)

The five edge profiles assessed are shown in Table 15. Each plate has four holes to bolt it securely in place during testing.
A digital tyre tread depth gauge was fitted to a stand and used to record the depth of tyre embedment or deformation between a set of plates with similar edge profile. All gap space measurements were taken from the top of the plate edges.

Two ASTM friction test tyres were evaluated (Figure 53). One was nearly new but full thickness the other was worn beyond acceptable limits. Visually the two tyres look similar, however their distribution of vertical load within their respective contact patches is quite different as a result of wear. This variation in vertical load pressure distribution is apparent in pressure pad assessment and considered later in this report.
The vertical loads used were 9.1, 11.3, 17.0, 23.8, 27.2 and 29.4 kg. The TEA MK1 testing reported was carried out in a static condition.

Figure 54 shows the ASTM friction measuring tyre located over a gap space. Figure 55 shows the modified depth gauge in measurement position. Figure 56 shows the three measurement locations across the width of the ASTM friction measuring tyre.

![Friction measuring tyre positioned over gap](image1.jpg)

**Figure 54** Friction measuring tyre positioned over gap

![Modified depth gauge in position under the ASTM friction tyre](image2.jpg)

**Figure 55** Modified depth gauge in position under the ASTM friction tyre
4.1.1 The TEA MK1 test procedure

The following steps summarise the TEA MK 1 test procedure:

- Edge plates bolted to the VGD and gap width measured using a digital vernier.
- The VGD placed in the MWTM.
- The ASTM tyre is fitted to the arm of the MWTM and its inflation pressure checked.
- The tyre is lowered to just above the VGD surface and its position aligned with the middle of the gap between plates.
- The depth gauge is aligned with the middle of the gap, either to the centre or edge of the tyre and zeroed flush with the plate surface.
- The tyre is lowered gently onto the plates, allowed to sit for 5 seconds and a tyre embedment reading recorded from the tyre depth gauge.

This process was repeated with increasing number of weights applied to the end of the arm of the MWTM and at different inflation pressures for the two tyres.

4.1.2 Example TEA MK1 data

Approximately 700 tests were carried out during the TEA MK1 investigation. The following examples illustrate the types of data that can be determined using the TEA MK1. Figure 57 illustrates the relationship between tyre embedment and gap space with increasing vertical applied load. At a given gap space the amount of embedment will increase as applied vertical load is increased. The data relating to increasing vertical load plot in two distinct trends relating to gap-width.

Figure 57 indicates a minimum gap space below which there is almost no change in the amount of tyre embedment. The embedment recorded below the minimum gap space is similar magnitude to the 0.4 mm reported by Woodward et al. (2016) for tests on PSV specimens.
Figure 57 Effect of vertical load - nearly new tyre, 20 psi, measured in central position, straight edge profile

The increase in embedment related to gap width is illustrated in Figure 58 which plots data relating to just the 233.4 N vertical load. The minimum gap space for this test condition is approximately 15 mm, and was the same for all the vertical loads assessed.
Figure 58: Nearly new tyre, 20 psi, 233.4 N load, measured in central position, straight edge profile.

Figure 59 illustrates the effect of edge profile. The data in this example shows profile edge to have less influence on the amount of tyre embedment compared to applied vertical load as shown in Figure 57.

Figure 59: Effect of edge profile type - nearly new tyre, 20 psi, 288.9 N, measured in central position.
Figure 60 illustrates the effect of tyre wear. This example compares the two tyres under similar conditions. The data shows slightly more embedment for the nearly new tyre due to its greater thickness of tread rubber.

\[ \gamma = 0.0144x^{1.3259} \quad R^2 = 0.9984 \]

\[ \gamma = 0.0062x^{0.9397} \quad R^2 = 0.9983 \]

![Comparison of nearly new and worn tyres - 20 psi, 288.9 N, measured in central position, straight edge profile](image)

**4.2 Design of the TEA MK2**

The TEA MK2 was based on the principles of the TEA MK1. The design is similar, but with larger dimensions, to accommodate larger diameter tyres, and constructed with stronger materials to withstand greater loads. A drawing of the TEA MK2 is shown in Figure 61.

![Drawing of TEA MK2](image)
The TEA MK2 consists of four main elements i.e. test tyre, tyre hub assembly with removable weights attached to the end of a lever arm assembly. The lever arm was connected in a similar fashion to the TEA MKI to accommodate the lever arm / tyre hub assembly. This can be raised or lowered to accommodate tyres of differing diameters by loosening 4 bolts at the rear as shown in Figure 62.

**Figure 62 Method of accommodating tyres of different diameters**

The apparatus accommodates friction measuring tyres used on the British and German sideways force based devices and the types of tyre used on cars and vans. It was not designed to assess HGV tyres. Figure 63 shows the finished fabricated TEA MK2 test rig. Figure 64 shows the sideways force tyre deforming into the space between two end plates.

**Figure 63 The TEA MK2 as built**
Figure 64 Sideways force tyre deforming into the space between plates measuring of this deformation

The three tyres investigated are summarised in Table 16. The testing of two sideways force tyres was to establish what significance tyre wear had on embedment into the space created by surface macrotexture. BS EN 7941-1:2006) states that a test tyre must be discarded when it loses 6 mm in diameter (3.0 mm tyre wear).

Table 16 TEA MK2 test tyre details and inflation pressures.

<table>
<thead>
<tr>
<th>Test tyre</th>
<th>Condition</th>
<th>Internal diameter (mm)</th>
<th>External diameter (mm)</th>
<th>Test inflation pressures (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trailer Tyre 195/50/R13C</td>
<td>New</td>
<td>330.3</td>
<td>520</td>
<td>90, 60, 50, 25</td>
</tr>
<tr>
<td>Sideways force tyre</td>
<td>New</td>
<td>508</td>
<td>669</td>
<td>15, 30, 50</td>
</tr>
<tr>
<td></td>
<td>Worn</td>
<td>508</td>
<td>661</td>
<td></td>
</tr>
</tbody>
</table>

The trailer tyre had a maximum allowable inflation pressure of 95 PSI. Use of the trailer tyre allowed investigation of heavier loadings and subjected the simulated test surface to much higher stresses. The standard inflation pressure for the sideways force tyre is 350 kPa or approximately 50 PSI. Testing was carried out at 15, 30 and 50 PSI. Testing was carried out at 20, 50, 60 and 95 PSI for the trailer tyre.

The edge of each plate used to simulate the gap spacing had two shapes i.e. straight and rounded. These were machined to be identical. Reversing the ends allowed either a vertical straight edged gap or a rounded gap to be available for testing. The two edges are shown in Figure 65.

Figure 65 Steel plate showing the two types of end edge detail
Table 17 summarises the calculation of reaction under the new sideways force tyre with successive application of 10 kg weights to the end of the loading arm. Table 18 summarises the calculation of reaction under the worn sideways force tyre with successive application of 10 kg weights. Table 19 summarises the calculation of reaction under the trailer tyre with successive application of 10 kg weights. The calculated values for all three tyres are plotted in Figure 66.

Table 17 Calculation of reaction under new sideways force tyre with successive application of weights.

<table>
<thead>
<tr>
<th>Number of weights</th>
<th>Arm (w1)</th>
<th>Tyre (P2)</th>
<th>Hanger</th>
<th>Weight</th>
<th>Cum Weight</th>
<th>P1</th>
<th>Rb (kN)</th>
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<td>29.1</td>
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<td>29.1</td>
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<td>1964.45</td>
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</table>

Table 18 Calculation of reaction under worn sideways force tyre with successive application of weights.

<table>
<thead>
<tr>
<th>Number of weights</th>
<th>Arm (w1)</th>
<th>Tyre (P2)</th>
<th>Hanger</th>
<th>Weight</th>
<th>Cum Weight</th>
<th>P1</th>
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<td>10</td>
<td>100</td>
<td>113.5</td>
<td>1962.69</td>
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</table>
Table 19 Calculation of reaction under trailer tyre with successive application of weights

<table>
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<tr>
<th>Number of weights</th>
<th>Arm (w1)</th>
<th>Tyre (P2)</th>
<th>Hanger</th>
<th>Weight</th>
<th>Cum Weight</th>
<th>P1</th>
<th>Rb (kN)</th>
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<td>10</td>
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<td>113.5</td>
<td>1946.79</td>
</tr>
</tbody>
</table>

Figure 66 Number of weights v. calculated static load on wheel

4.2.1 TEA MK 2 test protocol

The following test protocol was developed for the TEA MK2. This procedure was repeated for different gap widths, edge plates, inflation pressures and tyre combinations.

- Raise the arm assembly, fix the test tyre and secure in a raised position.
- Select plate edges – vertical or rounded.
- Adjust gap spacing width and via measurement ensure this is centred in line with the tyre when it is lowered into its test position.
- Centre digital depth gauge to record middle of tyre and ensure it is flush with the top of the edge plates.
- Lower tyre gently onto the gap and allow to rest for 5 seconds to allow embedment to occur.
- Record the amount of embedment from the digital depth gauge.
- Apply load to end of the assembly arm and record the change in embedment. Repeat
- Remove load and record the change in embedment.
4.2.2 Examples of TEA MK2 data

The variables investigated include tyre type, gap spacing, vertical load, and deformation during loading and unloading. The loadings used are summarised in Table 17, Table 18 and Table 19. Gap spacings are summarised in Table 20 for the different tyre / inflation pressure combinations.

Table 20 Gap spacing assessed for the tyres at different inflation pressures (using straight 90 degree plates)

<table>
<thead>
<tr>
<th>Trailer tyre gap spacing (mm)</th>
<th>Sideways tyre – new and worn gap spacing (mm)</th>
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</thead>
<tbody>
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<td>30 psi</td>
<td>50 psi</td>
</tr>
<tr>
<td>6.2</td>
<td>6.2</td>
</tr>
<tr>
<td>9.8</td>
<td>7.8</td>
</tr>
<tr>
<td>15.1</td>
<td>9.8</td>
</tr>
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</tr>
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<td></td>
<td>150.0</td>
</tr>
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</table>

4.2.2.1 New sideways force tyre test results

The recorded deformation of a new sideways force tyre inflated at 345 kPa (50 psi), on 9.8 mm and 150 mm spaced gaps and loaded to a maximum of 3.93 kN and then unloaded is plotted in Figure 67. At the 9.8 mm gap spacing, increasing the load did not cause any significant increase in the amount of deformation into the gap space. The amount of deformation during loading and unloading was the same.

At the 150 mm gap spacing, increasing load caused a significant increase in the amount of deformation. There was a small but significant increase in deformation as the tyre was unloaded at the 150 mm gap spacing. Although this gap size is significantly greater than aggregate spacing in TSCS or HRA (see section 4.4) it can be considered representative of defects within the pavement, as such it may be useful to investigate the impact of potholes on tyre deformation and damage.
Data for all gap spacings, from 9.8 mm to 150 mm, are plotted in Figure 68, for the new sideways force tyre inflated to 345 kPa (50 psi). This indicates a direct relationship for the data. There is minimal change in deformation with increase in load for the 9.8 mm and 20 mm gap, which approximates to the TEA MK1 results for the minimum gap spacing of 15 mm. This potentially indicates that up to a 20 mm gap the local structure of the tyre is governing the behaviour and beyond that the global structure of the tyre is influencing the behaviour.

Figure 67 Effect of loading and unloading for new sideways force tyre inflated to 345 kPa

Figure 68 Effect of load on tyre deformation into gap spacing for new sideways force tyre inflated to 345 kPa
Figure 69 shows the linear relationships between gap spacing and deformation into the gap at static loads of 1.86 and 2.16 kN. These values straddle the standard loading condition for the sideways force tyre of 2 kN, as specified in BS EN 7941-1 2006. The amount of deformation is slightly greater for the 2.16 kN load for gaps of in excess of 40 mm.

![Figure 69](image)

**Figure 69** Effect of gap spacing on tyre deformation at two loadings for new sideways force tyre at 345 kPa inflation pressure

### 4.2.2.2 Worn sideways force tyre test results

Figure 70 plots data for the worn sideways force tyre relating to gap spacing for 345 kPa inflation pressure. Figure 71 compares the data for 1.87 and 2.16 kN. This shows little difference between the two loading conditions especially at the smaller gap spacings.

![Figure 70](image)

**Figure 70** Effect of load on tyre deformation into gap spacing for worn sideways force tyre at 345 kPa inflation pressure
Figure 71 Effect of gap spacing on tyre deformation at two loadings for worn sideways force tyre at 345 kPa inflation pressure

4.2.2.3 Trailer tyre test results

Figure 72 plots data for the trailer tyre relating to gap spacing for 345 kPa inflation pressure. The amount of deformation is less than for the sideways force tyre. Figure 73 compares all the found data relating to load. This shows the amount of deformation to be relatively unaffected by the range of applied loading used.

Figure 72 Effect of load on tyre deformation into gap spacing for trailer tyre at 345 kPa inflation pressure
4.2.2.4 Tyre results comparison

Figure 74 compares the new and worn sideways force tyres with the treaded trailer tyre all the same inflation pressure of 345 kPa and load of 2.16 kN. This shows the two sideways force tyres to deform to greater amounts compared to the trailer tyre over the gap spacing 0 to 150 mm.
Figure 75 shows the deformation data to a maximum gap spacing of 60 mm to illustrate the difference between the sideways force friction measuring tyre and the treaded trailer tyre. At the smallest gap spacings the two types of tyre are similar. However, as gap spacing increases the sideways force tyre deforms to a greater amount into the gap space.

![Graph showing deformation data](image)

**Figure 75 Comparison of tyres for gap spacings up to 60 mm at similar vertical load of 2.16 kN**

### 4.3 Contact patch investigation

The static contact patch of the test tyres was investigated using XSensor pressure mapping. This allows measurement of contact patch properties such as contact area, contact length, contact width, variation of contact pressure within the patch, effects of inflation pressure and loading. Testing involves placing the XSensor pressure map underneath the loaded tyre. A loaded sideways force test tyre fitted to the TEA MK2 resting on the XSensor pressure pad is shown in Figure 76.

A sheet of Teflon paper was placed between the pressure pad and tyre to avoid damage to the pressure pad. Figure 76 shows real-time data from the pressure pad displayed on the computer screen.

The standard loading condition for the sideways force tyre of 2 kN specified in BS EN 7941-1 2006 was used.

Testing was carried out at three tyre inflation pressures i.e. 345 kPa (50psi), 241 kPa (35 psi) and 137 kPa (20 psi) to a maximum of 3.93 kN.
Figure 76 Test setup for contact patch investigation of a sideways force tyre

Figure 77 and Figure 78 compare the contact patches for the new and worn sideways force tyres at an inflation pressure of 345 kPa (50 psi). This shows the distribution of vertical stress within the contact patch to be different for the two tyres as a result of wear.

A central rib of higher vertical stress is apparent for the new tyre. With use, this central rib gets removed and vertical stressing becomes concentrated along the leading edge of the tyre reflecting its sideways interaction with the road surface.

Figure 77 Contact patch for new sideways force tyre at 345 kPa inflation pressure (pressure legend ranges from 70 to 700 kPa)
Figure 78 Contact patch for worn sideways force tyre at 345 kPa inflation pressure (pressure legend ranges from 70 to 700 kPa)

Figure 79, Figure 80 and Figure 81 plot the relationships between contact area, contact length and contact width with inflation pressure for the new and worn sideways force tyres. This shows comparable plots for the tyre in a new and worn condition over the three inflation pressures investigated. The plots show the worn tyre to have slightly greater contact area, less contact length and greater contact width.

Figure 79 Comparison of contact area for new and worn sideways force tyres
Figure 80 Comparison of contact length for new and worn sideways force tyres.

Figure 81 Comparison of contact width for new and worn sideways force tyres.
Figure 82 Test setup for contact patch investigation of ASTM friction tyre

Figure 82 shows the test setup for investigating the ASTM friction tyre contact patch. This shows the ASTM tyre fitted to the TEA MK1 resting on the XSensor pressure pad. Testing was carried out at tyre inflation pressures ranging from 14 kPa (2 psi) to 279 kPa (40.5 psi).

Figure 83 and Figure 84 compare contact patches for the new and worn ASTM friction tyres at an inflation pressure of 141 kPa (20.5 psi). Similar to the sideways force tyre, this shows the distribution of vertical contact stress to be quite different as a result of wear.
As the ASTM tyre wears, the distribution of vertical load becomes concentrated under both sidewalls of the tyre. This reflects the depth of rubber wearing away from the tyre due to contact with the road surface.

Figure 85 plots contact patch data for a new ASTM friction tyre using the 250 N loading condition at an inflation pressure of 141 kPa (20.5 psi). This shows good correlation between contact area, length and width with inflation pressure. The trends are comparable to those found for the sideways force tyre.
conditions the contact area for the sideways force tyre is approximately 5.8 times greater than for the ASTM friction tyre.

Figure 86 Comparison of contact area for the two measurement tyres

Figure 87 and Figure 88 compare the contact length and width respectively. At the standard loading conditions the contact length for the sideways force tyre is approximately 4.9 times greater than for the ASTM tyre. At the standard loading conditions the contact width for the sideways force tyre is approximately 1.8 times greater than for the ASTM tyre.

Figure 87 Comparison of contact length for the two measurement tyres
Figure 88 Comparison of contact width for the two measurement tyres

Figure 89 Composite contact patch showing contact area and pressure distribution for an ASTM tyre / 10 mm SMA (based on standard GripTester conditions of 20 psi and 25kg vertical load)

Figure 89 shows a composite of ASTM 1844 contact patches showing how this friction measuring tyre may contact with a 10 mm SMA asphalt surface. This illustrates the complexity of the tyre / road surface interface or envelope. It shows concentration of loading and the open spaces associated with the SMA texture. This is further explored in Section 5.
This complex three dimensional interface or envelope is further complicated should a treaded tyre be used. For this reason, the smooth treaded ASTM 1844 tyre was used as it removed a level of complexity from the laboratory investigations.

4.4 Determination of aggregate spacing for an asphalt mix

The investigations in this report illustrate the importance of understanding how a tyre rests on a surface to help understand enveloping. There are clear relationships between the factors considered suggesting that gap space or a distance between aggregate particles could be used to classify the macrotexture of a surfacing with respect to how it interacts with a tyre. If gap space could be measured using a non-contact method, this could be directly related to enveloping. A scale rule was used to physically measure the distance between aggregate particles.

Figure 90 shows a distance of 17 mm between two aggregate particles for a SMA10. Figure 91 shows a distance of 47 mm between two chippings for a HRA. This method of physical measurement using a rule is tedious to perform. However, it is possible to record variation in gap-spacing for a single asphalt mix type. Typically, the gap spacings were smaller for the SMA10 compared to the HRA which covered a greater range.

![Figure 90 Use of a scale rule to measure gap width for SMA10.](image)

Analysis of photographic images using image analysis software would be a more efficient method of investigating gap-spacing for an asphalt mix. Gap space could be determined from other data sources such as 3d point clouds. This is explored in Work Stage 3c (Section 5).
4.5 Main findings

The TEA MK1 and TEA MK2 apparatus have been developed to investigate the principle of enveloping as identified by the ROSANNE project under controlled laboratory conditions. Both apparatus have been used to simplify a complicated interface and demonstrate relationships that do not feature in literature relating to the measurement of skid resistance.

The role of asphalt macrotexture has been replaced by a space of known distance between two steel edges with a known profile. Note: Enveloping is a three dimensional interface based on x, y and z spatial data. Tyre embedment into the space between two parallel plates considers just the y and z directional co-ordinates.

The test method removes the influence of speed and dynamic loading by testing in a dry static test condition. Further research is recommended to investigate the influence of speed by reducing the contact time, to replicate transit of a passing vehicle. This would require automated data logging. Dynamic loading and tyre temperature variables could also be adjusted to investigate their influence on tyre deformation.

The laboratory investigations considered factors that can be controlled and thought to influence the envelope i.e. tyre/road interface factors including gap space, tyre wear, inflation pressure and applied vertical load.

Under static conditions and for all of the test conditions investigated, the main factor relating to tyre embedment or enveloping is gap space.

For the ASTM friction tyre, there is a distinct trend in the data i.e. the amount of embedment decreases in a predictable linear relationship until a critical gap space of approximately 15 mm is reached. The amount of embedment then remains fairly constant as gap space is further decreased.
At the smaller gap spaces it would appear that the larger diameter sideways force tyre behaves in a similar manner to a treaded tyre. However, with increasing gap space there is more embedment (enveloping) for the sideways force tyre compared to the treaded tyre used in the reported investigations.

Tyre wear did not significantly affect the amount of deformation into the gap space for the two friction measuring tyres. This is interesting considering the significant difference in vertical pressure distribution within the contact patch shown by pressure mapping for new and worn tyres. Similar variation in contact patch vertical pressure distribution is typical of treaded tyres with differing inflation pressures and degrees of tread wear.

The relationship between tyre vertical stress distribution within the contact patch and whether it has a significant effect on measured skid resistance needs further investigation.

The tyre interface is predictable for pneumatic tyres used. There are linear or log relationships with very strong correlations between variables such as load, inflation pressure, contact area, length and width and degree of wear. This offers scope to develop intelligent tyres to measure their road interface. For example, the wedge of water that builds up at the front of the contact patch could be measured by the tyre as a change in contact length.
5 2d and 3d pavement surface texture modelling

Different techniques were used to measure the texture and aggregate spacing of different asphalt samples. This was done in 2d and was then extended to 3d by creating a model using photographs. This gave an estimate of the characteristics of the different material types and could be related to water displacement.

![Model of asphalt surface](image)

Figure 92 Model of asphalt surface

Figure 92 shows extracted macrotexture data derived from photographic image of an asphalt surface. It illustrates a network of drainage channels including small areas of water entrapment highlighted in red as well as the general configuration of the texture. This demonstrates how a 3D model can provide more information than the 2d image from which it is derived.

5.1 Digital Surf MountainsMap surface analysis

Mountains Map is a surface imaging and metrology software published by the company Digital Surf. Its main application is to study surface texture and form in 3D at the microscopic scale, micro-topography. The software was used to analyse a sample of 14 mm TSCS shown in Figure 93. Figure 93 is one of 13 images captured using a Canon EOS6D digital SLR camera. Images were post processed using 3D Flow Zephyr photogrammetric software.

Dense point clouds were exported to Digital Surf Mountains Map surface analysis software for slices, furrows and motif analyses. A slices analysis was carried out to evaluate apparent contact areas and potential water entrapment. Furrows analysis was performed to demonstrate drainage path connectivity at and above a threshold level of 2.5 mm from the highest elevation on the point cloud. Motif analysis was carried out to delineate water micro catchment areas.
5.1.1 Application of slice and furrow analyses

Slices analysis is one of a number of studies available in Digital Surf surface analysis software. It is applied in this context in order to estimate areas of apparent contact between tyre and surface and define areas of potential water entrapment and displacement.

The study has two thresholds with the upper set at 1.81mm enveloping depth. This equates to a 20% apparent contact area as shown in Figure 94, and quantified the parameters table. This is based on the interaction of a smooth friction measuring type tyre.

The tread pattern of a tyre can be such that less than 20% is in contact with the plan contact patch between a tyre and asphalt surface. The potential impact of this is demonstrated using the slices study carried out in Digital Surf analysis software on a 3D model.

Given the array of tread configurations available on vehicle tyres it is likely that the apparent contact area could be marginally less and further reduced in vehicles travelling at high speed due to stiffening of the rubber compound. Moreover, work at Ulster as part of this project has indicated that the enveloping depth is significantly less than 1.81mm.

Figure 94 suggests that for this surfacing example for the depth shown that there is a continuous network of drainage paths highlighted in green that would facilitate the expulsion of water by the tyres of a moving vehicle. This is confirmed by a furrows analysis shown in Figure 95 which can be used to show the interconnectivity of the drainage paths.
Figure 95 Furrow analysis for enveloping depth of 1.81mm

Figure 96 shows a slices study for an enveloping depth of 2.5mm which equates to an apparent contact area of 54.2%. It has yet to be established that such a contact area is obtainable in practice for real, loaded tyres on a vehicle moving at high speed. However a network of continuous drainage paths still exists at this enveloping depth.

Figure 96 Drainage paths for enveloping depth of 2.5 mm

Figure 97 shows a slices study for an enveloping depth of 3mm. It indicates that the drainage network shown in green has become more confined. It is anticipated that water trapped below a depth of 2.5 to 3 mm for this surfacing type would contribute to excessive spray and hydraulic pumping effects. These could be considerable for tyres on loaded vehicles travelling at high speed. Residual standing water would also leave the surfacing vulnerable to structural damage from freeze/thaw effects. This suggests that there may be scope for reducing the texture depth in order to produce a more durable material.
Figure 97 Slices study for enveloping depth of 3 mm

Figure 98 plots depth into the surface against volume of voids for the proprietary TSCS (Figure 93). The depth interval is 0.5 mm into the surface from the highest elevation of the point cloud. The volume of voids equates to the potential volume of water that would be retained at a given depth if the surface was saturated which is considered to be a worst case scenario.

The plot has two regions, the first extending from 0 mm to approximately 2.5 mm and the second extending from approximately 2.5 mm to 7.5 mm. It shows that most of the void volume is contained within the top 2.5 mm. This is even though the maximum texture depth is approximately 8.27 mm for this example. Void volumes for depths below 7.5 mm are not plotted as the values returned are almost zero and therefore negligible.

Figure 98 Volume of voids for 0.5mm increments into the surface
The first region is plotted separately in Figure 99 which shows that the void volume increases linearly up to approximately 2.5mm with an $R^2$ correlation of 0.99. This further suggests that the texture depth of the material could be reduced as voids below this depth are likely to be deleterious to the surface.

5.2 Application of motif analysis

Motif analysis comprises the division of topography into regions consisting of hills or peaks and other regions consisting of dales or valleys in accordance with Maxwell’s proposals by means of segmentation as illustrated in Figure 100. The Maxwellian dale (watershed lines) has emerged as the primary tool of mathematical morphology of image segmentation as preparation for pattern recognition (BS EN ISO 25178-2:2012).

![Figure 100 Identification of motif features](image)

This method allows the automatic identification and characterization of features:

- Significant peaks ➔ applications in contact studies
- Significant holes ➔ applications in lubrication studies
- Texture cells ➔ quantification (volume, area, connectivity, ...)
- Cracks ➔ localization (length, depth, ...)

Figure 100 Identification of motif features (Mercier and Bloch 2005)
At the scales associated with highway surfacings in which the surface topography is subject to significant and rapid change motif analysis is a useful means of understanding water displacement. By definition, the boundaries between hills are course lines (watercourses), and the boundaries between dales are ridge lines (watershed lines) (BS EN ISO 25178 part 2, 2012).

Segmenting surface hills also offers additional insight into tyre-surface interactions with the peaks that are in direct contact with the tyre. Valley/dale segmentation identifies surfaces having the greatest capacity for the retention of water. An example of a segmentation analysis for the surface shown in Figure 93 is shown in Figure 101 with the catchments or valleys delineated in a series of motifs.

![Segmentation analysis](image)

<table>
<thead>
<tr>
<th>Parameters</th>
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</thead>
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<tr>
<td>Area</td>
<td>Mean</td>
<td>44.1</td>
<td>mm²</td>
</tr>
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</table>

**Figure 101 Segmentation analysis**

The deepest depressions are highlighted in the contour analysis shown in Figure 102. These represent potential wells of residual water which could be ejected under the hydraulic pressure of tyres on the pavement surface.

Figure 101 shows the potential for water entrapment at all levels within the thin surfacing. The analysis comprises a total of 59 motifs ranging in depth from approximately 0.37 mm to approximately 3.3 mm. The areas of the motifs range from approximately 2.4 mm² to approximately 180 mm².
Figure 102 Contour analysis of model of thin surface

Figure 103 shows frequency and cumulative % plots of height data for the motifs for Bin class intervals of 0.25 mm. If a potential tyre enveloping depth of 2.5 mm suggested by Figure 100 is adopted Figure 104 shows that over 98% of the motif heights lies within this value. Approximately 73% of motif elevations lie within 1mm and over 30% lie within 0.5 mm.

The maximum apparent contact area is approximately 180 mm$^2$. This is considerably smaller than the area of a 40 mm tread block of 1600 mm$^2$. There is therefore no region of the surface that would not be potentially sealed and subject to hydraulic pressures from loaded tyres. The resulting pressure may be offset to some extent by the presence of contaminants turning the effect into more of a flushing action but this has not been evaluated.

By way of comparison a similar motif analysis was carried out on models of Marshall Asphalt (MA). These were based on images of cores captured using the same camera technology as
for the TSCS and subject to the same post processing in 3D Flow Zephyr. One of the images is shown in Figure 104.

The model of the Marshall Asphalt core generated 3074 motifs as compared to 59 for the TSCS. Motif heights ranged from approximately 0.09mm to approximately 0.843mm. Motif areas ranged from approximately 0.434mm$^2$ to approximately 72.353mm$^2$. It is clear that the ranges are considerably smaller for this surface as compared to the TSCS. Figure 105 shows frequency and cumulative % plots of height data for the motifs for Bin class intervals of 0.25mm.

**Figure 104 Image of Marshall Asphalt Core**

**Figure 105 Frequency and cumulative % plot for model of Marshall Asphalt core**
Figure 105 indicates that all motif heights are 1mm or less as compared with up to approximately 3.3 mm for the TSCS material and over 82% at or around 0.25 mm. This is consistent with the characteristics of the two surfacing materials. The Marshall Asphalt (MA) shows less texture than the TSCS material and it would therefore be expected that the watersheds would be much smaller and shallower resulting in a greater number of motifs across the surface.

Figure 106 shows a comparative plot of the valley depth of each of the motifs for the TSCS and MA models.

![Figure 106 Depth of Valley against Cumulative % for TSCS and Marshall Asphalt models](image)

The entrapment and/or retention of water in the surface are likely to accelerate the breakdown of the material through hydraulic and freeze/thaw effects and are therefore a durability issue. Smaller and shallower motifs as in the MA, for example, in which the deepest motif is approximately 0.84 mm, are less likely to retain freestanding water and to dry out more quickly than in a saturated TSCS. The greater number of motifs is also indicative of a higher number of contact points and therefore potentially increased tyre/road interaction.

It is suggested therefore that Figure 106 is a potential indicator of durability for a given enveloping depth. For the MA the motif heights and therefore the enveloping depth are a fraction of those of the TSCS and is probably the more durable material. This study suggests therefore that the most durable materials are likely to have overall low textured surfaces.

### 5.3 Conclusions

It has been shown that 3D models can provide additional information in respect of water displacement. This includes the quantification of water for a given depth into a particular asphalt surface; analysis of the models show how this changes with depth. It offers information on channel connectivity which facilitates drainage and displacement if water under a tyre. It offers a new indicator of surface vulnerability to water related damage. This provides scope for consideration of the methods contribution to enveloping and durability studies.
References


http://www.engineeringmaterials.org/tribology (Da Vinci)


Van der Steen. (2007). Tyre/Road Friction Modelling, Literature Survey, DCT.


APPENDIX A – Laws of friction

Various friction theories have been developed on the different components of rubber friction (Gabriel et al. 2010). These include but are not limited to Moore (1972) and more recently Persson (1999). There are several bodies of literature exploring and affirming the laws of friction such as Persson et al. (2000), Bowden and Tabor (2001), van der Steen (2007) and Gabriel et al. (2010).

Persson has been involved in an extensive amount of research on this topic and continues on from the findings of Grosch that take into account that the sliding friction of rubber has the same temperature dependence as that of the complex elastic modulus (Van der Steen, 2007). Persson states that the friction force, under normal conditions, is related to the internal friction of the rubber therefore a hysteretic friction property. As previously discussed, the mechanism of hysteresis causes energy dissipation thus heat is generated. In a recent article Persson, (2006a) takes into account the local heating of rubber as the viscoelastic properties of rubber are strongly temperature dependant and found that as the temperature increases, the rubber friction decreases and the sliding velocity increases.

Tribology Current friction models

Tribology

Tribology is the science and technology of interacting surfaces in relative motion (Persson, 1999). The word is derived from the original Greek word tribos meaning to rub and has the idea of a worn way or path (Thayer, 1886) therefore inadvertently relating to the friction that is created between two surfaces rubbing together, creating an interface. As Persson (1999) points out: tribology has been of central importance for thousands of years, even though this has not always been generally recognized (Dowson, 1979).

Sliding friction is one of the oldest problems in physics and has certainly huge practical significance. It has been estimated that the monetary losses in the USA resulting from ignorance of tribology amount to 6% of the gross national product, an incredible $420 billion in (Persson, 1999).

Of particular importance is the area of contact within the tyre/surface contact patch which can be real or apparent. Persson (1999) notes that most real surfaces exhibit roughness on many different length scales. Thus when a block is put on a substrate the actual contact area will not be the whole bottom surface of the block but the real contact area which is usually much smaller than the apparent contact area.

Advances in tribology

In more contemporary research by Ivanov et al., (2008, 2010) there have been considerable advances in tribology through looking into non-contact analysis such as the use of computer image processing which is able to further explore the interaction of contact at the tyre/surface interface. McQuaid, (2015) extending work by Millar (2013) developed non-contact recovery of surfaces using Close Range Photogrammetry (CRP) to produce a 2.5D surface within the range of the microtexture. This facilitated successful assessment of the microtexture of asphalt surfacings to produce a better understanding of the tyre/surface interface.

Fundamental Laws of Friction

Introduction

Much of what is known and applied in the context of highway engineering has been gathered from the results of laboratory investigation. Experimental outputs led to the formulation of the Amonton’s - Coulomb’s model of surface friction. This section presents a brief overview of the
There are two broad kinds of friction which are applicable within the tyre/highway surface interface:

- Static which relates to the inertia required to overcome an object’s resistance to movement
- Kinetic which may be sub-classified into
  - Sliding: when inertia is overcome and one surface is sliding over the other and in a locked wheel sliding over another surface
  - Rolling: force opposing one body rolling over another as in a freely rotating wheel on another surface

**Amonton’s-Coulomb Friction Model**

The current accepted understanding of friction does not derive originally from Amonton or Coulomb but from Da Vinci’s experimental work in the sixteenth century (Bowden and Taylor (1950), Rabinowicz (1995), Persson (2000). Da Vinci proposed that the apparent area of contact had no effect on friction and that doubling the applied load resulted in a doubling of friction. Da Vinci’s findings would later be re-stated and ratified by Amonton in 1699 and would subsequently become known as Amonton’s law which states that:

- The coefficient of friction is given by the normal force/friction force experienced in sliding and object on the surface
- The friction force is independent of the apparent contact area

The third law of friction was proposed by Coulomb in 1781 which states that friction is independent of the relative sliding velocity between two objects.

According to Van der Steen, (2007), this is the widely used model in relation to friction and is based upon two bodies interacting with each other under dry conditions at relatively low speeds. This is not analogous therefore to tyre/surface interaction at high speed and under wet conditions. According to Van der Steen (2007) is that the often used Coulomb friction model with a constant coefficient of friction is in general not realistic in the case of rubber friction.

Amontons-Coulomb Friction Model shows that when one body (1) in contact with another (2) with an applied normal force is pulled horizontally there is a threshold friction value which body (1) needs to be overcome. This means that if the tangential force is larger than that of the threshold value, body (1) will start to move. Amonton’s-Coulomb friction characteristics are illustrated in Figure A-1.
This shows that the tangential force is proportional to that of the normal value and is given by:

\[ F_c = \mu F_n \]

Where:
- \( F_c \) is the Coulomb friction force of constant magnitude and acting in the direction opposite to motion
- \( \mu \) is the coefficient of friction
- \( F_n \) is the force pressing the surfaces together

The Amonton-Coulomb friction model is based on the interaction of bodies under dry or only partially lubricated conditions and at relatively low speeds which is not analogous to tyre/surface interaction at high speed. The friction which is created at the tyre/surface interface can also be related to the properties of the materials that are used, specifically in the tyres. Due to the dry conditions in which this model is considered, the coefficient of friction on the highway pavements tends to be generally high as measured using one of the standard techniques. However, as the lubricated surface either by water or other contaminants represents the worst case scenario in highway applications the Amonton-Coulomb model breaks down.

**Stribeck Effect**

The Stribeck model is a more advanced development and models friction as a function of velocity but includes the Coulomb and viscous friction aspects. The model is considered valid in steady state conditions only. A system is said to be in a steady state if the variables which define the behaviour of the system or the process are unchanging in time. Given the complexity of the highway surface and the range of variables to which it is subject it is unclear to what extent the Stribeck model applies in the context of highway surfacings. The Stribeck model is illustrated in Figure A-2.

![Stribeck friction characteristic](MOGI, 2015)

**Viscous Friction**

Figure A-3 demonstrates the effect of viscous friction combined with the coulomb friction element which models the friction force as a force proportional to the sliding velocity and is given by:

\[ (t) \neq 0: (t) = -F \nu \nu(t) \]
Static friction

Figure A-4 shows the graphical representation of the static friction model. This is a combination of the viscous friction, coulomb friction and the static friction. This is given by:

\[
(t) = 0
\]

\[
F_f(t) = u(t)(F_c + F_s) \text{sgn} u(t) |u(t)| \leq (F_c + F_s)
\]
Rolling friction

The rolling friction of a tyre can be given by:

\[ Fr = MR, \]

where:

\[ Fr = \text{Rolling friction}, \]
\[ M = \text{Torque}, \]
\[ R = \text{Radius of the tyre}, \]

According to Van der Steen., (2007) for an elastic wheel, the reaction force acts through the centre of the wheel therefore \( M = 0 \). However, for a viscoelastic material, like that of a tyre, the reaction force moves closer to the loading as the stresses are lower during unloading of the tyre.

For a viscoelastic tyre, \( M = Wz \) where \( W \) is the normal load and \( z \) is the distance from the centre of the wheel.

\( W \) is the normal load
\( z \) is the distance from the centre of the wheel. This is illustrated in Figure A-5.

Figure A-5 Rolling friction (Van der Steen, 2007)
APPENDIX B – Longitudinal and transverse friction devices

When a driver applies the brake for a vehicle travelling in a straight line a torque is applied to the vehicle wheels via the braking system. A reacting force develops in the tyre/road contact area.

Provided that grip is maintained, the angular or rotational speed of the wheels decreases and the vehicle slows down as kinetic energy is absorbed in the braking system.

However, as the braking torque increases, the wheel speed may reduce below the vehicle speed and consequently the tyre slips on the road.

This generates friction forces in the contact area due to adhesion and deformation processes slowing down the vehicle. With extreme braking the wheel may cease to rotate and become locked causing the tyre to slide or skid over the road surface.

Typically, longitudinal friction measuring devices attempt to simulate this by controlling the rate at which the wheel rotates relative to the road speed. This leads to the idea of slip ratio.

The tyre slip ratio $G$ is defined by $G = \left(\frac{V - \omega R}{V}\right)$ where $\omega$ is angular velocity of the wheel; $R$ is the wheel radius and $V$ is the vehicle speed.

$G$ varies between 0 and 1 and is generally expressed as a percentage. For example, at $G = 0\%$ the tyre speed is equal to the vehicle speed and the wheel is freely rotating. For $G = 100\%$ the wheel is in a locked condition.

![Longitudinal Friction Coefficient (LFC) curve](image)

Figure B-1 The longitudinal friction coefficient – G curve (Do and Roe, 2008)

The Longitudinal Friction Coefficient (LFC) varies with the tyre slip ratio as illustrated in Figure B-1. Friction increases as the slip ratio increases up to a maximum value before decreasing as the slip ratio continues to increase up to a locked wheel condition.
This variation can be explained by the movement of the tyre treads in the tyre/road contact area changing from a largely shear phase to a mainly slipping phase.

The maximum value of LFC denoted by $G_{\text{max}}$, is known as peak friction and typically occurs at a slip ratio between 15% and 20%. Some longitudinal friction measuring devices operate with a fixed slip ratio whereas others have a variable slip ratio.

The fixed slip ratio method is more suitable for general monitoring as the wheel continues to rotate during the test and so can be used continuously. Some locked wheel devices can measure the frictional forces during the whole braking cycle giving the friction slip curve whilst reporting the locked wheel value.

**The transverse friction device**

As a vehicle negotiates a bend, the driver uses the steering system to turn the vehicle’s front-wheels so that there is a difference between the vehicle direction and the wheel rotation-plane. The induced angular difference is known as the slip angle.

It induces tyre/road friction, which in turn generates a centripetal force opposing the centrifugal force exerted on the vehicle in the bend, allowing the vehicle to follow the curve of the road.

If the centrifugal force exceeds the friction force available, the tyre will slip sideways, even though it continues to rotate. Transverse-friction is also known as side-force, skid resistance measuring devices try to simulate this process.

This leads to the concept of the slip angle and it is important to appreciate how the transverse, or sideways friction coefficient varies with the slip angle. The slip angle is the angle formed by the wheel’s plane of rotation and the tangent to the wheel’s path.

On a skid resistance test device the wheel’s path normally follows the direction of travel of the test vehicle. This is known as Sideway Force Coefficient (also abbreviated to SFC).

---

Figure B-2 The SFC – $\delta$ curve (Do and Roe, 2008)
The SFC varies with the tyre slip-angle as illustrated in Figure B-2. Initially, friction increases as slip angle increases then reaches a maximum after which it starts to decrease as the slip angle continues to increase.

This process is comparable to longitudinal braking as the tyre tread in the tyre/road contact area moves from a shear phase to a slipping phase.

Typically, the maximum value of SFC occurs at a slip angle, denoted by $\delta_{\text{max}}$, of between 4° and 7° for a light vehicle and between 6° and 10° for a truck. Skid resistance measurement devices operating on the angled wheel principle normally operate at a fixed slip angle which is typically greater than $\delta_{\text{max}}$.

The force developed along the axle of the test wheel is measured and used to compute a friction value to represent skid resistance.

The current context SFC refers explicitly to the special case of the value measured with a skid-resistance device operating on angled-wheel principle under controlled conditions. The side-force method for measuring skid resistance allows continuous measurement and such devices are often used for routine monitoring purposes.

Some devices can vary the slip angle through the test but, as with variable-slip longitudinal systems, these are normally confined to research work.

**Appropriateness for a high speed network**

Use of a friction measuring tyre either in LFC or SFC measurement mode has been the method of choice since researchers such as Bradley and Allen first developed their ‘high speed’ SFC motor-cycle sidecar device, that was used to measure up to speeds approaching 30 mph.

This was the fastest speed that their motor-cycle could achieve given the sideways forces being generated by the measuring wheel interfacing with the road under investigation.

This interaction of the friction measuring tyre and the road surface is probably one of the key criteria influencing the choice of the most appropriate form of high speed friction measurement. At higher test speeds the tyre is subjected to greater stresses, especially for surfaces with greater macro-texture and to a lesser extent greater microtexture.

This effectively eliminates a SFC type of measurement as the tyre is constantly under stress and susceptible to high speed blow outs.

This is probably the reason why most of the devices identified in the TYROSAFE (Tyre and Road Surface Optimisation for Skid Resistance and Further Effects) Project (Do and Roe, 2008) were LFC devices.

All the devices that allowed friction measurement greater than 100 km/h were LFC devices. The ability of the friction tyre to run in the same direction of travel reducing stress on the tyre allowing it to last longer and to be run at higher test speeds.

Different LFC devices allow test measurements ranging from constant fixed slip to simulated locked wheel braking events. However, the nature of the interaction between friction tyre and the surface will be different.

This type of LFC testing causes wear of the friction measurement tyres and so offers limited life, with an inverse relationship between slip ratio and tyre longevity.

Devices can run discrete tests such as simulation of braking for short periods in order to prolong the life of the measurement tyre. However, this reduces coverage of the network and may miss localised locations with low skid resistance and high skidding risk.
Prolonged testing under more extreme conditions caused by higher speeds may cause changes in the properties of the tyre rubber during testing which may influence the measured data.

There are logistical problems in carrying a sufficient volume of water needed to create the necessary water films at the friction tyre/road surface interface. At network level this typically requires fitting the friction device to a water tanker or, driving a water tanker in front of the measuring device.

The speed and practical limitations of a system requiring a water tanker are obvious when measuring high speed friction at network level.

There is also the important factor that most friction measuring devices use a smooth rubber friction measuring tyre to interface with the road surface being measured. It is argued that this removes issues related to the wear of treaded tyres that will influence tyre/road interface.

However, it can also be argued that at high speeds, it is this interaction between the treaded tyre fitted to a vehicle and how this interfaces with road surface texture at different scales that is the property that should be measured.

Direct measurement using a smooth friction tyre is not a suitable means of measuring high speed friction at network level. This implies that a different method, involving either direct measurement or indirect measurement derived from some other related property potentially offers more scope.

The move from this traditional approach of measurement, which has not fundamentally changed for the last eighty five years, opens up many possibilities. These might include prediction of friction using non-contact measurement of road surface properties, extraction and evaluation of data from the vehicle or its tyres to using large datasets from orbiting satellite that measure all parts of the earth’s surface every few days.

These types of measurement are not restricted to the physical and practical limitations of smooth tread-less friction tyres and their unrealistic interaction with small areas of the inside wheel path, of the inside lane generating a single friction value once or twice a year.

Rather they allow the opportunity to gather data about the actual tyre/road interface that can be accessed by those involved in network administration/maintenance as well as the road user in real time for the entire network.

Factors contributing to a potential reduction in skid resistance can be linked to the car and its driver from weather forecasts warning the driver or car. This would also give better understanding of the impact of seasonal, daily and other short term changes.

Whilst all of this may seem ambitious or utopian this is potentially very much a reality and worthy of consideration in this project. In a project investigating Innovation of High Speed Friction Measurement, innovation implies transformative thinking rather than remodelling existing systems as has been for the past eighty five years.

Highway engineering and those involved with measuring and maintaining a safe network have to move away from concern with the measurement of surface parameters and embrace the perspectives and advancements achieved by the vehicle and tyre manufacturers in holistically delivering the user safety and vehicle performance enhancements.
APPENDIX C – Sideway force Coefficient Routine Investigation Machine

The development of the UK sideways force device dates from the work of Bradley and Allen (1930) who were requested by the then Ministry of Transport (Roads Department) to investigate the skidding of vehicles on road surfaces.

They were interested in devising a method of measuring slipperiness. They identified two distinct forms of slipping on road surfaces:

1. The first occurs when the brakes of a moving vehicle are applied with sufficient force to lock the wheels in which case the wheels begin to slip along the surface without revolving.
2. The second occurs on curves or on steeply cambered surfaces when the wheels continue to revolve but slip at right-angles to the direction of rolling.

Bradley and Allen considered this second form of slipping or sideway resistance offered by a rolling wheel to be the most promising field for investigation. They designed and constructed what they called a 'high speed' apparatus using a motor-cycle and sidecar outfit.

Figure C-1 compares the similarities between the motor-cycle sidecar outfit and the modern SCRM.

Figure C-2 shows the tyres used during their investigations and the corresponding contact patch for each of the different tyres evaluated. It is interesting to note that the tyre contact patch was of interest eighty five years ago.

Figure C-1 Comparison of the Bradley and Allen motor cycle and sidecar (Bradley and Allen, 1930) and SCRM (HD28/04 and HD28/15)
Innovation in High Speed Friction Measurement

FIG. 11.—Contact Areas of Tyres (710 × 85 mm.).

Load, 290 lbs. Pressure, 30 lbs. per sq. in.

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Figure C-2 The tyres and their contact patches used on sidecar wheels (Bradley and Allen, 1930)

The sidecar wheel was arranged to swing outwards from a pivot on the chassis. High speed in all the experiments detailed never exceeded 30 mph as their motor-cycle was not powerful enough.

Numerous experiments are detailed by Bradley and Allen (1930) that remain relevant today. For example, the 1930 research recommended an angle of 17 degrees which is close to the 20 degree angle of the current sideways force device.

Since this work different devices were developed in the UK. The measuring tyre moved from the side-car and became a fifth wheel mounted inside a vehicle fitted with a small water tank. These devices were used as research tools and were considered not suitable for testing at network level.

By the late 1960s the requirement for skid resistance testing at network level resulted in development of the Sideways force device now used in the UK.

This device was introduced in the 1970s to provide a method for routine measurement of the skid resistance of the road network. HD28/04 stated that measurements for monitoring the in-service skid resistance of UK Trunk Roads shall be made with a Sideway-force Coefficient Routine Investigation Machine (SCRIM).
APPENDIX D – Complete review of alternative methods that may be used to either directly or indirectly measure high speed friction

With regard to this project dealing with Innovation in High Speed Friction Measurement, this implies the need to appreciate, understand and possibly answer some fairly basic questions such as:

- Do smooth friction measuring tyres and treaded vehicle tyres interact with road surfaces in the same way?
- What is measured by a friction tyre and is it relevant to high speed friction?
- How do tyres fitted to a vehicle interact with different types of road surface asphalt made with different aggregates?
- How can the effects of detritus (water, grease, ice, dirt) between the tyre and road surface interface be mitigated or their influence be quantified?
- What happens to tyre/road surface interaction with increasing speed?
- What happens at the interface should the driver of the vehicle need to get stopped quickly?

There are a wide range of possibilities that either directly or indirectly address these questions or be used in developing a method to measure high speed friction. These range from laboratory testing to developing a friction device that uses either direct or indirect methods. This section of the review considers alternative possibilities for measuring high speed friction.

1 Laboratory testing methods

The main laboratory methods for predicting skid resistance are the PSV test for 10mm sized aggregate and asphalt mix tests such as Friction after Polishing or the Road Test Machine.

The PSV test would require development to include a high speed version of pendulum testing to replace the existing slow method.

A speed profile is measured during the friction measurement part of the FAP test. This profile could be re-evaluated to look at the higher speed measurements recorded during test.

The RTM is a slow speed method using the slow speed with the slow pendulum test used to measure changes in friction. The advantage of this method is however is the fact that it uses a slab 305 x 305 mm in size that could form the basis of some new form of high speed tyre/surface interface measurement.

2 A tyre based friction tester

The route of developing yet another friction tester with a friction measuring tyre is one that would probably result with the same problems associated with many of the existing devices. This would necessitate a low slip condition to take measurements rather than the traditional peak or almost peak friction value.

The proportional relationship between the slip ratio and the frictional behaviour of a tyre under low slip conditions illustrate that a system may be used at high speed with low slip ratio (<5%) in order to deliver the measurements required without rapidly damaging the tyre carcass.

This may not be feasible with the added complications arising from the heat generation of such testing. However, this aspect of heat generation may prove a viable indirect indicator of road surface friction.
3 A mobile test platform

It may be possible to develop a relatively economic trailer based device that gathers indirect or non-contact measurements of variables that can be shown to relate to friction. For example, a simple solution could show how tyre surface temperature changes with road surface texture. Changes in brake temperature might be similarly utilised.

4 Re-evaluation of 2D and 3D road surface parameters

2D and 3D profile data has been used to investigate road surface textures at different scales of texture. The main problem with this type of data is working with large datasets and extracting meaningful parameters from the measured 2D or 3D profile.

Work by Dunford (2014), Millar (2014) and McQuaid (2015) has started to highlight that not all of the measured data is relevant.

Analysis to show parameters such as contact area, surface volume and tyre draping would be feasible and allow indirect non-contact predictions of high speed friction.

Development of such systems would need laboratory verification using a rolling road to prototype a suitable device and if proven reliable retrofitted to a suitable vehicle for high speed testing.

5 Reconsidering the laws of friction

This idea revisits the laws of friction to help devise or develop an innovative measure of high speed friction. There are three basic laws of friction that have been recognised for quite some time (Amontons, 1699 and Coulomb, 1785):

- The friction force is directly proportional to the applied load (Amonton’s First Law)
- The friction force is independent of the apparent area of contact (Amonton’s Second Law)
- Kinetic friction is independent of the sliding velocity (Coulomb’s Law)

To say they have formed the basis of many studies relating to road surface friction would be an understatement. However, many studies and attempts to model tyre/road surface interface conditions do not consider the high speeds of this project.

Many friction studies have been carried out at slow speed and have not considered the complexities of real life i.e. a treaded tyre braking from high speed interacting with a road surface of different levels of texture. Neither do they consider the influence of different fluids such as bitumen during the early life of an asphalt surfacings; or water in the form of fog, light rain or prolonged heavy rain.

Many of the studies and models assume either a smooth surface and/or a smooth tyre i.e. conditions which do not simulate reality. These conditions need to be assessed.

Amonton’s Second Law states that the force of friction is independent of the apparent area of contact. Perrson (2004) proposed that the contact area traditionally accepted is greatly exaggerated over the tyre contact.

This has been shown in recent developments of 3D modelling of road surface textures at scales from macro to micro (McQuaid, 2015). Using methods such as the Abbot Firestone Curve, it is now possible to better understand and quantify the true area of contact as a tyre drapes over the macrotexture of a road surface and at the microtexture level of individual aggregate particles.
This new type of data, in conjunction with measurement methods carried out at high speed may offer better indication, prediction and/or understanding of friction and its measurement at high speeds.

6 Decelerometer braking devices

These types of devices are used by the police in crash investigations. Examples include the Skidman and the Vericom devices both of which involve the use of de / accelerometers. The Skidman device is positioned in the front passenger foot-well of the police car whilst the Vericom is typically mounted at windscreen level. Both devices measure the average deceleration of the vehicle through a skid from a defined speed to a stop.

The target speed is typically 50 km/h with the car’s Anti-Lock Braking System (ABS) disabled. Although these types of decelerometer braking type test are unrealistic at network level, it may present a concept of high speed acceleration / deceleration measurement that could be developed into a high speed measurement of tyre/road interaction.

It would also necessitate the co-operation of a test track to assess road surfaces at high speed under controlled safe conditions.

7 Braking type GPS test devices

Accurate brake testing is possible using high speed GPS-based systems such as the Racelogic VBox3i. With a sample rate of 100Hz the VBox3i can give an accurate measurement of braking time, distance travelled and longitudinal deceleration.

Although this type of testing is not suitable for network testing it has application in better understanding what happens when a vehicle brakes at different speeds over different surfaces in different conditions comparable with having to get stopped on a high speed road.

Different types of test are possible. For example brake stop testing with an ABS equipped vehicle can compare different types of asphalt surface. Using ABS means the stopping distances are repeatable, making the tyres performance results directly comparable for different surfaces.

The test is usually performed between two set speeds during the linear stage of the brake test in order to remove the response time of the braking system. For example, if the brakes are applied at 110 kph, the brake test could start at 100kph and finish at 15kph; this eliminates the first and final part of the brake stop which is less repeatable.

The speed at which either a tyre or road surface will begin to aquaplane is an important characteristic particularly at high speed where the ability to deal with water is important. There are two main tests which are used to determine this speed. The first is in a straight line, and the second is around a corner.

In the straight line aquaplane test the vehicle accelerates from a standstill with one side of the car running with the wheels in a shallow channel filled with water. When the aquaplane threshold speed is reached, the driven wheel in the water channel will start to slip, and by comparing the speed of this wheel with the overall vehicle speed obtained by GPS, this speed can be captured.

The challenge in this test is to calibrate the wheel speed inputs and relate these to the GPS vehicle speed. RACELOGIC supply dedicated aquaplane software which carries out the calibration and collection of the test results.

In the cornering aquaplane test the vehicle drives into a flooded section of track whilst turning on a prescribed radius. This test is carried out at different speeds, until the aquaplane threshold is reached, at which point the vehicle will start to slide upon entering the bath.
The GPS based VBOX can measure the vehicle speed and lateral acceleration allowing the aquaplane threshold to be measured very accurately. RACELOGIC’s aquaplane windows software is designed to work with a VBOX for easy and accurate aquaplane testing.

Although these methods are typically used on test tracks to assess tyre performance, these methods could be modified to assess differences in road surfaces.

8 Indirect measurements provided by the vehicle

Numerous systems designed to improve driving safety have been developed by the motor vehicle industry. Some selection and combination of these systems are used by almost every car manufacturer world-wide. Given the scope and capability of vehicle systems now available, road surface skid resistance may now be of less importance and possibly even a thing of the past.

This is particularly relevant if the English SRN is compared to most other European and developed countries around the world. Many counties have not had the historical benefit of high PSV aggregates either available within their country or as a specification requirement.

Yet they do not demonstrate abnormally high accident rates even though the values of road surface skid resistance are low. Limestone road surfaces in Florida and Greece for example may deliver values so low that they are difficult to measure yet the modern car makes them relatively safe to drive on.

The following are some of the systems developed:

**Anti-lock braking (ABS)** allows the wheels on a motor vehicle to maintain tractive contact with the road surface according to driver inputs while braking, preventing the wheels from locking up (ceasing rotation) and avoiding uncontrolled skidding. It is an automated system that uses the principles of threshold braking and cadence braking. It does this at a much faster rate and with better control than a driver could manage. ABS generally offers improved vehicle control and decreases stopping distances on dry and slippery surfaces. However, on loose gravel or snow-covered surfaces, ABS can significantly increase braking distance, although still improving vehicle control. Recent versions not only prevent wheel lock under braking, but also electronically control the front-to-rear brake bias. This function, depending on its specific capabilities and implementation, is known as electronic brakeforce distribution (EBD), traction control system, emergency brake assist, or electronic stability control (ESC).

**Electronic stability control (ESC),** also referred to as electronic stability program (ESP) or dynamic stability control (DSC), is a computerized technology that improves a vehicle's stability by detecting and reducing loss of traction (skidding). When ESC detects loss of steering control, it automatically applies the brakes to help "steer" the vehicle where the driver intends to go. Braking is automatically applied to wheels individually, such as the outer front wheel to counter oversteer or the inner rear wheel to counter understeer. Some ESC systems reduce engine power until control is regained. ESC does not improve a vehicle's cornering performance; instead, it helps to minimize the loss of control.
Electronic brakeforce distribution (EBD or EBFD) or electronic brakeforce limitation (EBL) is an automobile brake technology that automatically varies the amount of force applied to each of a vehicle’s brakes, based on road conditions, speed, loading, etc. Always coupled with anti-lock braking systems, EBD can apply more or less braking pressure to each wheel in order to maximize stopping power whilst maintaining vehicular control. Typically, the front end carries the most weight and EBD distributes less braking pressure to the rear brakes so the rear brakes do not lock up and cause a skid. In some systems, EBD distributes more braking pressure at the rear brakes during initial brake application before the effects of weight transfer become apparent.

Traction control systems (TCS) are typically (but not necessarily) a secondary function of the electronic stability control (ESP) on production motor vehicles, designed to prevent loss of traction of driven road wheels. TCS is activated when throttle input and engine torque are mismatched to road surface conditions. Intervention consists of one or more of the following: Brake force applied to one or more wheels, Reduction or suppression of spark sequence to one or more cylinders, Reduction of fuel supply to one or more cylinders, Closing the throttle, if the vehicle is fitted with drive by wire throttle, In turbocharged vehicles, a boost control solenoid is actuated to reduce boost and therefore engine power. Typically, traction control systems share the electrohydraulic brake actuator (which does not use the conventional master cylinder and servo) and wheel speed sensors with ABS.

Vehicle Dynamics Integrated Management (VDIM) is an integrated vehicle handling and software control system developed by Toyota. It involves an omnibus computer linkage of traction control, electronic stability control, electronic steering, and other systems, with the intent of improving responsiveness to driver input, performance, and overall safety. VDIM integrates the company's Electronically Controlled Brake (ECB), Anti-Lock Brakes (ABS), Electronic Brakeforce Distribution (EBD), Traction Control (TRC) and Vehicle Stability Control (VSC) active safety systems with the Adaptive Variable Suspension (AVS), Electric Power Steering (EPS) and Variable Gear Ratio Steering (VGRS) systems. This way all the systems function together rather than the ECU prioritizing which is the most important. VDIM takes measures to prevent skids, slides, or wheel spins rather than just take action after tire slippage has occurred. This is done by constantly making corrections in a subtle manner that are transparent to the driver.

These are just some of the systems available. It is quite possible that should contact be established with the vehicle manufacturing industry that a viable method of high-speed friction measurement either exists, be modified or be developed.

9 Provided by the tyre industry

Similar to the vehicle industry, extensive research has been done by the tyre industry to improve tyre performance. Wet braking performance is now reported for each car tyre. According to the tyre labelling legislation wet grip can be tested in one of two ways.

The first is the wet braking vehicle test, which measures wet braking performance on a wet road surface, braking from 50mph to 12mph. The second test is a skid trailer test, which measures friction between the road and a tyre, conducted at 40mph. The end result of both tests provides a Wet Grip Index (WGI), which describes the improvement in percentage in relation to a reference tyre.

There is now much interest in the intelligent tyre with conferences such as the 11th Annual Conference Intelligent Tires Technology 2015, 17 - 19 November, 2015, Dresden, Germany. However, review of the content shows little involvement with the roads industry.

Research has shown how water influences the contact patch at speed. The classic theory is that a wedge of water develops in front of the contact patch that reduces particularly along the y-axis of the foot-print.
This reduction in footprint is related to the factors involved in the need to get stopped from high speed in wet conditions. Recent work by Hartikainen (2014) explores the use of an optical sensor fitted inside the tyre that was developed during the EU funded APPOLLO (2005) and FRICTI@N (2009) projects.

Figure D-1 shows how the inner ring of the tyre deforms during aquaplane testing at 110 kmh compared for a dry surface. This has obvious application as it quantifies how a particular tyre is interacting with a particular road surface and how water is being managed at high speeds.

![Figure D-1 Tyre inner ring deformation during aquaplane testing at 110 kph (Hartikainen, 2014).](image)

10 3D road surface texture big data

3D road surface texture (macro / micro) scales can be measured in static conditions using different types of laser and photogrammetry based system (Dunford 2014, Millar 2014 and McQuaid 2015). If this type of information could be captured and processed at high speeds then this would offer insight into road surface contact phenomena. However, it will require development to efficiently analyse the amounts of big data captured during measurement.

11 Satellite derived big data

Probably the most interesting method with greatest potential to monitor a network is to make use of satellite derived big data. Europe has invested billions of euros in satellite systems and is now seeking applications for using the data being constantly measured using the Galileo system.

The advantage of this type of big data is that England is scanned every few days. Should an application for this big data be determined then the project can have truly world significance and impact.

Whether the available big data can be directly related to macrotexture is as yet unknown. However, the different types of satellite sensor systems may be capable of measuring changes in the observed road network that can be related to frictional change.

For example, it may be possible to pick up differences in rock type, differences in early life road surfaces as they lose their bitumen coatings and aggregate becoming exposed, to the build-up of contaminants that may detrimentally affect skid resistance.

The analytical potential of these big data sources remains considerable for assessing something like a national road network. The reason being that the big data set is renewed every few days as the satellites continue to remotely monitor the earth’s surface.

12 Measurement of oscillatory movement of a falling lever

This idea relates to a lever arm mounted to the underside of a vehicle in close proximity to the highway surface. The metal lever would be free to rotate and impact onto and react from the surface.
The reaction of the lever and its impact would be measured by a small pressure plate fixed above it on the underside of the vehicle body. This would be combined with a positional transducer fixed to the pivot which would be used to measure rotational movement.

The measurements recorded could be used to assess the tyre surface interaction. It is anticipated that at the investigatory phase image analysis would be required in order to extract the pavement surface geometric properties.

13 Measurement of radial line distortion

Rapid acceleration or deceleration can result in significant distortion of the tyre. It is proposed to mark a series of radial lines on the side walls of a vehicle tyre. It is anticipated that distortion of the tyre under a locked wheel test for example will be reflected in a corresponding distortion of the lines.

Images of the tyre captured before and during the test would be used to construct three dimensional models. Measurements of radial line distortion would be extracted before and after testing and used to make an assessment of the tyre/surface interaction.

A similar type of comparison could be made by measuring the migration of a series of radial dots during testing. The apparatus required to prove the principle is already available at Ulster University.

14 Measurement of displacements of an arrangement of spring balances connected to a towed vehicle

A spring balance extends and recovers in response to applied loading. The acceleration required to move a vehicle or deceleration required to stop it will be governed ultimately by the extent to which its tyres interact with the surface.

Changes in inertia or momentum would be reflected by changes in the spring balance readings which could be recorded remotely. Use of a moving test platform would facilitate considerable scope for adjusting applied loads and tyre pressures. Measurements could be captured remotely.

15 A drop test using high impulse acceleration

This involves a standard passenger vehicle sized tyre dropped a small (defined) distance onto a road surface while travelling at normal highway speed. An Infrared sensor would then be used to determine the temperature achieved by the tyre in the initial landing contact area.

The proposed system would use a mobile test platform with a free rolling or variable slip axle allowing tuning of testing criteria. The platform would house the water storage for testing purposes.

Frictional characteristics may be inferred from the magnitude of heat generation in the instantaneous acceleration event for the tyre. The use of a short drop onto the surface would simulate the sudden application of full brake from locked wheel to free rolling.

16 Friction measurement with a low slip wheel

The principle of the system would use a common vehicle tyre mounted on a mobile testing platform with control gear and water storage for surface wetting. The axle would be loaded through the normal operation of the trailer. The low slip ratio would be controlled to maximise tyre life.

Tyre surface temperature would be recorded as an indirect measure of interface conditions. This system varies from the Breaking force trailer in its use of low slip for measurement instead of locked wheel measurements.
17 **The accelerated tyre method**

The legal requirement within the UK for a towed trailer is that a vehicle has a maximum speed of 60mph. This limits the measurement of high speed friction. A possible method to circumvent this restriction is to accelerate the testing tyre prior to contact with the road surface. Measurements would be recorded from the power requirements on the electric motor driving the test axle.

The ULTRA apparatus in Ulster University could be used to simulate a rolling road the test tyre could be driven using an electrical motor. The tyre dropping onto the rolling road could be used to generate an electrical pulse that could be related to the tyre surface interaction.

18 **High speed water footprint method**

The contact area between the tyre and the road surface is impacted by the development of water skin on the tyre during rolling interaction. As the degree of hydroplaning increases the tyre contact decreases. The interaction with the surface will reduce as the water layer increases to a point where the tyre is only interacting with the water layer on the surface. The measurement of this water layer that causes full hydroplaning at high speed may then be related to the friction characteristics.

19 **Water displacement method**

Friction interaction at high speed in wet conditions is dependent on the ability of the tyre to displace water during the contact interaction with the surface

A known value of water can be delivered to the front of the test tyre travelling at high speed and the dispersion of water measured.
Decision Matrix

The following matrix is presented as a means of narrowing the selection of outline proposals in terms of probability of delivery and potential limitations associated with delivery.

<table>
<thead>
<tr>
<th>Proposal</th>
<th>Level of Innovation</th>
<th>Potential Difficulty in Delivery</th>
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A number of projects are feasible in principle, 1, 2, 4, 7, 12, 13, 14, 15, 17 and 18.
Proposal 1 requires development of a high speed pendulum type instrument driven at high speed by an electric motor to assess the interaction with real asphalt samples subject to slow speed high stress simulated trafficking using Ulster University’s Road Test Machine (RTM). The deliverable would comprise a new high speed pendulum apparatus.

Proposal 2 is less innovative as it is to some extent dependent on existing technology but it is anticipated that the heat generated at the interface could be used to assess the extent of tyre/pavement interaction. This is not currently practiced by the industry. Deliverables would comprise thermal imaging data expressed as heat signatures for different pavements under variable load, pressure and condition. It is also feasible that this proposal could be combined with any proposals that required an instrumented towed vehicle viz; 7, 14 and 17.

Proposal 4 is standalone requiring re-evaluation of 2D and 3D parameters. Deliverables would include tyre draping indices, tyre embedment, 3D contact areas, contact-to-surface void ratios and roughness indices.

Proposal 7 has important applications to wet friction, specifically conditions of aquaplane. Deliverables would include aquaplane thresholds for different surfaces which could be related to tyre/road interaction.

Proposal 12 is a straightforward method of attempting to gauge the tyre/surface interaction as it relates to the reaction of a simple lever off the pavement surface and its impact on a small pressure plate. Deliverables would include traces plots of the reactions along the wheel paths of a range of surfacings.

Proposal 13 requires capturing images of radial line distortion of tyres under braking or acceleration. As the work done is a function of force times displacement this could offer a measure of the work done in bringing the vehicle to a stop which could be expressed as a measure of tyre/surface interaction. Deliverables would include estimation of work inputs required to stop on highway surfacings in varying conditions.

Proposal 14 would utilise a spring loaded connection between a mobile test platform and a towing vehicle. The resultant forces on the connection arising from the tyre/surface interaction would be monitored. The test platform would permit variation of loading and slip ratio to determine the most effective for high speed measurement.

Proposal 15 would require the use of an instrumented passenger vehicle wheel with precise rotational control. The wheel would be dropped onto the road surface with the resultant forces from the instantaneous acceleration event upon contact being used to derive the surface frictional performance. The system would need to have control of water delivery rate, axle load, IR sensor(s) and slip values for varying conditions of measurement.

Proposal 16 would operate in similar fashion to that of 15, with addition of an electrical motor to accelerate the tyre beyond the permissible speed of a trailer on the HSN. The tyre interaction with the surface when dropped into contact would allow determination of frictional characteristics from instantaneous heat generation on the tyre surface, water squeeze out, axle loading, etc.

Proposal 18 involved the development of a Digital Image Correlation (DIC) system to examine how the vehicle wheel dewateres the contact area. This would be examined through the spray generation and tyre deformation from varying speed and water delivery rates; examining how they impact on the tyre aquaplaning behaviour. The simplest method to attempt this experiment would be to apply a proof of principle experiment within the ULTRA apparatus in the laboratory.