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Bituplaning: A Low Dry Friction Phenomenon of New Bituminous Road Surfaces

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Abstract

The potential for binder rich bituminous road surfaces to deliver low levels of dry friction was first noted in 1944. Using established test methods exploiting basic principles of physics first tested in criminal court in the 1940s (and still in use today) it has been possible to show statistically that modern negative textured road surfaces (NTS) deliver levels of dry friction significantly below those considered typical by collision investigators for the more traditional positive textured surfaces (PTS) . NTS surfaces are shown to perform relatively worse in the absence of ABS (Anti-Blockier System, Anti-lock braking) than PTS equivalents such as Hot Rolled Asphalt (HRA). Skid tests undertaken on DRY NTS surfaces with ABS braking have been shown to manifest momentary low levels of deceleration similar to those experienced during NOABS tests on the same surfaces and to generate dash like skid marks atypical of ABS tests on DRY PTS surfaces. The ratio of peak to sliding friction also appears lower for dry NTS surfaces than for Dry PTS surfaces documented in the literature.

Using high-speed video and false colour infrared imaging it has been possible to see the low friction phenomenon termed "bituplaning". Vehicles equipped with ABS have also been shown to suffer momentary "bituplanes" resulting in less than optimum performance. Tyre deformation during dry skidding on NTS appears reduced in relation to a PTS equivalent.

The mechanisms potentially responsible for the "bituplaning" have been investigated and no evidence found to support strongly the previous assumption that simple melting was responsible for the low dry friction. Acoustic analysis, fluorescence microscopy, and dynamic shear rheometry have also been used to investigate further the bituplaning phenomenon.

A lack of skilled investigation rather than a lack of instances of bituplaning may be responsible for a lack of evidence of the possible role of bituplaning in crashes. Key collisions in the UK in 2001 appear to have been commonly misinterpreted to project a worse case scenario for the risks of low dry friction on NTS.

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1. Bituplaning: A Low Dry Friction Phenomenon of New Bituminous Road Surfaces

1.1 Introduction

An AA Foundation for Road Safety Research (AAF) Report (Bullas, 2004) highlighted concern over the dry frictional properties of a certain type of bituminous road surfacing used in the UK and elsewhere, termed Negative Textured Road Surface (NTS). These concerns have also been raised by other researchers both in The Netherlands (Fafié, 2004) and in the UK including those at the Transport and Road Research Laboratory (TRRL) (Roe, 2001, Roe and Lagarde-Forest, 2005).

This problem was typically encountered during the period directly following laying when a thicker than hitherto layer of bituminous material existed between the tyre and the coarse stone aggregate (the "chippings") on the road surface. A number of concerns were raised in the Press over the frictional behaviour of NTS road surfaces, before, during and after the AAF work was undertaken. In the UK specifically, events in Derbyshire in 2001 and in New South Wales (NSW) marked the beginning of media interest in this area. A broad though not comprehensive study of references in the media to the issue has been undertaken (Morgan, 2005, Farrell, 2005, Anon, 2003, Chilcott-Moore, 2005a, Chilcott-Moore and Gregory, 2005, Cole and Chilcott-Moore, 2005, Giles, 2005, Anon, 2005b, Odgers, 2005, Anon, 2005c, Chillcott-Moore and Carter, 2005, Chillcott-Moore, 2005, Chilcott-Moore, 2005b, Anon, 2005a, Walsh and Thorpe, 2005, Thorpe, 2003, County Surveyors Society, 2003, Fleming, 2002, Anon, 2001, Brewster, 2001, Anon, 1988).

The research described in this thesis was undertaken with a view to addressing a number of areas worthy of further investigation that were unable to be explored by the Researcher either in the course of the AAF study or which were not considered within the remit of Foundation funding.

1.2 Video content of the research

Viewing of the video-based component of this work is almost essential to the broad understanding of the manifestation of the low dry friction phenomenon in practice and a better understanding of the analysis of the data collected in the course of the study.

By example, a key output of the Research was the capture of high-speed video footage of low dry friction or "bituplaning" events as part of an imaging exercise (sponsored by the Highways Agency and administered by Atkins Highways & Transportation) using infrared and high-speed video, of skid tests undertaken on new NTS surfacing at Madingley in 2006.

The novel application of advanced thermal image analysis is also best-illustrated using video capture of the software in use.

The moving media in Appendix 4 includes a number of simulated ABS and NOABS emergency braking events on both "traditional" and "bituplaning" road surfaces in real time. Viewing these additional videos in association with the "bituplaning" video illustrates the very noticeable differences the use of ABS braking and/or the presence of a "traditional" surface texture can make to the behaviour of the vehicle.

1.3 The phenomenon under investigation

The phenomenon under investigation is that responsible for the manifestation of low levels of dry friction generated between tyre and road surface aggregate during emergency braking manoeuvres on certain bituminous road surfaces.

The material properties responsible for the delivery of levels of dry friction at magnitudes of less than those "typically" encountered at the tyre/road interface were to be investigated as key in understanding how the low dry friction phenomenon occurs.

The low dry friction phenomenon was to be described using the epithet "bituplaning". The association between aquaplaning, hydroplaning, and this new term bituplaning was to be discussed later.

1.4 Aims and Objectives

Key aim

The key aim of this research was to develop more in depth understanding of the nature, characteristics and extent of low levels of dry friction generated between the tyre and the road surface during emergency braking manoeuvres on certain bituminous road surfaces: the process involved is described as bituplaning.

The Specific Objectives to be addressed were:

This research thus aimed to answer the following questions via the completion of the tasks associated with each.

1) To explore the extent to which the dry frictional properties of negative textured surfaces (NTS) significantly different to those of traditional positive textured surfaces in the dry (PTS) (Task One: This question was to be addressed by the statistical analysis of a database of simulated emergency stop tests recorded using existing decelerometer equipment used in collision investigation).

2) To determine if the low dry friction events described in the literature are similar in nature to those observed in this work and do the findings of this work (Task two: This question was also to be addressed by the analysis of decelerometer data from experimental simulated emergency stop tests in the UK and elsewhere).

3) To determine if the frictional properties of NTS surfaces significantly different to those of traditional positive textured surfaces at the point of loss of control where critical speed is reached (Task Three: This question was to be addressed by the analysis of deceleration data recorded during simulated loss of control testing on a test track pursuant to the investigation of an active collision case).

4) To determine if the likely mechanism (or mechanisms) responsible for the generation of the low levels of dry friction observed on certain NTS surfaces (Task Four: This question was to be addressed by the study of thermal and high-speed video images of simulated emergency braking events on bituminous surfaces. Fluorescence microscopy was also to be used on samples of bituminous materials taken from t he line of skidding on an NTS test section. The technique employed were commonly used in the study of changes in bitumen in response to artificial treatments or geological processes (Michels et al., 1996, Stasiuk et al., 2000). By examining the bitumen layer that had been exposed to the action of a sliding tyre is hoped that changes identified in the morphology of the bitumen may indicate exposure to heating of a known magnitude).

5) To estimate the period of time following surfacing during which low levels of dry friction still manifest themselves and the circumstances leading to changes in the low dry friction phenomenon with time (Task Five: A limited study was to be undertaken of friction/deceleration measurements made over time for a limited number of locations where surfacing age and other relevant values are known. This work would augment documented studies over time of dry friction measurements in the literature).

6) To estimate the extent to which collisions in the UK (or elsewhere) had been attributed to the low dry friction phenomenon (Task Six: This question was to be addressed through

direct liaison with collision investigators and highway engineers in the UK along with a discussion of factors likely to assist or hinder the identification of occurrences of the low dry friction phenomenon. It was also to be addressed by direct study of the Police collision reports for the key cases that have been identified as fundamental in the generation of concern over bituplaning in the UK. The researcher's experience of accident statistics was also to be exploited).

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1.5 Research Methodology

This section describes the activities undertaken in the course of this work; the initial literature review provided the initial focus for the subsequent activities described herein:

The order in which the experimental work proceeded was dictated by the availability of funding, the availability of free services provided by third parties and, with respect to data submission and analysis by third parties, their availability to complete such tasks.

Certain activities were inter-related with others such as the high speed imaging and infra red imaging (the bulk of which took place at the Madingley trial on the A428).

1.5.1 Initial Literature Review

A literature review was initially undertaken to establish the depth of understanding of past events where low dry road friction was observed. The initial literature review also encompassed texts relating to the fundamentals of the tyre/road interaction, vehicle braking systems, road surface material performance testing, material behaviour modelling techniques and measurement technologies likely to be relevant to the planned experimental phase and to provide a background understanding of the tyre/road dynamic relevant to all tyre/road interactions.

This literature review provided input to all the tasks described in Section 1.4, in particular evidence of past bituplaning events contributed towards addressing Task Three in particular

1.5.2 Additional Literature Reviews

Following the various experimental activities undertaken, additional literature reviews were deemed necessary to assist in the both the understanding of specific elements of these experimental activities.

These additional literature reviews, in certain cases, prompted additional practical investigations.

1.5.3 Ongoing Literature Reviews

With particular reference to documented cases of the low dry friction phenomenon, it was essential to undertake an ongoing review of the literature via the search functionality of Google News, Google and the Zetoc (British Library Bibliography) database. These services delivered weekly or monthly reports on the occurrence of keywords such as "SMA", "dry friction" and "dry, slippery"; though typically many unrelated results were delivered, a number of the valuable references in this work became known via these routes.

These ongoing literature reviews provided input as appropriate to all the tasks described in Section 1.4

1.5.4 Third Party Data Acquisition – Friction Test Database

In order to establish the significance the characteristics of the bituplaning events identified in the literature review, a database of deceleration time-series data from actual friction tests was assembled from tests undertaken by third parties in the UK.

This activity provided input to addressing tasks 1,2,3 &5 described in Section 1.4

The two devices commonly used by the police to collect the decelerometer time series data, The Vericom VC3000 DAQ and the Turnkey Instruments Skidman are shown in Figure 3.

1.5.5 Third Party Data Acquisition – Dry Friction Benchmarking

A database of multiple deceleration time series data from dry friction tests on a single length of road was assembled following tests undertaken in North Wales in early 2007 (Appendix 1 provides more detailed information). This exercise in association with North

Wales Police provided a valuable measure of the observed variation between vehicles and test devices for the same surface.

This activity provided input to addressing tasks 1,2,3 &5 described in Section 1.4

1.5.6 Third Party Data Acquisition - Questionnaires

Contact was made with a number of Local Authorities, Manufacturers/Installers, and Police Collision Investigators in an attempt to establish their own particular understanding of, and attitudes towards bituplaning.

This activity was intended to provide input to addressing task 6 described in Section 1.4

Three similar sets of questionnaires were sent out to establish:

- If any evidence existed of any collisions where low dry friction of uncontaminated road surfaces had played a role, and to later secure such evidence from collision records.

- If any concerns existed within both local authority and police groups relating to the issue of low early life friction.

The recipients of these three blocks of questionnaires were:

1) Registered manufacturers of BBA/HAPAS thin surfacing materials, the address list being taken from the BBA website (bbastar.co.uk).

2) Local authority members of the CSS (County Surveyors Society), address list being provided by the CSS themselves.

3) Police Collision investigators attending the annual Senior Collision Investigators Conferences in 2004 and 2005 (the recipients of the questionnaires all being practicing collision investigators).

The poor response (less than 5%) to these three sets of questionnaires combined with a lack of additional information forthcoming from their content has lead to the decision not to include the results in this document as the information contained in the few responses simply mirrors the observations made elsewhere (where the data was elicited from the literature).

1.5.7 Third Party Data Acquisition - Questionnaire on typical road friction

Via an established internet based collision investigation discussion group (**RTA_Investigators@yahoogroups.com**), a questionnaire requesting indications of what was considered typical wet and dry friction was undertaken to augment evidence from the literature of what was considered typical.

This activity provided input to addressing task 1 described in Section 1.4

1.5.8 Experimental Data Acquisition - Numerical Temperature Measurements

The initial literature review of the tyre/road interface highlighted the fundamental role of energy transfer between tyre and road in the delivery of tyre/road friction and vehicle deceleration. An attempt was therefore made to measure the temperatures generated between the tyre and the road surface during locked wheel and ABS braking using non-contact temperature measurement devices outputting only numerical data.

This activity provided input to addressing task 4 described in Section 1.4

1.5.9 Experimental Data Acquisition – Thermal Imaging Exercise

An early attempt was made to image the temperature distribution over time between the tyre and the road surface during locked wheel and ABS braking using infrared imaging equipment.

The output of these first exercises was purely video based however they suggested the resolution of the imaging had the potential for more detailed analysis of the output to provide valuable information concerning the thermal transfer between tyre and road during simulated emergency braking.

This activity provided input to addressing task 4 described in Section 1.4

1.5.10 Experimental Data Acquisition - Thermal & High-speed Imaging Exercise

£11,000 of funding by the highways Agency enabled testing to be carried out on a stretch of closed highway on the A428 at Madingley in Cambridgeshire. The surfaces on site comprised sections of both new and entirely untrafficked NTS surface and a well-trafficked positive textured surface (PTS), a chipped hot rolled asphalt. The closed environment enabled multiple tests to be undertaken under controlled conditions.

Thermal imaging work undertaken at Madingley provided linked image and numerical temperature data streams enabling the plotting of linear- or area-based temperature distribution time-series for discrete areas of interest within the visual field of the camera.

Real-time numerical thermal data thus could be manipulated via a specialised graphical user interface (FLIR Researcher, which included the generation of false colour graphics from the data) to enable a more detailed study of the tyre/road thermal interaction at key phases during simulated emergency braking manoeuvres.

Detailed thermal mapping also enabled the observations made in earlier highway based tyre/road thermodynamic work in the literature to be reviewed.

High speed imaging work undertaken at Madingley included the capture of the bituplaning event in real-time along with the tyre/road interaction during simulated emergency ABS braking manoeuvres.

This activity provided input to addressing task 4 described in Section 1.4

1.5.11 Experimental Data Acquisition - Grip/Slip data

The literature review provided numerous references to the idealised form of the level of grip generate between tyre and road and the degree of slip of the tyre relative to the road surface it was traversing, these interrelationships have been termed the "grip/slip" models. The literature review and the results of the decelerometer testing on surfaces manifesting the bituplaning phenomenon suggested that the classic grip/slip curves described might not correspond to those likely to be established for surfaces with a binder film likely to interfere with the direct contact interaction between tyre and road chipping.

With the support of Devon County Council, tests were undertaken at Smeatharpe in Devon. On a surface coated with a thick bitumen layer (Colas GripClean bond coat) using a decelerometer linked to a slip/measurement device using a high-resolution (1000 pulses per revolution) wheel rotation sensor (WRT) enabled a limited comparison of the established rules relating to tyre/road interaction (grip/slip) with direct measurements of a surface manifesting the low dry friction phenomenon.

This activity provided input to addressing task 4 described in Section 1.4

1.5.12 Experimental Data Acquisition - Frictional Properties of NTS over time

A limited opportunity existed for repeated testing of NTS sections, to either directly establish changes in dry friction over time with repeated measurements (for the same surface), or to infer changes over time by testing similar surfaces of different ages.

This activity provided input to addressing task 5 described in Section 1.4

1.5.13 Experimental Data Acquisition - Laboratory Determined Material Properties of NTS

Samples of the bituminous binder material from the NTS surfacing laid where the infrared video and high speed camera study was undertaken was submitted for Dynamic Shear Rheometry (DSR) testing at the Virginia Department of Transportation (VDOT). The DSR testing was undertaken to establish an association between the laboratory properties and observed field behaviour of the material with respect to their decelerometer and infrared and visible light video imaging.

Thin sectioning, impregnation, and subsequent examination under fluorescent light resulted in images of skidded road surfaces from a road trial in Devon. The limited work undertaken gratis by the National Oceanographic Centre (NOC) again provided a basis for future work in this area.

It was important to balance observations made on any bituminous binder material in isolation against the likely effect of particulate material such as stone filler on the bituminous mastic in-toto.

This activity provided input to addressing task4 described in Section 1.4

1.5.14 Experimental Data Acquisition - Acoustic analysis of Skidding Events

In Rasmussen (Rasmussen et al., 2007) nine discrete mechanisms for the generation of tyre/road noise were described, it was thought any difference between the noise generated by tyres undergoing emergency braking between NTS and PTS surfaces may be indicative of the difference in the behaviour of the tyre at the tyre/road contact.

A pilot trial recording ABS and NOABS skids using a MiniDisc recorder for later acoustic analysis using open source software was proposed as an initial proof of concept without plans to extend the work further.

This activity provided input to addressing task 4 described in Section 1.4

2. Literature Review

2.1 Nomenclature and Background Concepts

An effective understanding of the terminology used in the discussion of highway engineering methodologies, the terminology used in the description of the measurement of road surface characteristics and the terminology used in the description of highway structures are all required for the best understanding of this work.

Reference should be made to the bibliography for general texts to support specific references. Where it was of assistance, key figures from these references are reproduced in the text, to assist in the understanding of the topic under examination.

The principles of the measurement of road surface friction and the design of road surfaces for acceptable performance may be easily gleaned by reference to only a few key publications: (Collis and Smith, 1993, Hosking, 1992, Henry, 2000, Highways Agency, 2003a, Highways Agency, 2002, Highways Agency, 2004a, Highways Agency, 2004b, Bullas, 2004). The principles involved are based on empirical measurement rather than theoretical modelling.

For the purposes of this work, there still exist a few technical terms in need of clarification, in particular a number of acronyms and terms that feature commonly throughout but are not adequately described in mainstream texts:

2.1.1 Negative textured surfaces (NTS)

The term "negative textured surface" or NTS is used in the context of this discussion to describe materials such as Stone Mastic Asphalt (SMA) and NTS thin surfaces approved via the British Board of Agrèment / Highway Authorities Product Approval Scheme (BBA/HAPAS products) with or without added fibres or polymers.

If the reader visualises the surface of a sponge as similar to that of a NTS they will not be far from the appearance of a NTS such as porous asphalt (PA) or Stone mastic Asphalt (SMA). Figure 1 provides an idealised representation of NTS and PTS.

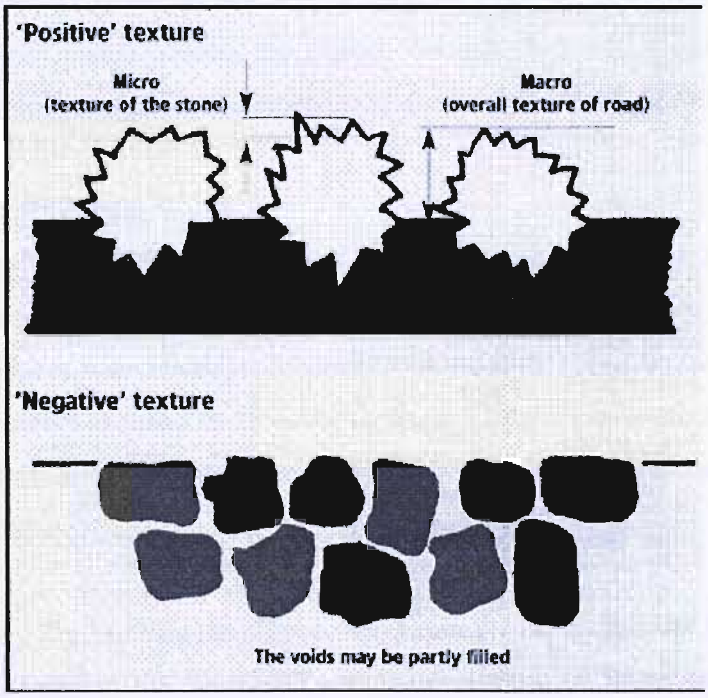


Figure 1 Idealised negative and positive textures (Walsh, 2000)

The term "positive textured surface" or PTS is used in the context of this discussion to describe materials such Hot Rolled Asphalt with chippings (HRA) or surface dressing (SD) or any other material similar in nature. If the reader visualises the surface of the coarsest sandpaper they have ever seen, as similar to that of a PTS surface, they will not be far from the true appearance of a PTS such as a surface dressing (SD).

2.1.2 ABS Brakes

ABS stands for Antiblockiersystem with German automotive parts manufacturers leading the development of anti-lock braking systems. Wikipedia (http://en.wikipedia.org/wiki/Anti-lock_braking_system) and Newcomb (Newcomb and Spurr, 1989) provided the bulk of this overview of ABS braking and it is important to understand that the development of braking systems is a complex process and the following section is very much a summary.

The effectiveness of ABS brakes in practice has been the subject of detailed study, one selected paper in this area is that by Delaney and Newstead (Delaney and Newstead, 2004) which reflects the typical thought that ABS makes little difference to secondary safety outcomes despite its obvious effect on vehicle handling.

ABS History

Anti-lock braking systems were first developed for aircraft in 1929 by the French automobile and aircraft pioneer Gabriel Voisin (Delaney and Newstead, 2004) . An early system was Dunlop's Maxaret system, introduced in the 1950s and still in use on some aircraft models, in 1936 the German Companies Bosch and Mercedes-Benz developed a first electronic version that was made of more than 1000 analogue electronic parts and was still slow.

A fully mechanical system saw limited automobile use in the 1960s in the Ferguson P99 racing car, the Jensen FF and the experimental all wheel drive Ford Zodiac, but saw no further use; the system proved expensive and, in automobile use, somewhat unreliable. However, a limited form of anti-lock braking, utilizing a valve that could adjust front-to - rear brake-force distribution, when a wheel locked, was fitted to the 1964 Austin 1800.

The first true electronic 4-wheel multi-channel ABS was co-developed by Chrysler and Bendix for the 1971 Imperial. Called "Sure Brake", it was available for several years and had a satisfactory performance and reliability record. The German firms Bosch and Mercedes-Benz had been co-developing anti-lock braking technology since the 1930s; they first appeared in trucks and the Mercedes-Benz S-Class. ABS Systems were later introduced on other cars and motorcycles.

ABS Operation

A typical ABS is composed of a central electronic unit, four speed sensors (one for each wheel), and two or more hydraulic valves on the brake circuit. The electronic unit constantly monitors the rotation speed of each wheel. When it senses that one or more of wheels are rotating considerably slower than the others are (a condition that will bring it to lock*) it moves the valves to decrease the pressure on the braking circuit, effectively reducing the braking force on that wheel. Wheel(s) then turn faster and when they turn too fast, the force is reapplied. This process is repeated continuously, and this causes the characteristic pulsing feel through the brake pedal. A typical ABS rotation sensor and toothed ring setup is shown in **Figure 2**.

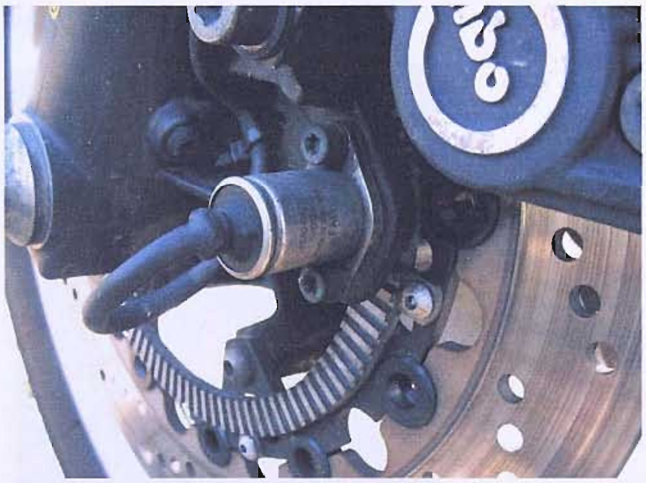


Figure 2 Front ABS sensor of BMW K 1100 LT SE, Bj. 1994 (Source: Wikimedia Commons)

One-step beyond ABS is modern ESC systems. Here, two more sensors are added to help the system work: these are a wheel angle sensor, and a gyroscopic sensor. The theory of operation is simple: when the gyroscopic sensor detects that the direction taken by the car does not agree with what the wheel sensor says, the ESP software will brake the necessary wheel(s) (up to three with the most sophisticated systems) so that the car goes the way the driver intends. The wheel sensor also helps in the operation of CBC, since this will tell the ABS that wheels on the outside of the curve should brake more than wheels on the inside, and by how much.

* The electronic unit needs to determine when some of the wheels turn considerably slower than any of the others because when the car is turning the two wheels towards the centre of the curve inherently move slightly slower than the other two - which is the reason why a differential is used in virtually all commercial cars.

ABS Effectiveness

Video content in Appendix 4 \ABS versus NOABS and stopping distance illustrates the difference in stopping distances between ABS and NOABS emergency braking distances.

On high-traction surfaces such as bitumen, or concrete some ABS-equipped cars are able to attain braking distances better (i.e. shorter) than those that would be easily possible without the benefit of ABS. Even an alert, skilled driver without ABS would not be able, even with techniques like threshold (or cadence) braking, to match or improve on the performance of a typical driver with an ABS-equipped vehicle. ABS reduces chances of crashing, and/or the severity of impact. The recommended technique for non-expert drivers in an ABS-equipped car, in a typical full-braking emergency, is to press the brake pedal as firmly as possible and, where appropriate, to steer around obstructions. In such situations, ABS will significantly reduce the chances of a skid and subsequent loss of control.

2.1.3 "Skid Test"

Tests involving the skidding of a vehicle at the scene of a road traffic accident (to aid in the investigation of the circumstances) have been routinely undertaken since the 1940s (New York State City Magistrates, 1940). The first prosecution made on evidence concerning the length of skid marks left by a test vehicle braking at a known speed versus those made by a vehicle that braked at an unknown speed relied on fundamental rules of physics still used in court today in connection with similar cases.

Tests where a vehicle is braked to a halt from given speed and the deceleration of the vehicle recorded or measured by some means to generate a regular sampling of the momentary deceleration of the vehicle, are commonly termed "brake tests" or "skid tests".

The term "skid test" is used in this work especially as this parlance has been encountered by the Researcher in day-to-day contact with collision investigation professionals.

Unfortunately tests where routine test vehicles are driven down the road at a controlled and constant speed are also called "skid tests" despite the fact that, unlike the true skid tests described above, the test vehicle maintains a fixed speed during the testing and does not, itself, skid.

2.1.4 "Skidman" and "Vericom"

Two devices are in common use by collision investigators to record the momentary decelerations experienced by a braking vehicle during a simulated emergency braking manoeuvre.

Both of the devices in question, the Skidman (manufactured by Turnkey Instruments of Cheshire, UK) and the Vericom (manufactured in the USA by Vericom Computers Inc), operate by being triggered by a threshold level of deceleration being achieved during a simulated emergency braking manoeuvre, (or alternatively set to continuously record as a data logger in the case of the Vericom).

Before testing begins, either device has to be placed in position in the test vehicle (see **Figure 3**) and the test vehicle halted at the location skidding is likely to occur and the device zeroed for the slope of the location. Recording is commenced by arming the device and recording into volatile memory begins until the threshold deceleration is achieved when the momentary decelerations are committed to hard memory. At the end of the skid, the vehicle has to remain stationary to enable the final slope of the device to be established. It is only after this time that internal calculations are undertaken to output summary statistics to the operator (on screen on the Vericom, on screen and as a printout in the case of the Skidman).

Both devices are usually identified by their product name and "Skidman tests" and Vericom tests" relate to tests undertaken using these devices.

The Skidman Decelerometer

The most commonly used device in the UK, the Skidman offers limited additional functionality and no commercial means of extracting the deceleration data for external analysis as it is designed to maintain evidential integrity and prevents changes o the recorded information in its memory. An analysis package called Skidcalc is available at extra cost that can import data from the device and automatically carry out a number of common collision investigation orientated calculations. A limited number of additional input devices and sensors are available for connection to the DIN port of the Skidman. The device required annual calibration to be able to provide evidence in court. The decelerometer can be set to zero ("trim zeros") via an inbuilt function.

The Skidman device is described in various works: (Logan, 2004b, Logan, 2004a, Logan, n.d., Turnkey Instruments Ltd, 1994?, Viner et al., 2001, Highways Agency, 2003a), and is the standard device used in the UK for measuring friction in connection with police collision investigations and subsequent independent investigations.

There is no easily discernable external indication of the age of the Skidman device and internal changes made with the passage of time do not appear to be documented. To all intents and purposes, the devices look identical and are all described as "Skidman" with the exception of the "Braketest" which outputs additional information pursuant to the needs of vehicle examiners.

The Vericom VC3000 DAQ Decelerometer

The Vericom device offers many additional sensors, a number of which have been used in the course of this research. The data transfer software for the device is freely downloadable and the device can accept third party input devices such as accelerometers and load gauges via an easily configurable RC-45 connection (the same as a typical LAN plug used in office networking). The Profile software enables the summary of multiple tests and a user driven graphical interface for plotting and comparing data.

The Vericom device is described in a number of works including that by Brown (Brown and Wingrove, 2004) and is the standard device used in the USA for measuring friction in connection with police collision investigations and subsequent independent investigations . The Vericom device has changed over time, there currently exist a number of models of varying functionality, and the model loaned to the Author was a Vericom VC3000 DAQ, which can function as a multi-channel data logger rather than simply a skid tester.

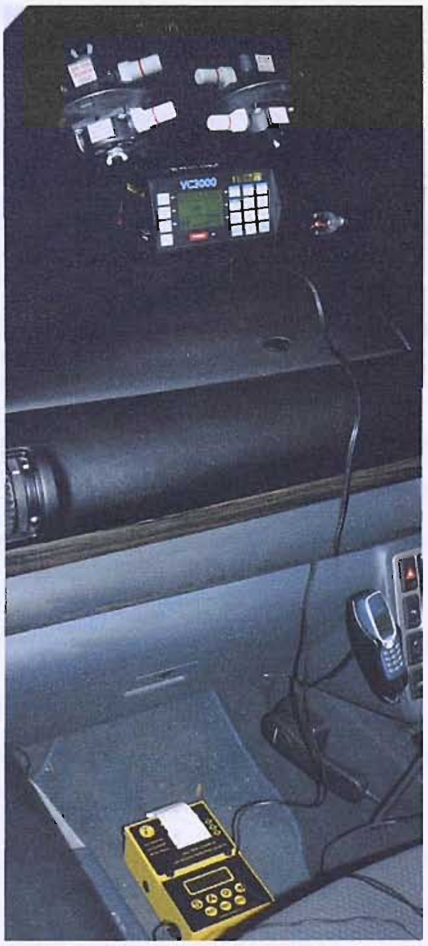


Figure 3 Typical mounting position in Ford Galaxy for the Vericom VC3000 DAQ (top) and Turnkey Instruments Skidman (bottom)

2.1.5 Wet and Dry Friction

Collision investigators commonly talk of friction to describe the deceleration measurements they make that respond to the measurable level of skidding resistance at a location. Thus the more compact terms "wet friction" and "dry friction" will be used henceforth to describe (i) wet and dry road skidding resistance measurements in terms of surface friction coefficients or their derivatives (using designed highway testing vehicles) or (ii) wet and dry road deceleration based measurements (using fundamentally standard road vehicles with decelerometer devices within).

The name of the device used along with the unit of measurement enables the reader to determine easily whether a deceleration based technique or a highway engineering technique generated the results.

The results of deceleration tests (either expressed in percentage or decimals of G (1G, Acceleration due to Gravity = 9.81 m/sec^2) or absolute deceleration in metres per second per second) are commonly used as an inferred measure of friction in collision reports. The relationship between measured deceleration and measured friction is a complex one.

Acceleration is commonly averaged over a skidding event thereby encompassing all speeds from the speed at first braking to the skidding vehicle becoming stationary, whereas friction measurements are commonly made at a standard test speed. However research (Viner et al., 2001) has shown that measurements of friction made at standard test speeds commonly correlate well with the momentary deceleration measurements sampled from the output of decelerating "skid cars" at the same effective test speeds.

Rudram (Rudram and Lambourn, 1981) reported on the generally small variation in skid test results observed between different vehicles and tyres (**Figure 4**), notice the large resolution scale (0.7-0.8) used.

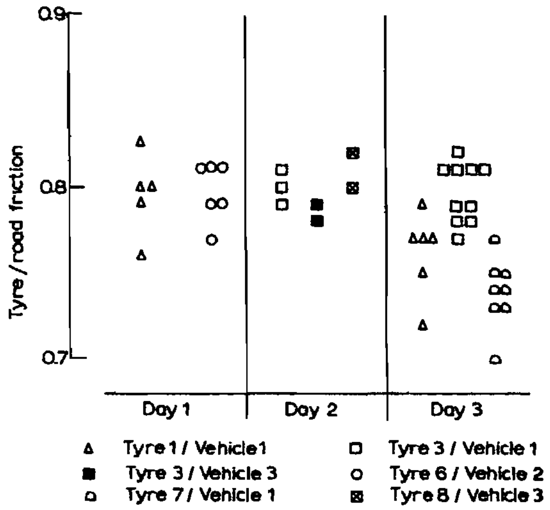


Fig. 2. The variation in tyre road friction for six tyre/vehicle combinations on a surface crompirsing asphalt and coated stone chippings.

Figure 4 Variation in skid test friction measurements over three days (Rudram and Lambourn, 1981)

2.1.6 "Bituplaning"

For the purpose of this work, the term 'bituplaning' more than adequately suffices as an easy descriptor for the low dry friction phenomenon under investigation here. The term will be used henceforth to identify low dry friction events taking place either during simulated or actual emergency stop braking manoeuvres. No assumption is made (or implied) that any similarity exists between the mechanism(s) responsible for the delivery of the low friction in the dry and the low friction during aquaplaning in the wet.

The firm origin of the term "Bituplaning" is unknown, it is therefore impossible to reference a source for the term though the ease of understanding of this term may ultimately lead to its adoption in highways parlance. The term "Bituplaning" appears to have been born primarily through the inference of a similarity of the event to that of aquaplaning (or hydroplaning) which can occur on wet roads when a wedge of water develops that separates the rotating tyre from direct contact with the road surface beneath it. Aquaplaning can occur when insufficient surface macro-texture (coarse road surface texture) exists to allow the water trapped between the tyre and the road to be displaced.

It is important to note that the dynamics of aquaplaning are broadly understood by many but commonly misunderstood in detail, (Gallaway et al., 1979). Aquaplaning generally requires the wheel to be rotating at less than 10% of road speed; members of the public probably commonly associate a general loss of grip in the wet with the "aquaplaning" event that is in fact a far more severe loss of friction and vehicle control.

In the case of bituplaning, interaction of some nature takes place between a locked car tyre and a bituminous road surface during emergency braking which generates a low level of dry friction. "Bituplaning" infers some similarity between this and the manner in which low levels of wet friction are generated by the film of water between the tyre and road surface during aquaplaning (or hydroplaning, as it is termed in the US).

It is the Authors experience as a passenger in a vehicle experiencing a low dry friction event typical of those under investigation in this work, that the low level of noise and low level of vibration experienced during such an event may be felt similar to the low level of noise and low level of vibration experienced during aquaplaning.

2.1.7 The fundamental formula relating measured deceleration to surface Friction co-efficient (Mu or μ)

- This study uses as its main source of experimental skidding data, deceleration time series collected from deceleration measurement devices in routine use by collision investigators worldwide. These decelerometer devices are carried in standard road vehicles that are broken to a halt in simulated emergency stops.

Decelerometer devices used in collision investigation do not measure Mu in the same way as routine highway survey devices such as SCRIM, Grip Tester and the PFT (described in detail in a number of publications: (Viner et al., 2001, Highways Agency, 2003a, Highways Agency, 2002, Henry, 2000, Hosking and Woodford, 1976, Hosking, 1992).
Friction survey devices operate at a constant speed test using a standard test tyre in direct contact with the road surface, decelerometer tests use an established relationship between

Mu and deceleration to estimate Mu from the deceleration measured when a vehicle is brought to a halt. The estimate of Mu from deceleration data represents the frictional interaction between the road surface and all four tyres of the vehicle used in the skid test (Viner et al., 2001) and the measure of one is synonymous with the measurement of the other.

The derivation of the formula used to estimate Mu (μ, surface friction coefficient) or speed at start of braking (v) in association with brake tests commonly undertaken in collision investigation is described in Smith (Smith, 1990). This derivation forms the fundamental means of delivery of estimates of Mu in the output of decelerometer devices such as the Skidman and the Vericom VC3000 DAQ. The formula is reproduced in Figure 5

It should be observed that the intermediate processing strategies between the recording of the raw deceleration data as momentary readings of Mu (during brake test events), and the ultimate output of average and maximum deceleration for a given test, are unknown owing to commercial interests. Observations relating to the differences between these internally calculated statistics and values of peak and average deceleration calculated from the raw time series data are made in the analysis of the database assembled from these tests (Chapter 3.2).

DERIVATION OF THE FORMULA

Consider one dimensional motion in a straight line under constant acceleration a. If the car is moving forward and $a>0$ then the car's speed is increasing and it is accelerating. While if the car is moving forward and $a<0$ then the car is decelerating. For $a = 0$ the car's speed will remain unchanged.

Use v to denote the car's velocity and s the distance it has travelled. The easiest way to obtain the equation which relates v to s is to use calculus. Acceleration is $v(dv/ds)$ so that

$$v \frac{dv}{ds} = a.$$

Integrate with respect to s to get

$$\tfrac{1}{2}v^2 = as + C$$

where C is a constant of integration. If $v = u$ when $s = 0$ then $C = \tfrac{1}{2}u^2$ and the equation becomes

$$v^2 = u^2 + 2as.$$

Here u is the initial velocity and v the final one.

The same result can be obtained without the use of calculus. Use t to denote time. For constant acceleration the rate of change of velocity with respect to time is constant, so

$$v = u + at.$$

The average speed is $\tfrac{1}{2}(u + v)$ so that

$$s = \tfrac{1}{2}(u + v)\,t.$$

Thus the equation for s becomes

$$s = \tfrac{1}{2}(u + u)/a + \tfrac{1}{2}(v-u)^2/a$$

This simplifies to

$$v^2 = u^2 + 2as.$$

When the car is performing an emergency stop, the friction is slowing the car down so $F<0$. For a car braking on a level road simple friction theory gives

$$F = -\mu\, mg,$$

where μ is the coefficient of friction and g is the acceleration due to gravity. (In Great Britain this is 9.81 m/s^2). Compare this with Newton's second law of motion to get

$$a = -\mu g.$$

For a skid to stop $v = 0$ so that the equation becomes

$$u^2 = -2as = 2\,\mu\, gs.$$

Figure 5 Skid to Stop Formula (Smith, 1990)

2.1.8 Automotive Industry Standard Brake Testing Procedure

In automotive engineering an analytical measure called "Mean Fully Developed Deceleration" (MFDD) is used to define braking deceleration - and it is mandated by vehicle homologation authorities in regulations PVGTR2005-2c (UNECE Transport Division - WP.29, 2005) as a "steady state" brake performance measure.

The mean fully developed deceleration (d_m) shall be calculated as the deceleration averaged with respect to distance over the interval v_b to v_e, according to the following formula:

$$MFDD \quad d_m = \frac{v_b^2 - v_e^2}{25.92\ (S_e - S_b)} \quad m/s^2$$

Where:

v_0 = initial vehicle speed in km/h,
v_b = vehicle speed at 0.8 v_o in km/h,
v_e = vehicle speed at 0.1 v_o in km/h,
s_b = distance travelled between v_o and v_b in metres,
s_e = distance travelled between v_o and v_e in metres.

The speed and distance shall be determined using instrumentation having an accuracy of ± 1% at the prescribed speed for the test. The d_m may be determined by other methods than the measurement of speed and distance; in this case, the accuracy of the dm shall be within ± 3%.

For the purpose of this work, the standard method using decelerometers such as Vericom and SkidMan has been adopted with the addition of improved precision via identification of the period of average deceleration and peak deceleration using a Microsoft Excel Macro and spreadsheet combination.

The remainder of this document details the research methodology, the literature based evidence, followed by the statistical analysis of deceleration time-series data followed by details of the field and laboratory based experiments undertaken. It concludes with discussion of the finding of this work in the light of the literature review.

2.2 Negative Textured Surfacing & Bituplaning

The potential for bituplaning became an issue with the increasing use of Negative Textured Surfacing (NTS) despite the potential for earlier PTS surfaces to manifest the same phenomenon. The key factor is that NTS surfaces deliver a consistently thick binder film between tyre and road surface chipping by design rather than in the case of a PTS by mistake.

A thorough understanding of the reasons behind the engineers preferred choice of NTS over PTS (the benefits in their laying and in-service performance) and the industries focus on NTS over PTS (the lack of availability to the client of the older more traditional materials as production and installation concentrates on the new products) help to understand why NTS dominates.

Recent innovations in road construction since the early 1990s have resulted in the current exclusive use on the UK Trunk Road Network of "negative textured" pavement surfacing materials in place of more traditional Hot Rolled Asphalt and Surface Dressings (see **Figure 6** below for an idealised negative textured surface). The nomenclature relating to negative textured (NTS) surfaces is somewhat confusing: the main non-proprietary negative textured surfacing laid in the UK off the trunk road network is SMA (Stone Mastic Asphalt):

"Stone Mastic Asphalt is SMA is a dense, gap-graded bituminous mixture with high contents of stone, filler, and bitumen, modified with a suitable binder carrier such as cellulose fibre. The essential elements of mixture design comprise the formation of an interlocking stone skeleton that provides high resistance to deformation and the filling of the skeleton voids with a rich bituminous mortar to provide high durability. The conventional structure is illustrated in **Figure 6** *and compared with those of Porous Asphalt and textured thin wearing course, both of which have high*

contents of aggregate coated with relatively thick binder films. In very general terms, however, shifting from Porous Asphalt to thin wearing course and on to SMA, the air voids content and surface texture are reduced, but each material still has a relatively quiet surface compared with that of chipped HRA".
Text from Richardson (Richardson, 1999)

Stone Mastic Asphalt is termed Stone MATRIX Asphalt in the USA and some other countries by virtue of the matrix the aggregate forms with the binder and mastic infilling of the voids.

2.2.1 BBA/HAPAS approved proprietary NTS Materials

Proprietary (freely commercially available and not manufactured by the Local Authority) materials may be described as BBA/HAPAS approved thin surfacing systems rather than SMAs, whilst still retaining a very similar structure, but having passed the BBA/HAPAS approval process (British Board of Agrèment, 2000). The UK Highways Agency now only utilises BBA/HAPAS approved thin surfacing systems on their road network: the UK Trunk Road Network.

Local Authorities commonly request BBA/HAPAS certified thin surfacing systems as the approval process is recognised as indicative of good performance. Some proprietary BBA/HAPAS materials are effectively SMAs and used on the trunk road network however, the hierarchy of nomenclature results in the Highways agency stating that they do not use SMA at all.

"Negative textured road surfaces are constructed as a complete layer incorporating the same crushed stone aggregate that is contacted by the tyre, at the tyre/road interface, throughout its thickness; This is completely different to the traditional method of construction of positive textured road surfaces: bituminous road surfaces where either a layer of bitumen (a binder) is sprayed on the existing road surface and a controlled grading of aggregate is then applied to the surface to form a SURFACE DRESSING (SD) or where a thick layer of asphalt is rolled to achieve a smooth level

surface and chippings are subsequently rolled into the surface to form a Hot Rolled Asphalt (Chipped HRA)"

Nicholls (Nicholls et al., 2002)

The coarse crushed aggregate used for the chips (or "chippings") in HRA or as surface dressing chippings can be coated with bitumen but such a coating is designed to reduce dust generation and optimise adhesion between the chipping and the binder layer and thus only needs to be relatively thin (typically less than 5 microns thick).

Negative textured surfaces by virtue of their internal structure, utilising a high percentage by volume of a narrow grading of aggregate particles, rely on the characteristics of the binder layer to provide strength to the layer and deliver resistance to rutting and other problems. The grading of these negative textured surfaces results in the potential for the binder layer to "drain down" through the stone matrix during the manufacture and laying process while the material is still hot, thus, additives such as fibres and/or polymers are added which can also contribute to the structural strength of the finished material.

2.2.2 The Effect of Significant Binder Films on Tyre/Road Friction

The bituminous coatings of negative textured surfaces are commonly thicker than those of positive textured bituminous surfaces (see Figure 6) and may possess properties necessary for long-term durability but may be less than ideal for the rapid generation of the direct tyre/aggregate contact necessary for the delivery of optimum skidding resistance. The binder layers on the coarse aggregate particles in negative textured surfacing are considerably thicker than for PTS (positive textured surfaces) such as HRA or SD.

The bituminous coating acts as a barrier between the tyre and the exposed aggregate surface and the development of in-service skidding resistance has been shown to be closely related to the polishing resistance of the aggregate (Hosking, 1992), this property relates to the level of MICROTEXTURE developed on the aggregate particles. MICROTEXTURE is measured on the sub millimetre scale and is commonly measured INDIRECTLY using devices that measure the friction developed between the road surface and a test tyre. Microtexture can be thought of as the very fine detail on the individual particles of stone aggregate, microtexture is at the micron scale and thus cannot easily be directly measured.

The generation of friction at the tyre/road interface at speed (in excess of 40mph) has also been linked to the presence of sufficient MACROTEXTURE (Roe et al., 1998) which can be measured DIRECTLY using laser based texture meters or volumetric methods such as the glass sphere test. Macrotexture can be thought of as the coarse texture of the road surface akin to the texture on sandpaper delivered by the coarse grains of abrasive media; macrotexture is on the millimetre scale and can be directly measured.

Any layer obstructing the tyre/aggregate interface may therefore have a deleterious effect on the development of optimum friction between tyre and road stone contact. Coatings on HRA and SD chippings must obstruct the tyre/aggregate contact; this has been documented as compromising road friction on the M4 in 1986 (Shelshear, 1986a). This case will be discussed at length in a later section.

A thicker layer of bitumen containing additives to improve the structural characteristics of the complete layer is an essential part of an effective negative textured surface, thus these negative textured road surfaces may produce surface friction characteristics that challenge the widely held belief that uncontaminated bituminous road surfaces cannot be "slippery when dry".

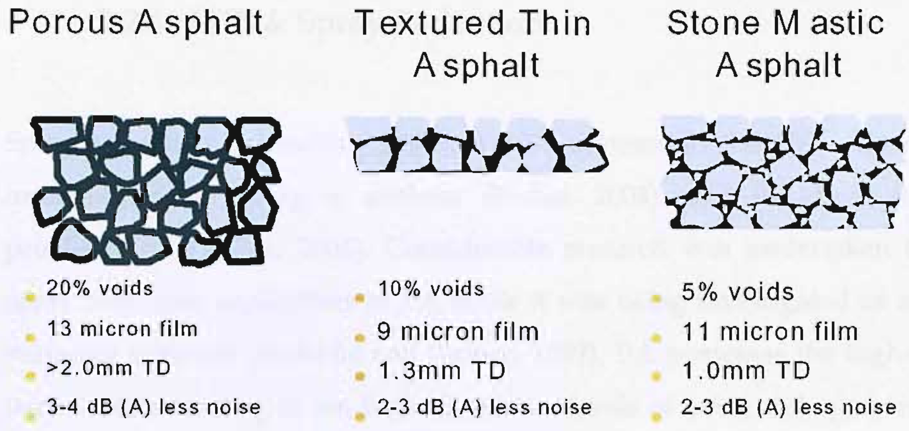


Figure 6 The conventional SMA, Porous Asphalt and textured thin wearing course structures (Richardson, 1999)

Figure 6 summarises the typical void contents, bituminous film thicknesses, macrotexture depths, and acoustic attenuations of SMA, Porous Asphalt and textured thin wearing courses.

2.2.3 The Benefits of Negative Textured Surfacing (NTS)

The benefits of using negative textured surfacing have resulted in its increasing use worldwide. An overview of these benefits assists our understanding of how the negative aspects such as Bituplaning and low early-life wet friction are possibly being outweighed in the mind of the highway engineer by these benefits.

Negative textured road surfaces have been in use in Europe for a number of decades with a wealth of evidence supporting, for example, the reduction of noise (especially in the wet) along with spray reduction for PA (Van Der Zwan et al., 1990). It is interesting to note that the reduction in spray on PA is not recognised as an improver of road safety by some, as vehicle tend to drive closer in wet conditions with better visibility (Swart, 1997) however network capacity is improved.

2.2.4 NTS & Spray Reduction

Spray reduction is a selling point of NTS systems in the UK. However the accurate measurement of spray is difficult (Bullas, 2004), and its effect on drivers equally problematical (Bullas, 2004). Considerable research was undertaken in the UK on the spray reduction capabilities of PA while it was being investigated as a mainstream road surfacing material (Nicholls and Daines, 1992). PA possesses the highest levels of water permeability leading to the highest relative levels of noise and spray reduction. PA has been shown to result in reduced headways and higher speeds in wet conditions, thereby increasing the roads vehicle capacity owing to the reduction in spray (Luis, 1997, Cifre, 1997, Swart, 1997, Bonnot, 1997)

SMA and BBA/HAPAS NTS systems lack the connected porosity of PA but still offer a degree of spray reduction over those of PTS such as HRA.

Spray generated by vehicles travelling on wet roads has been recognised as a hazard when road speeds exceed approximately 40 mile/h (Nicholls and Daines, 1992). The issue of spray was considered "important" on motorways and trunk roads by 35 out of 36 highway authority responses to a CSS survey (CSS, 1994) 21 of the 35 considered it also an issue on local roads and 15 of them had used lengths of porous asphalt (a spray reducing surface) to reduce surface spray. Spray results from the turbulence created by vehicles entraining and dispersing water droplets. About 10 per cent of the water dispersed by the tyre treads is being released in a form likely to generate spray. Putting this 10 per cent in context, the volume of water displaced by a truck tyre driving through water 3mm deep at 80 km/h is nearly 2 litres per second. (Bullas, 2004).

2.2.5 The problem of Road Noise: NTS as a solution

Highway traffic noise is generated from four vehicle sub sources: the engine-drive train, the exhaust system, the aerodynamics and the interaction of the tyres with the pavement (Bernhard and Sandberg, 2005). This report along with that by Nelson and Phillips

(Nelson and Phillips, 1997) and that of Rasmussen, Bernhard et al. (Rasmussen et al., 2007) give a good overview of tyre/road noise issues.

Macrotexture is also closely linked to skid resistance and the risk of skidding accidents (Cenek et al., 2005, Liu et al., 2004, Roe et al., 1998, Roe et al., 1991, Viner et al., 2000) and the relationship between increased road texture and increase in noise is unclear. NTS surfaces such as PA, SMA, and other proprietary NTS materials have been shown to be capable of reducing tyre/road interaction generated noise (Rasmussen et al., 2007, Bernhard and Sandberg, 2005, Sandberg, 2001, Richardson, 1999). Noise reduction is a thus a strong selling point for BBA/HAPAS proprietary NTS materials.

The association of increased road noise with higher levels of macrotexture and tyre tread depth, two properties show to contribute to improved wet grip, have led to a common assumption that reduction in tyre/road noise compromises road safety (Sandberg, 2001). However, conflicting evidence exists in this area. Unpublished research by TRL (Nelson et al., 1993) identified a significant relationship between tyre noise and safety performance, i.e. a decrease in tyre noise was associated with a reduction in tyre safety performance and vice versa, for the tyre sample studied. One example provided was that a reduction in tyre noise of 4 dB(A) (within the range studied) was associated with an increase in braking distance from 90-60 km/h of 7 per cent for car tyres. For guidance, a 10 dB(A) reduction would normally be judged as a halving in the loudness of the noise, a 3 dB(A) reduction is broadly equivalent to halving the acoustic energy of the sound. Clearly a reduction of 4 dB(A) represents a significant reduction in noise. The TRL work also identified a need to establish minimum safety requirements for tyres irrespective of the introduction of noise limits (Bullas, 2004).

However, the findings of work carried out in Sweden (Sandberg and Ejsmont, 2000, Sandberg, 2001) suggests there is no significant conflict between the requirements of noise and tyre safety.

The noise generated by the tyres of passing vehicles has always been of concern in the UK especially when the noise becomes unacceptably high as was the case for residents near to a stretch of the A30 (Anon, 2000). Road noise has also been the subject of debate in the UK Parliament (Reference: House of Commons Hansard Debates for 05 July 2006 (pt 0293)).

Approximately twelve years ago, the Highways Agency (HA) in the UK decided to give a higher priority to tyre noise, especially in urban situations (Parker, 2003).

"The noise arising from the newest quieter surfaces, compared to the more traditional ones, is about the same as if the amount of traffic had been halved." (DETR, 1998).

This came about at the same time as a decision to develop performance based specifications for their road surfacing materials (this became the BBA/HAPAS procedure (British Board of Agrèment, 2000)).

In 2003, HA detailed their aim for 60% of their network to be resurfaced with low noise materials by 2011 (Parker, 2003)though this target recently suffered a setback when the decision was made to cancel the noise driven resurfacing programme until further notice. A typical reduction in noise quoted by Tarmac for the UK for their Masterflex (A typical BBA/HAPAS NTS) is 5.5 Db(A) below HRA (Newton, 2005).

2.2.6 Specific UK NTS Materials

Porous asphalt is not in routine use in the UK. Research carried out on PA sections in the UK by TRL (Nicholls, 1997, Nicholls, 2001) indicated a service life of seven to ten years for a motorway with 4000 commercial vehicles per lane per day (CVD) . 4000 CVD is not now a large commercial traffic flow with relatively recent research investigating sites typically with CVDs 50% or greater than this (Roe and Hartshorne, 1998).

Other poorly documented issues such as premature failure in service and problems with delayed thawing in winter conditions combined with high demand for de-icing salt and other issues caused by the connected porosity of the material (Hernandez and Verburg, 1997, Van Der Zwan et al., 1990) have generally resulted in PA falling out of favour in the UK.

In the UK, the predominant type of NTS in use is Stone Mastic Asphalt (SMA) and similar proprietary BBA/HAPAS NTS materials. These have effectively replace HRA and other PTS systems with the exception of high-friction surfacing (HFS) and surface dressing (SD) on some non-trunk routes. Good overview of UK NTS materials exists in the literature review in Nicholls (Nicholls et al., 2002) and in Richardson (Richardson, 1999).

2.2.7 Unresolved Issues relating to the positive benefits of using NTS in the UK

- Long term reduction of the noise and spray.

The first issue that appears not to have been considered over the long term is any reduction in the magnitude of the noise and spray improvement over time as the surface texture reduces with traffic. Such a reduction in texture was noted for PA by Nicholls (Nicholls, 2001) and for NTS by Nicholls & Carswell (Nicholls and Carswell, 2004).

- Early Life Issues versus Noise and Spray Reduction.

The second issue is that of the "proven" benefits in terms of spray and noise reduction are possibly offset by the potential problems regarding the early life wet (Bastow et al., 2005) and dry (Bullas, 2005d) friction in the material choices being made by Clients in the UK. Since this research has confirmed little evidence of a link between low DRY friction and collisions, doubt as to the real risks that could result from using UK NTS systems may be outweighed by their benefits in terms of noise and spray reduction.

2.2.8 Noise and Spray Reduction and increased road speed

Though not directly reported in the UK, evidence from studies on Porous Asphalt sections suggest traffic speeds increase and separation distances decrease in response to reduced spray/noise (Bonnot, 1997, Cifre, 1997, Luis, 1997, Swart, 1997) this accommodation of the improved visibility in the wet does not consider that an improvement in wet friction may not exist to maintain road user safety at these shorter distances and higher speeds. Less noise in the passenger compartment can equally lead to an increase in road speed as the noise increase with increase in speed is reduced allowing more comfortable driving as speed.

2.3 Road Skidding Resistance: General Concerns

Looking beyond the limited study of the potential of NTS and PTS surfaces to deliver low levels of dry friction, concern exists in highway engineering regarding the maintenance of acceptable or adequate levels of WET road surface friction during the life of the road. The standards used to compare measured values of road friction against, the devices used to secure those values and the methods of maintaining wet frictional properties are well documented. However, a limited review of this area assists in the understanding of where issues of low DRY friction sit in the day-to-day activities of the highway engineer.

2.3.1 Wet Friction

- Identifying Wet Friction Issues

The two most accessible test devices in the UK to determine wet friction over significant lengths of highway are SCRIM (manufactured by WDM) and Griptester (Manufactured by Findlay Irving). Both of these devices have a proven track record in the measurement of WET friction but have been show in various reports (Hosking and Woodford, 1976, Lomas, 2004) not to be suitable for generating a representative measurement of dry friction (wet friction devices tend to generate erroneous and unrepresentative high readings when measuring dry surfaces).

The test procedures for both the SCRIM and Griptester are detailed in the relevant British Standards (British Standards Institution, 1999, British Standards Institution, 2000).

An overview of other devices used worldwide is provided in Henry (Henry, 2000). Standards are in place in a number of countries to address wet friction deficiencies either in a reactive or pro-active manner: either proactively testing or treating to meet established levels (below which collision risk increase) s or reactively testing and treating sites when they are identified as having a "wet skidding problem".

Site category and definition		Investigatory Level at 50km/h							
		0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65
A	Motorway								
B	Dual carriageway non-event								
C	Single carriageway non-event								
Q	Approaches to and across minor and major junctions, approaches to roundabouts								
K	Approaches to pedestrian crossings and other high risk situations								
R	Roundabout								
G1	Gradient 5-10% longer than 50m								
G2	Gradient >10% longer than 50m								
S1	Bend radius <500m – dual carriageway								
S2	Bend radius <500m – single carriageway								

Table 1 Levels of UK in-service Skidding Resistance used to prompt investigation of a site in the UK from HD 28/2004 (Highways Agency, 2003a)

Agency	Interstate/ Motorway	Primary	Secondary	Local
		United States		
Arizona	34 (MuMeter)	34 (MuMeter)	34 (MuMeter)	
Idaho	SN40S > 30	SN40S > 30	SN40S > 30	
Illinois	SN40R > 30	SN40R > 30	SN40R > 30	
Kentucky	SN40R > 28	SN40R > 25	SN40R > 25	SN40R > 25
New York	SN40R > 32	SN40R > 32	SN40R > 32	SN40R > 32
South Carolina	SN40R > 41	SN40R > 37	SN40R > 37	
Texas	SN40R > 30	SN40R > 26	SN40R > 22	
Utah	SN40R > 30–35	SN40R > 35	SN40R > 35	
Washington	SN40R > 30	SN40R > 30	SN40R > 30	SN40R > 30
Wyoming	SN40R > 35	SN40R > 35	SN40R > 35	
Puerto Rico	SN40R > 40	SN40R > 40		
		Non-United States		
Denmark	Speed < 80 km/h; $\mu = 0.4$; Speed > 80: $\mu = 0.5$ at 60 km/h			
Hungary	SCRIM > 0.50	SCRIM > 0.40	SCRIM > 0.33	
Japan Highways	Friction > 0.25			
Netherlands, The	DWW > 38	DWW > 38		
New South Wales	Varies (see Guidelines): SCRIM > 0.30–0.55			
New Zealand	SCRIM > 0.55 on event sites, 35 for no-event sites			
Poland	"Units not comparable with US standards"			
Quebec	SCRIM > 70%	SCRIM > 70%	SCRIM > 55%	SCRIM > 40%
South Australia	BPN > 45	BPN > 45	BPN > 45	BPN > 40
Switzerland	Same as for Construction and Rehabilitation (see Table 6)			
United Kingdom	Investigatory levels (*23*) (see Note)			
Victoria	Depends on conditions: SCRIM > 0.35–.55			

Note: SCRIM = Sideway-Force Coefficient Routine Investigation Machine; DWW = Dienst weg- en Waterbouwkunde friction tester; BPN = British Pendulum Numbers.

Table 2 Levels of in-service Skidding Resistance used to prompt intervention/ investigation of a site (Henry, 2000)

An overview of "skidding standards" used worldwide is also provided in Henry (Henry, 2000). The process of investigating wet friction deficiencies is well documented where local standards exist in the form of investigatory or intervention levels or both (e.g. New Zealand (Haydon, 2005)) . Wet friction measurements have been shown to be seasonal and influenced by traffic and site severity (Hosking, 1992) if the deficiency is sufficiently high to be of immediate concern and is linked to a history of WET skidding collisions, remediation in the form of resurfacing (or in the short-term) retexturing (Bullas, 2004) may be required.

- Investigation & Remediation of wet friction issues

The process of investigating wet friction deficiencies identified against established criteria (see Table 1 and Table 2) is well documented. Local standards may exist in the form of either investigatory levels or intervention levels (or both (e.g. New Zealand (Haydon, 2005)) There is a wealth of available surface treatment for the restoration or replacement of highway surfaces shown to have insufficient wet skidding resistance.

If the deficiency is sufficiently high to be of immediate concern and is linked to a history of WET skidding collisions, remediation in the form of resurfacing (or in the short-term) retexturing (Bullas, 2004) may be required. Regardless of the solution chosen, the road can easily be retested for wet skidding compliance using SCRIM or Griptester.

2.3.2 Dry Friction

- Identifying Dry Friction Issues

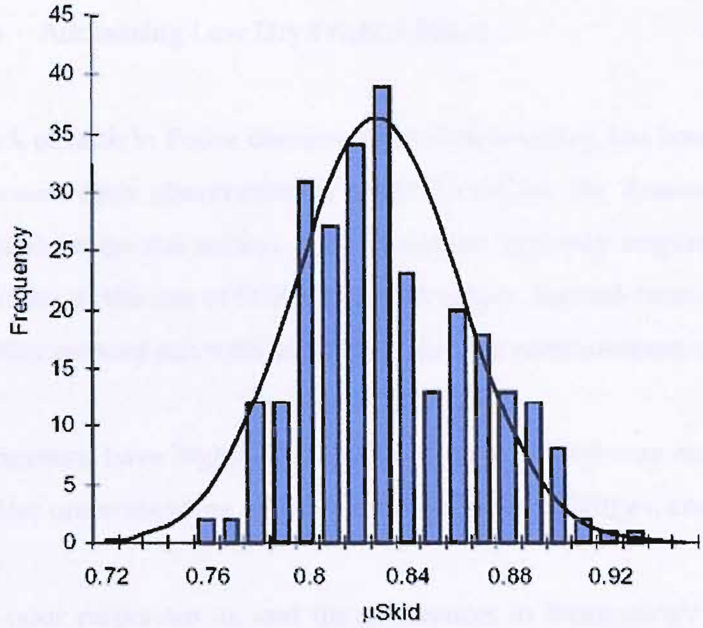
Reported measurements of dry friction on UK roads (using recognised dry friction measurement tools) are currently very limited. Only the police can easily undertake skid decelerometer skid tests and the PFT cannot legitimately be used for any significant testing off of the Trunk Road Network as it is Crown Property), with no routine measurement of dry friction being undertaken in the public domain.

Lambourn (Lambourn, 2004) reported typical dry friction values for the UK (See Figure 8) and Goudie (Goudie et al., 2000) provided a similar figure from work in the USA (see Figure 7).

The UK highway engineer is also unlikely to have easy access to equipment suitable for the measurement of dry friction on the road surface. The Highways Agency (HA) owns and operates a PFT however; this device is unlikely to be available for local authority use as it is not within the remit of HA to carry testing off the trunk road network.

The PFT was however used in the Derbyshire investigation in 2001 (Roe, 2001) and has contributed towards more recent TRL research on the early life skid resistance of asphalt surfaces .

Since existing devices such as SCRIM or Griptester have been shown not to measure dry friction in a meaningful manner, this leaves only the decelerometers used by collision investigators as the remaining viable device.



Distribution of µSkid values for all three tire sets under dry road conditions with a superimposed normal distribution (0.828 ± 0.033).

Figure 7 Distribution of Dry Mu Values (Goudie et al., 2000)

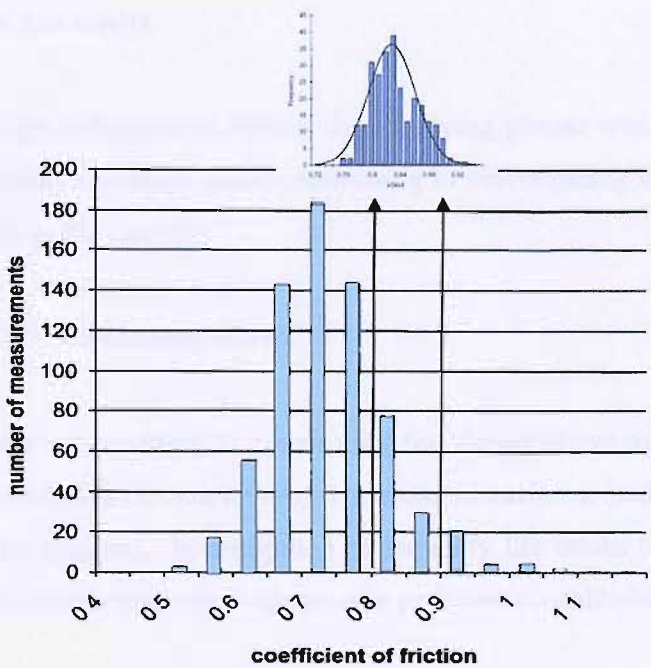


Figure 8 Distribution of Typical Southern UK Values of Dry Friction (Lambourn, 2004) compared against that given in Goudie et al (Goudie et al., 2000)

- Addressing Low Dry Friction Issues

A lack of faith in Police decelerometer-based testing has been expressed by some highway engineers (this observation is made based on the Researchers personal experience of discussions on the subject with numerous highway engineers). Highway engineers are seasoned in the use of SCRIM friction values derived from annual or three-year averages for 50m sections not with individual discrete measurement of a surface.

Discussions have highlighted the need for both highway engineers and the police to have a better understanding of the others equipment, abilities, and knowledge.

The poor responses to, and the differences in terminology that had to be used between, two sets of questionnaires sent to Police collision Investigators and local authority highway engineers may have resulted from a combination of an unwillingness to reveal current understanding and commonly mistaken assumptions about the skidding resistance of negative textured road surfaces. The responses to the questionnaires (less than 5%) were so few and variable in the degree of completion to justify omitting them from this report.

Though colloquial in nature, the following phrase was spoken by a consultant regarding his client's feelings about committing to investigating the early life frictional properties of roads in the County:

"...they are running scared"

A senior Consulting Engineer used the phrase above during a discussion on the subject of low early life friction on negative textured surfaces: (sadly, he cannot be directly attributed, on his request). Investigation of the early life issues are being taken as an admission of guilt even before any evidence of a problem is established.

If dry friction measurements are made, what are these values compared with? The standard for minimum levels of dry friction for PA developed over a number of years in

The Netherlands (Jordens et al., 1992, Leusink and Bennis, 2000, Keift, 2000, Schroten, 1993, Veldhuis, 2004) offers one possible answer .

The investigation and remediation of dry friction issues are hampered by a lack of standards for in service dry friction. Deficiencies cannot be easily quantified and there is a lack of available test equipment to establish the presence of a deficiency (if it can even be defined). The efficacy of its subsequent remediation cannot be determined as **no effective test and treatment strategy exists for dry friction issues in the UK.**

Work by DWW (Jutte and Siskens, 1997) attempted to identify means of improving the dry friction of new PA, unfortunately all the processes investigated were either too expensive, impractical or variable in result to be considered viable. The surface is simply tested and signs remain erected until any deficiency has "gone away" as a result of trafficking and weathering.

2.4 Early Life Skidding Resistance Issues

Reference to documentation such as the Highways Agency Design Manual for Roads and Bridges (Highways Agency, 2003a) and the Best Practice Guide for Highway Maintenance (Roads Liaison Group, 2005) confirms that the routine measurement of levels of skidding resistance below those considered acceptable is generally considered to be of concern.

The issue of the measurement of unsatisfactory skidding resistance on modern negative textured road surfaces during their early life is of even greater concern: the anticipation is generally that "the new road performs better than the old road it replaced". The potential for poor frictional performance of this new road surface type shortly after installation is of general concern (Bastow et al., 2005).

This issue of early life skidding resistance can be divided into two discrete areas: low **wet** skidding resistance during **early** life and low **dry** skidding resistance during **early** life.

The following sections of this Report provides an overview of the general issue of early life skidding resistance on bituminous surfacing in general, and specifically on negative textured bituminous surfacing. Areas of interest relating to the application and precision of typical test equipment used to measure dry friction are discussed and individual dry friction measurement projects are discussed along with their findings.

- The definition of "early"

The duration of the period during which unsatisfactory performance can be seen to manifest itself during "early life" may be a function of traffic characteristics (number of vehicles, severity of manoeuvres), binder characteristics (film thickness, additives) leading to the removal, over time, of the binder between the tyre and the road surfacing aggregate.

Work undertaken at The University of Ulster (Woodward et al., 2005) and in Australia (Parfitt, n.d.) suggests that the use of polymer-modified binder (PMB) may increase the period the binder film is retained on the aggregate. This view is indirectly supported by observations relating to the mechanical (rather than frictional) properties of thin surfacing as a whole which suggest the use PMBs may result in a more tenacious film (from ravelling resistance in (Hassan et al., 2005, Hassan and Al-Jabri, 2005)) or indeed mooted as providing improved performance in many applications (Glanzman, 2005).

Polymer Modified Binders (PMBs) have been indicated as almost a pre-requisite for small chip size materials to give better resistance against the shearing and scuffing action of traffic (Parry, 1998), improving the performance of these materials at both high and low temperatures (Zanzotto L et al., 2000, Marasteanu et al., 2005) . Polymers are already in use in industry to reduce frictional drag in pipeline transportation and oil production via the Toms phenomenon (Borodin et al., 2005). Asphalthenes and resins have been shown to reduce drag in oil pipes by up to 45%, however their chemistry and structural interaction with the liquids is likely to be dissimilar to the polymers in bituminous road surfacing materials.

- Wet and Dry Friction: Two very different properties of the same road surface

The physics at play in keeping a vehicle on the road during both routine and emergency manoeuvres are generally better understood by those involved in the day-to-day investigation of collisions than by highway engineers; conversely, the routine measurement of road surface friction for the purposes of network maintenance is the province of the highway engineer. Differences in the method of interpretation of data commonly collected using fundamentally different methods has led in the past to a general lack of common knowledge between specialist from one camp with respect to the data collected by the other.

The mechanics of the measurement (and interpretation of measurements) of wet skidding resistance are well documented and widely understood by the Highway engineer, with a number of easily accessible devices available to both trunk road and local authority road stakeholders. However, when one considers the measurement of early life dry skidding resistance, the early assumption made, that road surfaces are only commonly 'slippery in the wet', has subsequently led to a lack of available test equipment to measure this property. A fundamental lack of understanding exists within highway engineering, of the levels of dry skidding resistance that, if measured, should be considered "acceptable" on our roads.

- Wet Skidding Resistance: Early Life Issues and Treatments to remedy them

Though not always stated explicitly, the highway engineering literature, until recently, has been almost entirely devoted to the investigation of the frictional properties of the wet road rather than the DRY.

Nunn (Nunn, 1994) commented on the potential for SMA (Stone Mastic Asphalt, a negative textured surface) to deliver low levels of wet skidding resistance due to the thick binder film on the exposed surface of the aggregate, though he continued to observe that this layer is subsequently worn away by traffic. The use of rolled in sand to reduce this short-term period of low dry friction was also described.

Evidence (Bellin, 1997, EAPA, 1998) suggests that gritting of SMA during laying to address early life skid resistance problems was standard practice in a number of European countries before SMA was used to any extent in the UK:

"To avoid vehicle skidding during service in the first winter period, uncoated grit is commonly spread and compacted into the surface at the time of construction."

(Richardson, 1999)

A controlled application of a grading of fine aggregate on new SMA to mitigate low levels of early life wet friction is routinely used by Devon County Council who has observed this effectively raises low early life wet friction (Figure 9) to acceptable levels on first trafficking.

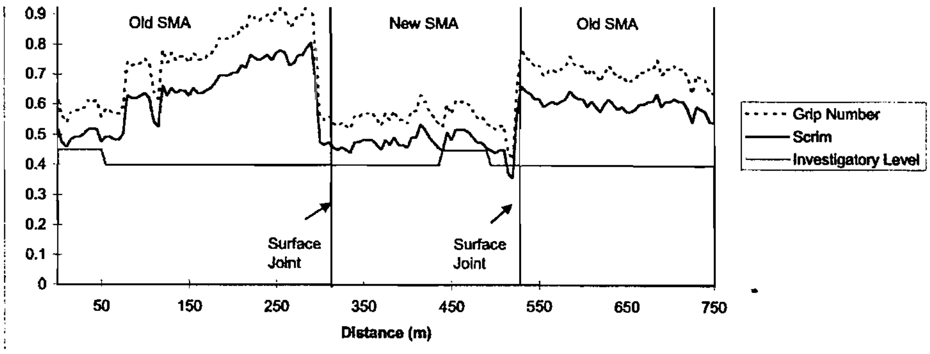
Devon was currently investigating the optimisation of spread rates and have moved towards a more expensive but better controlled mechanical application method (chipping spreader) from hand broadcast (by shovel).

Cambridgeshire appear to have recently adopted (Mid 2005) the use of gritting using the same material as Devon according to their Soils and Materials Engineer.

Derbyshire County Council are routinely gritting new SMA surfaces likely to be used by a significant number of horse riders.

Colloquial evidence gained from conversations with Materials Engineers suggest that early experiences with low levels of wet friction delivered by new SMAs (determined from SCRIM measurements) in the late 1990s may also have resulted in modification of binder contents/mixes to reduce the thickness of the film first exposed to traffic. Concern regarding the "early life" wet frictional properties of SMA remained.

Bastow (Bastow, 2005) reports on a study made in Dorset of "The Skid Resistance of Stone Mastic Asphalt laid on a Rural English County", this study was prompted by events in Derbyshire rather than a locally encountered problem, and is a valuable example of reasoned investigation of the status of road surfaces under investigation elsewhere. The reports observations should be of great interest to other Authority engineers:



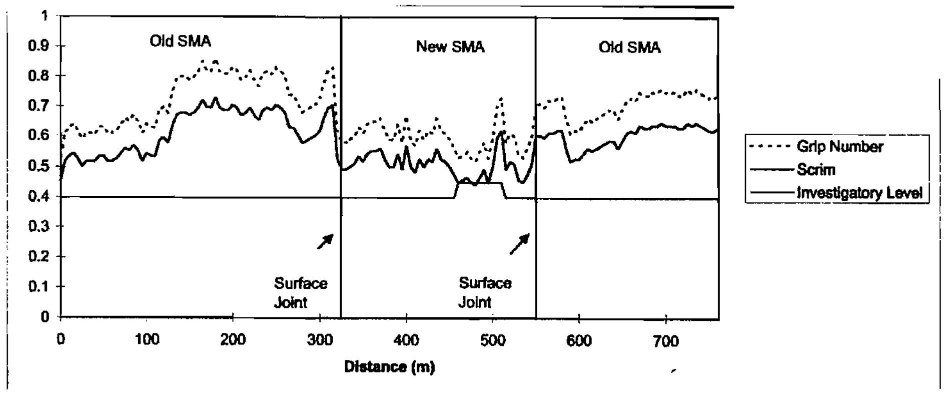


Figure 9 Low wet friction on New SMA observed in Devon County Council Griptester data (Devon CC)

"The early life skid resistance was similar to that of conventional bituminous surfacings and improved with time but this could take up to two years and in exceptional cases three years to achieve. Thereafter the material remained consistent before experiencing a decrease in skid resistance in the following years as the aggregates at the surface polished."

"There is a 30% chance that new stone mastic asphalt surfaces will not meet the investigatory level for wet road skidding resistance in the 12 months after laying."

- Dry Skidding Resistance: Early Life Issues and treatments to remedy them

Research undertaken by The Metropolitan Police: (Shelshear, 1991, Shelshear, 1998, Shelshear, 2005, Shelshear, 1986a, Shelshear, 1986b, Shelshear, 1993, Shelshear, 1986?-b), TRL: (Roe and Lagarde-Forest, 2005, Roe, 2001, Roe, 2005, Roe, 2003, Roe, 2004), and by researchers from The Netherlands: (Tarrega and Costell, 2005, Leusink and Bennis, 2000, Jordens et al., 1992, Keift, 2000, Veldhuis, 2004, Schroten, 1993, Fafié, 2004); collectively constitutes a broad summary of early life Dry friction issues arising, along with a number of solutions to remedy them.

There may be parts of road networks in the UK or elsewhere which, because of the use of particular surfaces, possesses low levels of dry friction. With no routine testing of dry friction being undertaken in the UK, and the lack of sensitivity in the non-fatal collision reporting system (see Chapter 5.1) these locations, overall, remain unknown.

2.5 Low Dry Friction and Bituplaning in the Literature

This section contributes towards addressing Question 2 in Section 1.4: Were the low dry friction events described in the literature similar in nature to those observed in this work and do the findings of this work support past findings?

A number of "Bituplaning" events have been documented in the literature: the most comprehensive study undertaken is that by the Authorities in The Netherlands (Fafié, 2004, Jutte and Siskens, 1997, Swart, 1997, van der Zwan et al., 1997, Van Der Zwan et al., 1990, Jordens et al., 1992, Keift, 2000, Leusink and Bennis, 2000, Schroten, 1993, Veldhuis, 2004).

Low dry friction and/or bituplaning has been observed though not investigated in detail by many researchers and the following sub-sections represent a chronology of bituplaning in the literature:

2.5.1 PTS Surfaces: Motorbike Combination Skid Tester 1930's

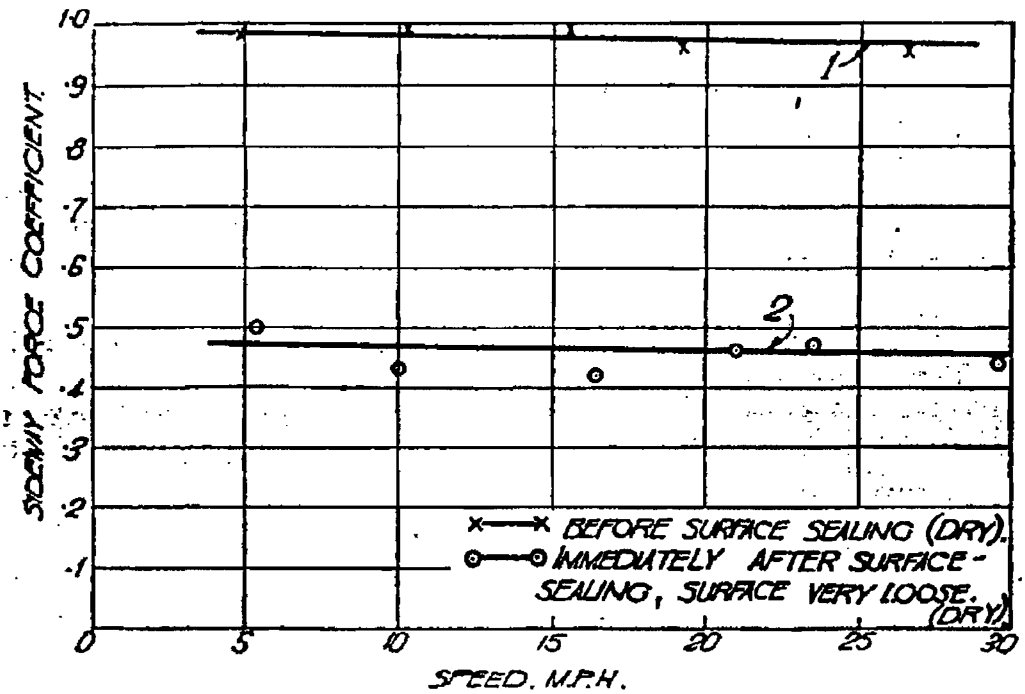


Figure 10 Low dry friction in the 1930s (Bird and Scott, 1936)

In 1936, the first report produced by what would become TRRL observed low dry friction (**Figure 10**) as measured by a motorcycle combination skid tester on a new road surface caused by loose construction material (Bird and Scott, 1936).

2.5.2 PTS Surfaces: The role of a bitumen layer in the generation of dry friction 1940's

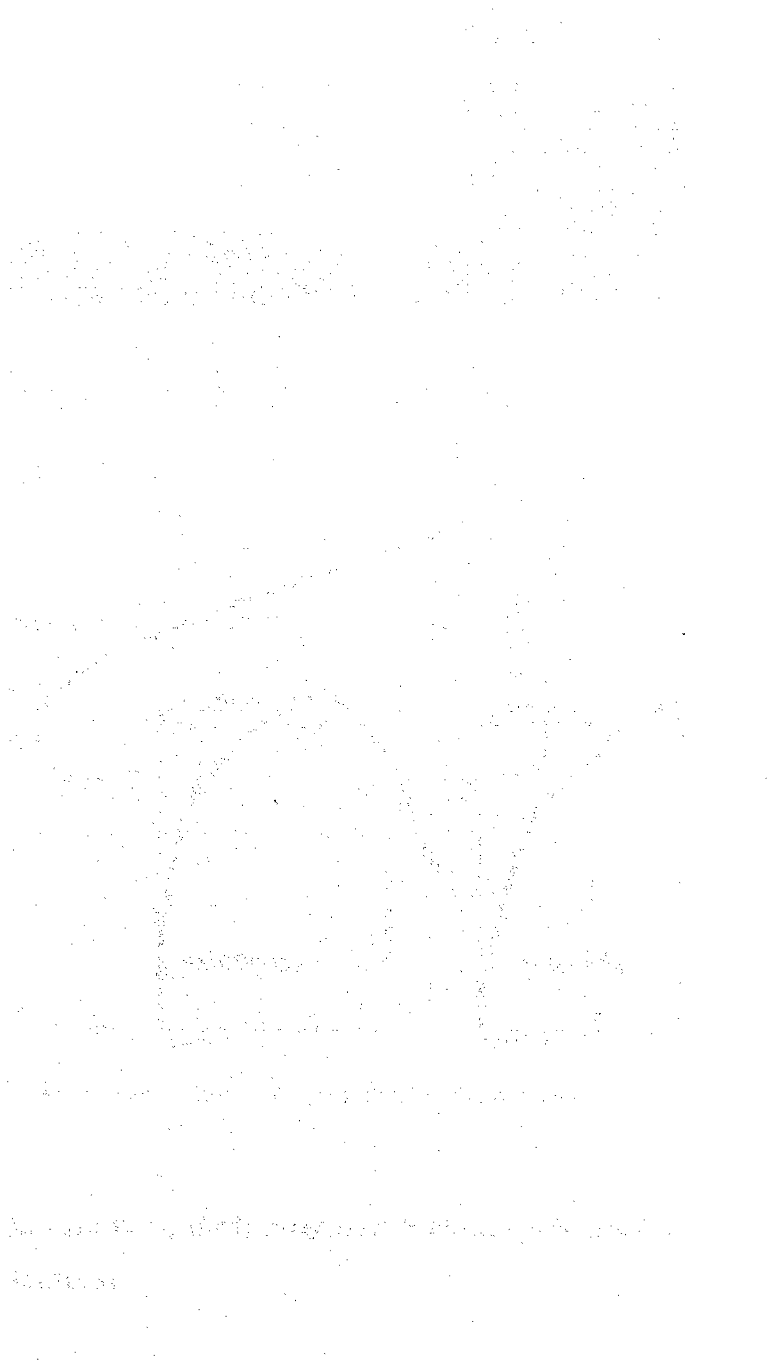
In the 1940's Zipkes (Zipkes, 1944) first postulated that a dry tar or asphalt coated road surface could generate a lower level of maximum friction than the tyre during a hard braking manoeuvre leading to a loss of friction and skidding caused by the road surface before the tyres frictional properties were exhausted.

"On some road surfaces, the melting point of the binder....(the bituminous layer) ...may be reached before that of the tread rubber, in which case the slipping co-efficient will have a different value from that on which the rubber melts first" Translation from the Swiss (Department of Scientific and Industrial Research, 1963).

This may have been the first suggestion that the bituminous coating between the tyre and the aggregate chipping on the road could directly contribute towards the overall frictional characteristics of the road surface. **Figure 11** below is reproduced from (Zipkes, 1944) and shows the lower level of dry friction measured for a bitumen rich "Stampf Asphalt" on the top right where bitumen existed between the tyre and the road surfacing chipping. Similarly, the maximum achievable temperature between tyre and road was reduced where excess bitumen existed (bottom).

Zipkes monitored the temperature generated on the surface of an instrumented tyre as it was skidded over a surface (**Figure 11,** bottom) to the point that the tyre broke free from the surface. His equipment was also capable of generating a plot of friction over time

(**Figure 11**, top) which has a very similar appearance to the SkidMan deceleration plots presented later in this work.



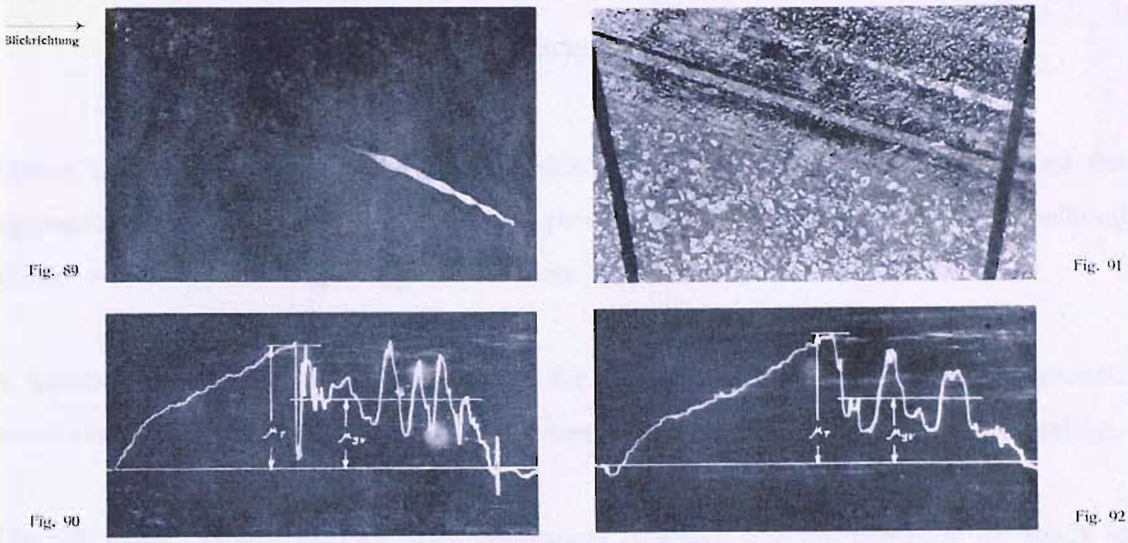


Fig. 89. Bremsspur bei verändertem Material in der Gleitphase (Aufnahme im Gegenlicht).
Fig. 90. Diagramm der Bremsmomente (zu Fig. 89), Reibungskennziffer = 0,55.
Fig. 91. Gleitspur. Das Bindemittel zwischen den Splittkörnern ist erwärmt und verflüssigt worden.
Fig. 92. Diagramm der Bremsmomente (zu Fig. 91), Reibungskennziffer = 0,50.

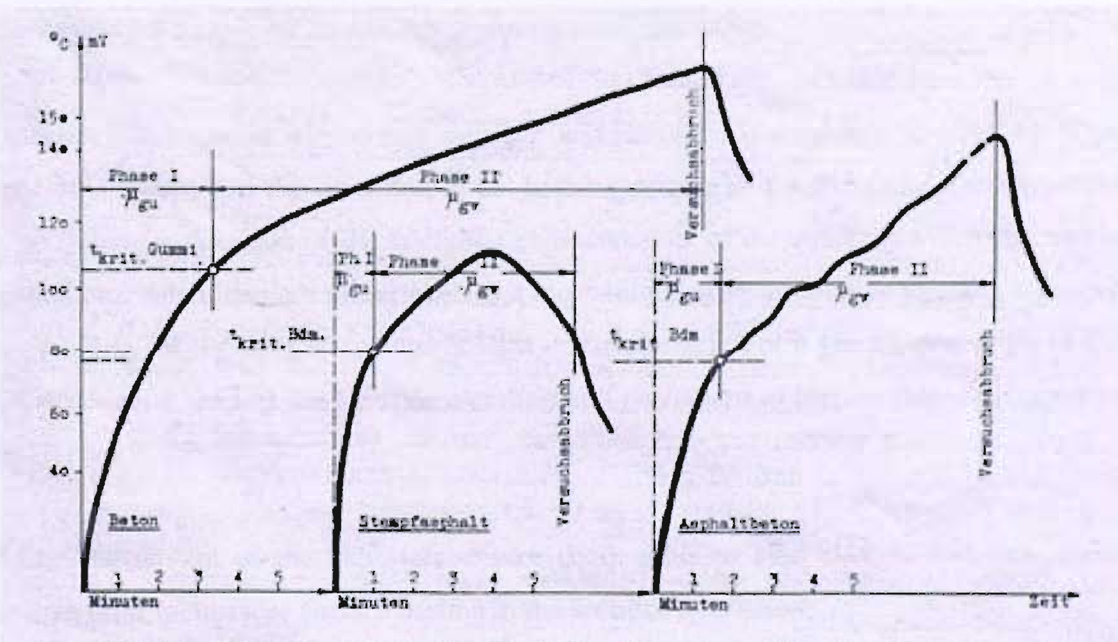


Fig. 50. Zusammenstellung der gemittelten Kurven aus Fig. 36, 42 und 46.

Figure 11 Zipkes (Zipkes, 1944) tyre/road friction spots (top) and tyre/road contact temperatures (bottom)

2.5.3 PTS Surfaces: Low Dry Friction on Traditional Uncontaminated Road Surfaces (1980's 1990's)

Zipkes (Zipkes, 1944) observation of a thick bitumen film between the tyre and the aggregate on the road surface being able to produce low levels of dry friction was echoed in later work in the UK regarding PTS surfaces.

A number of reports were generated by the Metropolitan Police and Police Forensic service relating to events where low dry friction was measured on traditional PTS surface.

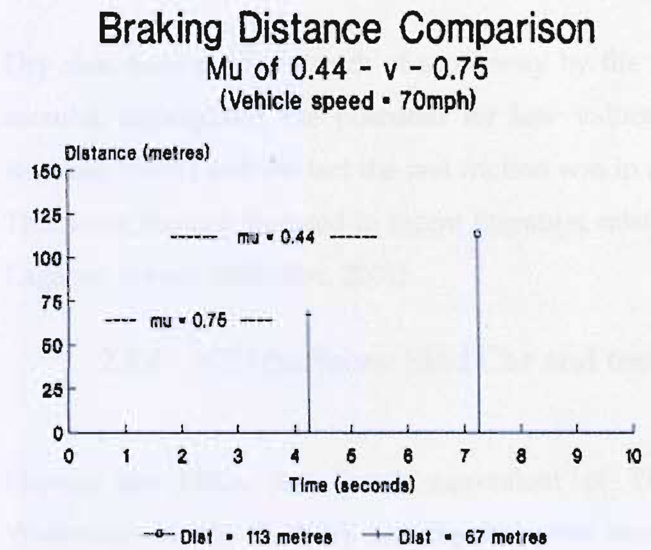
The UK Road Construction Industry commonly observes that the potential for roads to deliver low levels of friction during early life is not the sole province of NTS (negative textured surfaces) such as Porous Asphalt (PA or ZOAB in NL) and Stone Mastic Asphalt (SMA) and refers to the PTS related incident already discussed.

Collision investigators now commonly use acceleration measurement devices either to provide a measure of the condition of the braking system of a vehicle under examination or to deliver a measure of the frictional characteristics of the road on which the test is carried out. Such tests are undertaken as a more informative alternative to using highway engineering survey devices such as SCRIM or Griptester). For a good explanation of the physics behind the link between deceleration and coefficient of friction (MU or μ) refer to Smith (Smith, 1990).

Before the advent of the SkidMan, device chalk guns or skid sledges were the main devices used to measure surface friction at the scene of a collision.

2.5.4 Skid Car Decelerometer/Chalk Gun Tests 1980s

A well documented instance of low levels of dry friction on a traditional PTS surface relates to a stretch of the M4 laid in 1985, Shelshear ((Shelshear, 1986a) et seq.) investigated and reported at length on the low levels of friction generated by the bituminous coating on HRA chippings. The collision he investigated cost the lives of twelve people. Subsequent reports (Anon, 1986a, Byrd and Dadson, 1986, Anon, 1986b) appear to focus the cause of the fatalities on crash barrier irregularities, the low dry friction issue forgotten .



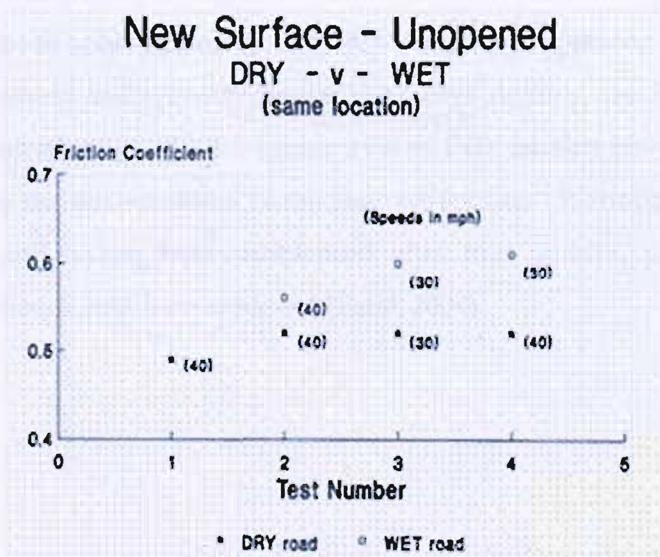


Figure 12 Figures after Manderson et al. (Manderson and Rudram, 1993)

Shelshear commented later on his report on the M4 crash in 1986 (Shelshear, 1998), observing that the SCRIM device was unsuitable for measuring dry friction confirming observations made by TRL (Hosking and Woodford, 1976); the Findlay Irving Grip Tester is equally designed only for wet testing (Lomas, 2004).

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2.5.5 PTS Surfaces: Skid Car Decelerometer Tests 1990s

Dry skid testing on a stretch of motorway by the Metropolitan Police over a number of months, highlighted the potential for low values (reported in 1993, (Manderson and Rudram, 1993)) and the fact the wet friction was in fact better than the dry (see Figure 12). This work has not featured in recent literature relating to low dry friction issues (Roe and Lagarde-Forest, 2005, Roe, 2001).

2.5.6 NTS Surfaces: Skid Car and test trailer tests 1990s

During the 1990s, the Dutch equivalent of TRL, Rijkswaterstaat Dienst Weg- en Waterbouwkunde (DWW), investigated what soon appeared to a common characteristic of a high percentage of new porous asphalt on their motorway network: low dry friction during early life (Jordens et al., 1992). A research programme resulted in the both the development of a dry friction testing device (similar in layout to the Dynatest 1290 tester owned and operated by the Highways Agency, see: http://www.dynatest.com/) and the introduction of a minimum level of DRY friction to supplement the standards that related to the measurement of routine wet friction. Warning signs were erected on first opening until testing that commenced after four months, confirmed the required level of dry friction had been achieved (Fafié, 2004).

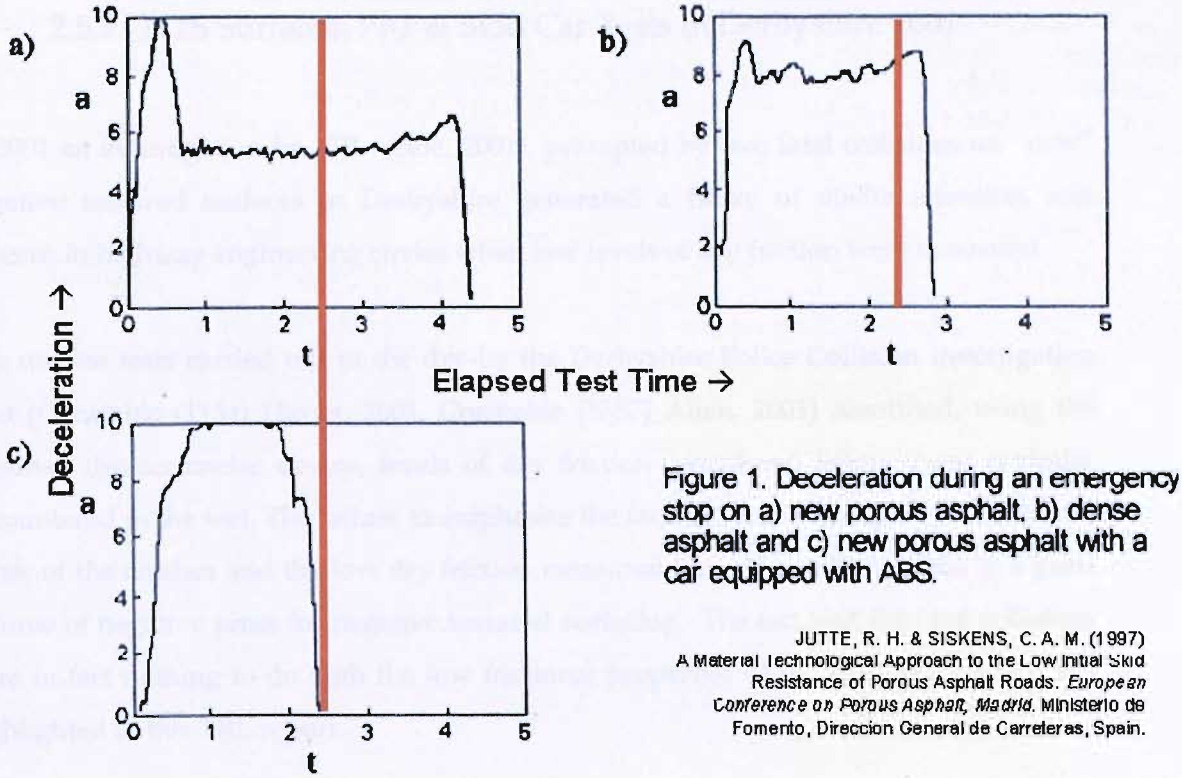


Figure 13 The effect of ABS braking on braking times after Jutte (Jutte and Siskens, 1997)

DWW identified the potential for vehicles without ABS to experience low levels of braking deceleration accounted for by the melting of the thick PA binder film between the tyre and the surfacing aggregate. They also identified that for certain porous asphalt (PA) surfaces, the time to stop was greatly extended in the case of vehicles where the ABS braking was disabled or not fitted, the PA surface out-performed the typical surfaces used where ABS was functional, (Figure 13). Graph (a) on Figure 13 shows the NOABS braking time for the same PA surface as graph (c) where ABS is on.

An acceptable level of dry friction was arrived at both by examination of the levels seen on older PA surfaces and with reference to the deceleration requirements for car braking systems in automotive engineering. A number of solutions to produce a new PA surface, with higher dry friction on day one, were investigated (Jutte and Siskens, 1997) without success.

2.5.7 NTS Surfaces: PFT & Skid Car Tests in Derbyshire 2001

In 2001 an investigation by TRL (Roe, 2001), prompted by two fatal collisions on "new" negative textured surfaces in Derbyshire generated a flurry of media attention, and concern in highway engineering circles when low levels of dry friction were measured.

The routine tests carried out in the dry by the Derbyshire Police Collision Investigation Unit (Constable (1154) Harris, 2001, Constable (1357) Allen, 2001) identified, using the Skidman decelerometer device, levels of dry friction considered below those typically encountered in the wet. The failure to emphasise the fact that there was not a link between either of the crashes and the low dry friction measured has ultimately resulted in a great volume of negative press for negative textured surfacing. The fact that the fatal collisions were in fact nothing to do with the low frictional properties of the road surface was not highlighted in this TRL report.

In the case of the crash at Pebley Reservoir, Derbyshire, Monday 20th August 2001 (Constable (1357) Allen, 2001), skid tests revealed dry Mu values of 0.496, 0.478, 0.48. These results were "significantly below what... would expect for a dry flat road surface". A typical value in these circumstances would be 0.7 to 0.75" according to the Investigator.

In the case of the crash at Car Top, Derbyshire on Wednesday, 18th July 2001 skid tests revealed damp road Mu values of 0.519, 0.506, 0.532 & 0.546. These results were considered "markedly lower than ...expected. The road surface at the scene was very new, having apparently been overlaid with a new wearing course the previous week.

It was later confirmed by Derbyshire County Council that the surface was indeed new, and was formed of a material known as "Stone Mastic Asphalt". On 25th July 2001, a further skid test was carried out in the same position with the surface dry and the Coefficient of Friction was 0.585, in the opinion of the investigator: " still some 20% lower than might be expected on a dry flat road, despite being on an uphill gradient. " As a comparison, a skid test was carried out on the A621 hot rolled asphalt. At this site, the Coefficient of Friction was 0.696 considered "much closer to the value expected".

A more detailed discussion of the circumstances of the two fatal crashes in Derbyshire is given in the official collision reports (Constable (1154) Harris, 2001, Constable (1357) Allen, 2001).

2.5.8 NTS Surfaces: Skid Car Tests in Dorset 2003 & 2004

Two separate fatal crashes on SMA in Dorset documented low levels of dry friction, in the case of a fatal collision in 2003 between a Vauxhall VX220 sports car and a single decker coach on the A35 a value of dry Mu of 0.447 was measured (Boardman, 2003). In the case of a collision between a TVR Griffith motor car and a Vauxhall Vectra on the A30 in 2004 , values of dry Mu of 0.548 and 0.547 with an adjacent HRA giving 0.699, 0.473 had been measured in the wet at the same location (Wandless, 2004).

Notwithstanding the low levels of dry Mu recorded in each investigation, the low measures were not implicated in the causation or outcome of either crash.

2.5.9 NTS Surfaces: Skid Car Tests in New Zealand 2005

The researcher was invited by Fulton Hogan Ltd (New Zealand) to attend the field trials forming part of the 2005 International Conference on Surface Friction of roads and Runways. The published report on the trials (Austroads, 2006) identified a NONABS average deceleration value of 0.51 for the UTA (Ultra thin asphalt) compared against typical values in excess of 0.60 for other surfaces with the exception of the NTS Stone Mastic Asphalt (SMA) where the values were omitted.

Figure 14 illustrates the deceleration plots for the tests undertaken on these materials comparing their ABS to NOABS performance and the similarity to the Dutch work shown in Figure 13 is most obvious.

Figure 15 illustrates the finding that the UTA was in fact delivering poorer deceleration in the dry without ABS than in the wet without ABS. This finding corroborates earlier findings that roads with thick binder films can deliver lower dry friction than wet when ABS braking is not active.

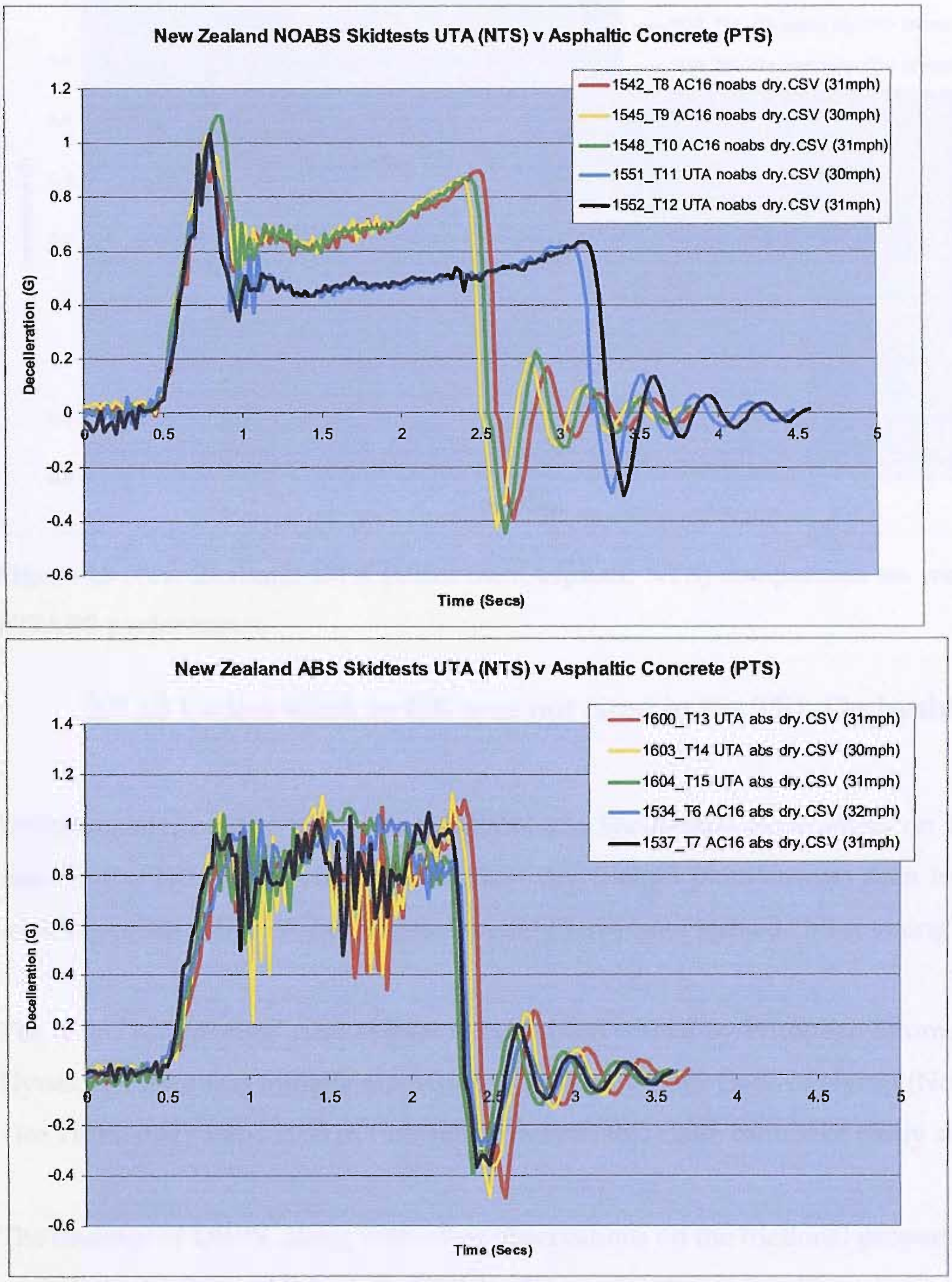


Figure 14 Asphaltic Concrete (AC PTS) versus Ultra thin Asphalt (UTA NTS) NOABS (top) versus ABD (bottom) (raw data from Author)

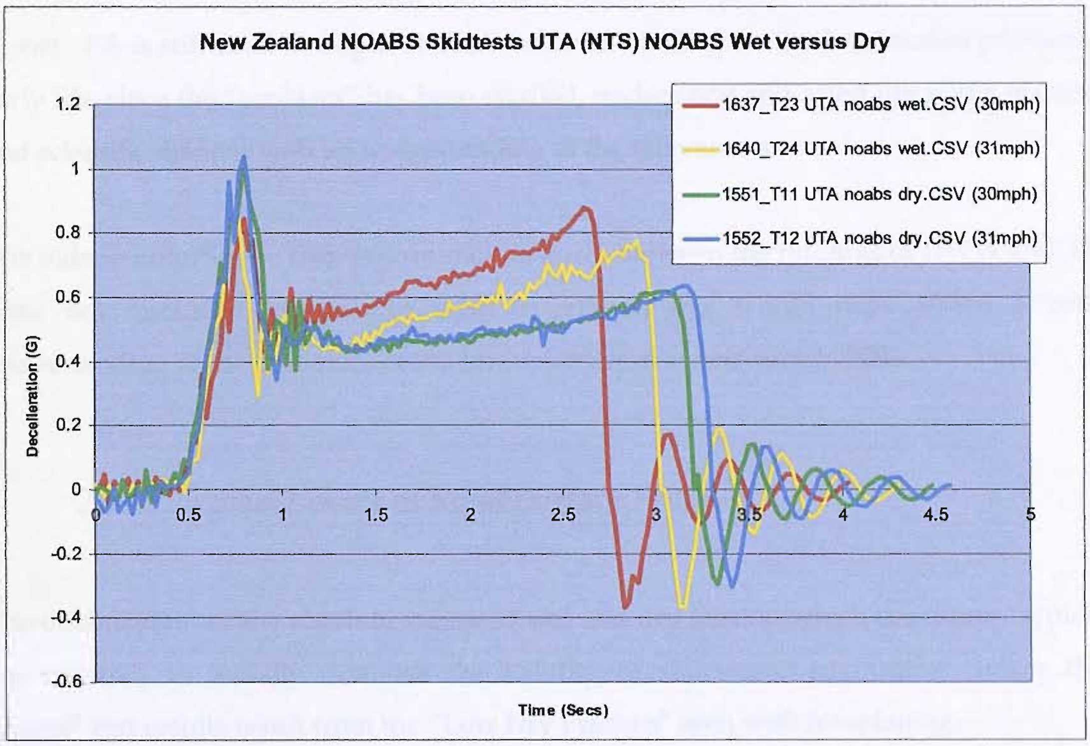


Figure 15 New Zealand: UTA (Ultra thin Asphalt: NTS) comparison on wet versus dry NOABS performance

2.5.10 Earlier work in UK was not cited in the TRL Derbyshire Report

Unfortunately, neither the work by DWW nor Shellshears experiences on the M4 were cited in the TRL interpretation of the low dry friction phenomenon seen in Derbyshire, which because of DWWs investigations could have been termed "bituplaning".

The term "bituplaning" also appear to have been coined by European bitumen specialists Nynas, the term was initially attributed to Nynas by Derk Goos of Nynas (Netherlands) at Tire Technology Expo 2005 in Cologne; however, this claim cannot be easily substantiated.

The findings of DWW, along with other observations on the frictional properties of Porous asphalt had been published in 1997 in the proceedings of a European conference on porous asphalt (PA) (Jutte and Siskens, 1997, van der Zwan et al., 1997, Hernandez and Verburg, 1997, Bonnot, 1997, Swart, 1997). The fact that PA was no longer in common use in the UK by 1997, probably accounted for the lack of reference to these papers in the TRL report. PA is still used throughout The Netherlands. Despite the low friction problem in early life, since the "problem" has been studied, understood and acted upon in a reasoned and scientific manner with an understanding of the relevant issues.

It is indeed unfortunate that the common features between the findings of DWW and TRL were not discussed by TRL in their reports, as this would have added a better understanding of the dynamics of the low dry friction events seen in 2001.

2.5.11 Typical Levels of Road Surface Friction

The qualification of the absolute values of wet and dry friction which constitute "typical" are required to initially establish the validity of statements suggesting "lower than typical" test results result from the "Low Dry Friction" seen with bituplaning.

The following section brings together the results of the literature search in this area.

There exists within every profession or industry, values of performance for processes and services which are to considered "typical": whether they be the time for delivery of a product requested from a mail-order company, the line voltage delivered by a transformer or the response time for a recovery truck despatched to attend a breakdown on the highway. For each of these processes, a failure to delivery a product or service to a level recognised as "typical" can equally be described as "not typical", "atypical" "lower (or less) than normal" or "Higher (or greater) than normal" by those charged with expediting the service.

The definition of "not typical" or "below typical" performance does not require an understanding of the mechanism(s) responsible for the event, and all the observer needs is an understanding of what is considered "typical", to actually define "typical" requires a statistical study, then whether or not the difference between "typical" and "atypical" is significantly different can be established.

Why the "less than typical" event occurs requires a study of the events or characteristics associated with the event that are different to those observed for "typical events".

The routine measurement of road surface friction has historically focussed on the measurement of WET road surface friction. Devices designed to measure WET road friction generally do not measure DRY road friction, this fact is supported by a number of studies undertaken in the development and/or correlation of road surface friction test devices.

This work seeks to establish a range of "acceptable" friction for dry road surfaces in an attempt to formalise the subjective terminology commonly used in the press to describe the lower levels of friction seen on problematic negative textured surfaces.

As has already been observed, a number of works such as that by Shelshear (Shelshear, 1993) and Manderson (Manderson and Rudram, 1993) incorporate suggested limits based on the authors own experience, which, in the case of collision investigators, is experience in measuring dry friction far above that of any highway engineer.

2.5.12 'Typical' WET Road Friction

As already described, the highway engineer is likely to refer to local guidelines detailing in-service requirements for WET friction based on site location. There are a large number of such specifications subject to revision as the understanding of the relationship between road surface macro-texture, wet skidding accidents and high speed wet friction reported on by TRL (Roe et al., 1998, Roe et al., 1991) and others is applied.

In the UK, the requirement for in service wet skidding resistance as determined by the SCRIM device is contained within HD 28/2004 ((Highways Agency, 2003a) commonly known as "The Brown Book" by virtue of the cover colour of its earlier editions).

NCHRP Synthesis 291: Evaluation of Pavement Friction Characteristics: A Synthesis of Highway Practice, National Cooperative Highway Research Program (Henry, 2000) provides a useful overview of the use of friction measurements in network management. Though some of the content may now be out of date, it does give an insight into the application of in-service skid resistance criteria outside of the UK.

2.5.13 Specifications to deliver acceptable levels of wet skidding resistance

To support the routine testing of the wet friction of the Trunk Road network, the performance of the road surfacing aggregates have been specified using tests developed many years earlier. Road surfacing aggregates may vary greatly in their resistance to the polishing action of the tyres passing over them, the Polished Stone Value (PSV) test returns a laboratory controlled measure of this resistance and is now routinely specified for such materials to ensure the road can deliver appropriately high levels of in-service skidding resistance. Likewise, road surfacing aggregates may vary greatly in their resistance to the abrasive action of the tyres passing over them causing a wearing away of the stone chippings). The Aggregate Abrasion Value (AAV) test returns a laboratory controlled measure of this resistance and is now routinely specified for such materials to ensure the road can maintain a suitable high level of macrotexture during its service life.

The effect of different levels of macrotexture required on the road has been researched in the past and has been shown to influence not only wet, but dry road collision levels (Viner et al., 2000, Roe et al., 1998).

2.5.14 The definition of "Typical" WET Road Friction

The definition of low levels of WET road friction are thus made with reference to the wet frictional requirements of a given road networks and as such are related to the classification (possibly a risk rating) applied to a given location, riskier locations require more "grip". Thus, a single value of typical wet friction cannot be suggested without such a number be specific to a given location or set of locations.

To publish a suggested typical value for WET friction without reference to the location of the site can only be described as misleading to those who may choose to use it in investigations without the necessary Highway engineering background.

2.5.15 The Reliability of a Typical WET friction value

As wet friction has been shown to vary in response to the traffic levels and severity of manoeuvres they carry out, a NETWORK WIDE typical value of wet friction cannot be given. Reference has to be made to the variation in wet skidding resistance with the "risk rating" of the general location as this approach in an integral part of the implementation of the "skidding standard".

Thus to quote a "typical" value of wet skidding resistance using this table the "typical value" would need to be qualified by reference to the necessary requirement of the site in question (risk rating etc) and the assumption that the majority of the network possesses levels of wet skidding that satisfy these requirements.

Results of the annual National Road Maintenance Condition Survey (NRMCS, (Anon, 2004)) suggest that a number of sites within each risk rating are likely to be at or below their investigatory level(s). **Figure 16** illustatres this. Combined with the fact that the investigatory levels are a MINIMUM requirement, existing or new surfaces may possess MORE or LESS skidding resistance than is required; this resulting from of over specification of PSV, lower than expected stress or traffic levels OR due to the fact the surfacing aggregate has not yet reached "equilibrium skidding resistance".

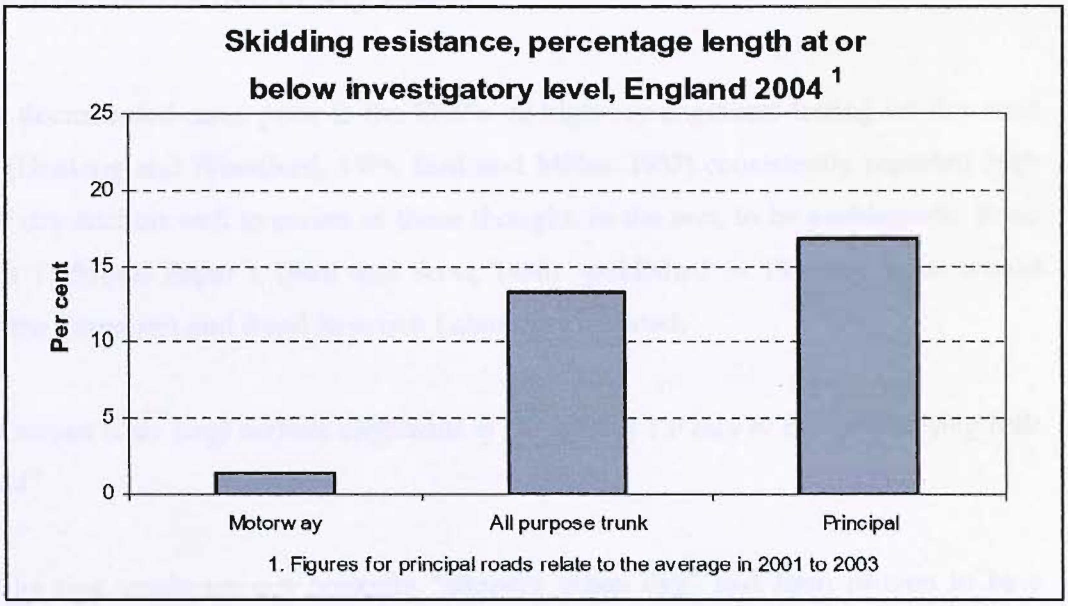


Figure 16 Percentage length of roads in 2001-2003 at or below investigatory level (Anon, 2004)

If laid before 1988 in the case of a Trunk Road, or if laid before the implementation of a Local Authority Skidding Standard, the section will not have had its Polished Stone Value (PSV) specified at time of construction. Without this laboratory-determined measure of how likely an aggregate is to suffer unacceptable polishing under the action of traffic this earlier surfacing is more likely to be delivering skidding resistance at or below the investigatory level. It is also assumed that all sites are correctly classified in terms of their risk rating.

Thus, the requirement for describing a TYPICAL level of WET skidding resistance should practically be replaced with a DESIRED level of skidding resistance for a location based on the National or Local Skidding Standard. The literature within the collision investigation realm frequently list typical values for wet friction, such values should be viewed with some trepidation as they cannot be applied (at least in the UK) without reference to the more rigorously established in-service skidding resistance requirements from local or National standards.

2.5.16 The Friction of Dry Roads

The few documented cases prior to the 1990's of highway engineers testing for dry road friction (Hosking and Woodford, 1976, Bird and Miller, 1937) consistently reported high levels of dry friction well in excess of those thought, in the wet, to be problematic. Road Research Technical Paper 1 (Bird and Scott, 1936) published in 1936 (by what would become the Transport and Road Research Laboratory1) stated:

".... On normal clean (dry) surfaces coefficients of the order of 1.0 may be expected varying little with speed"

This belief that roads are not typically "slippery when dry" had been proven to be a correct one after many years of studying the wet frictional characteristics of surfacing materials such as chipped hot rolled asphalts (HRA) with their 'positive' macrotextures and relatively thin (if any) bituminous coatings on the aggregate particles embedded in them.

The UK Highways Agency's Design Manual for Roads and Bridges (Highways Agency, 2003a) states:

"In practice, it is found that the skid resistance measured on dry, in service road surfaces is generally high, but lower and more variable measurements are obtained when the same road surfaces are wet or damp. For this reason, measurements of skid resistance for the purpose of routine condition monitoring are made on wetted road surfaces."

Thus, highway engineers generally believe that wet, rather than dry, road surfaces deliver the lowest levels of surface friction and highway research has focussed on the effect on safety and vehicle handling of the frictional characteristics of WET roads.

2.5.17 The Definition of 'Typical' DRY Road Friction

The simple definition of low levels of DRY road friction may be made with reference to the literature (predominantly in the realm of the collision investigator) along with consultation with those who typically measure dry friction as part of their work: collision investigators.

Examples of unqualified subjective terminology used by journalists and highway engineers include:

"Lower-than-expected skid resistance" (Silke, 2005)

"Newly laid SMA has lower than expected skid resistance" (Anon, 2001)

These statements do not provide sufficient guidance to those with an interest in quantifying unfamiliar units of measurement of dry friction with ACCEPTABLE levels of the same unit of measurement.

From the highway engineer's perspective, a typical value is only of use if it can be compared with established requirements based on location or other criteria. Only then can "typical" be translated into far more valuable specific guidance, unfortunately there is a lack of literature from the highway engineering domain as regards dry friction measurement; such work, would it be undertaken, would output values in a form more likely to be of value to the highway engineer.

Despite observations made in specific research projects by Dutch workers studying porous asphalt (Fafié, 2004) and UK workers studying thin surfacing (Roe, 2001, Bullas, 2005) there are no guidelines for setting in-service dry friction levels outside of those relating to new porous asphalt in The Netherlands. Minimum deceleration values (Keift, 2000) and more lately minimum levels of locked wheel friction (Veldhuis, 2004) are now in use for dry new porous asphalt in The Netherlands (ZOAB: zeer ofen asphalt beton).

2.5.18 Values for Typical Dry Friction: collision investigation and tyre development sources

The fields of collision investigation and tyre development fortunately provide a wealth of dry friction data which when summarised may suggest a rule of thumb value for dry friction on a road surface. A study of the relevant literature revealed a number of published ranges for typical friction coefficients between tyres and wet or dry road surfaces. On account of the observations already made regarding the fact a single typical level of wet friction is an over simplification, no attempt has been made to made to tabulate the values observed, similarly the dry friction values given in the literature cover a range of surfaces. The figures are therefore presented as an overview since the method of presentation of the data varies greatly:

Bartlett (Bartlett and Fonda, 2003) state average, low high and standard deviations for braking coefficients, Marks (Marks, 2005), Wallingford (Wallingford et al., 1990) and Veith (Veith, 1998) state ranges in speed bands, Fafié (Fafié, 2004) states typical values.

Lambourn (Lambourn, 2004) however provides a useful comparison of the distribution of dry friction values from tests in the UK and Goudie (Goudie et al., 2000) for dry MU values from the US.

Several papers exist that quote collision investigators individual understanding of the term "normal", for example Axup (Axup, 2003) describes f=0.74 as "normal" for a wet surface compared with f=0.45 for a "flushed" surface (equivalent to the UK term "fatted up" to describe a surface dressing where chip embedment or binder migration has produced a smooth surface almost entirely made up of binder). Shelshear (Shelshear, 1986b) and Manderson (Manderson and Rudram, 1993) both suggest values of around 0.7 for dry roads.

A valuable finding of this specific search of the literature was a measure of the magnitude of difference "typically" observed between the peak and sliding levels of friction WITHIN A SINGLE TEST. A number of road and track tests using commercial tyres were carried out by General Motors in 1986 (Ebert, 1989), the data from Tables 1 & 2 of this paper were tabulated and are represented in **Figure 18** , a broad difference can be seen between the values for wet and dry tests at all speeds and loadings. Comparison can be made between this "typical" understanding and values of sliding friction as a percentage of peak for tests undertaken on surfaces under examination in this work.

	Average	SD	Low	High
Dry Peak	0.90	0.069	0.75	1.08
Dry Slide	0.69	0.075	0.45	0.87
Wet Peak	0.65	0.072	0.47	0.81
Wet Slide	0.43	0.065	0.28	0.58

Table 3 Average Braking Coefficients from Bartlett & Fonda (Bartlett and Fonda, 2003)

	Porous asphalt		Dense asphalt	
	New	Old	New	Old
Without ABS	5,4 m/s^2	7,0 m/s^2	7,0 m/s^2	8,0 m/s^2
With ABS	9,0 m/s^2 - 9,5 m/s^2		9,5 m/s^2 - 10,0 m/s^2	

Table 4 Typical deceleration figures for PA and Dense Asphalt from Fafié (Fafié, 2004)

		Typical values of factors @ indicated criticality level	
Factor group	Individual Factor	Low	High
External	1. Speed 2. Pavement Texture 3. Water Depth 4. Traction force demand time [b]	(32-48 k/hr) [a] Mod-High (0.5 mm, or less) Large [> several secs]	90 k/hr, 90+ k/hr Low 1, 1+ mm Small [1-2 seconds]
Tyre	1. Groove void fraction 2. Aspect ratio 3. Hysteresis(tan δ/E') 4. Adhesion (E")	0.30, 0.30+ (75, 78) Texture, speed dependent Texture, speed dependent	0.20 or less 65, 55 Texture, speed dependent Texture, speed dependent
	Dominant lubrication mode:	BL ⇒ BL + EHL ⇒ EHL	

[a] Use of parenthesis indicates that the factor has minimal influence in this criticality region
[b] Time required for emergency manoeuvre

Table 3 Effect of speed and rubber modulus on dry braking traction [a]

	Peak coefficient at k/hr:				Slide coefficient at k/hr:			
	48	64	80		48	64	80	
E* [b]				% change for 48 to 80 k/hr				% change for 48 to 80 k/hr
27.0	0.89	0.90	0.91	2.2	0.62	0.58	0.55	-11.3
16.0	1.01	1.02	1.03	2.0	0.73	0.75	0.77	5.5
11.0	1.06	1.08	1.10	3.8	0.82	0.83	0.84	2.4
% change for 27.0 to 11.0	19.1	20.0	20.9		32.3	43.1	52.7	

[a] for testing on high textured surface S (Appendix 1) from data in Ref. 11
[b] Complex modulus in MPa, at 25°C, 10 Hz with essentially constant tan δ

Table 5 Typical values of slide and peak coefficient for a range of tyre moduli and vehicle speeds from Veith (Veith, 1998) along with other tyre and external factors and when they are influential

DESCRIPTION OF ROAD SURFACE	DRY			
	Less than 30 mph		More than 30 mph	
	From	To	From	To
PORTLAND CEMENT				
New, Sharp	.80	1.20	.70	1.00
Travelled	.60	.80	.60	.75
Traffic Polished	.55	.75	.50	.65
ASPHALT or TAR				
New, Sharp	.80	1.20	.65	1.00
Travelled	.60	.80	.55	.70
Traffic Polished	.55	.75	.45	.65
Excess Tar	.50	.60	.35	.60

Table 3: Coefficients of friction for dry Portland cement and dry asphalt or tar [1].

Table 6 Typical co-efficients of friction for a range of surfaces for two speed ranges from Wallingford et al (Wallingford et al., 1990)

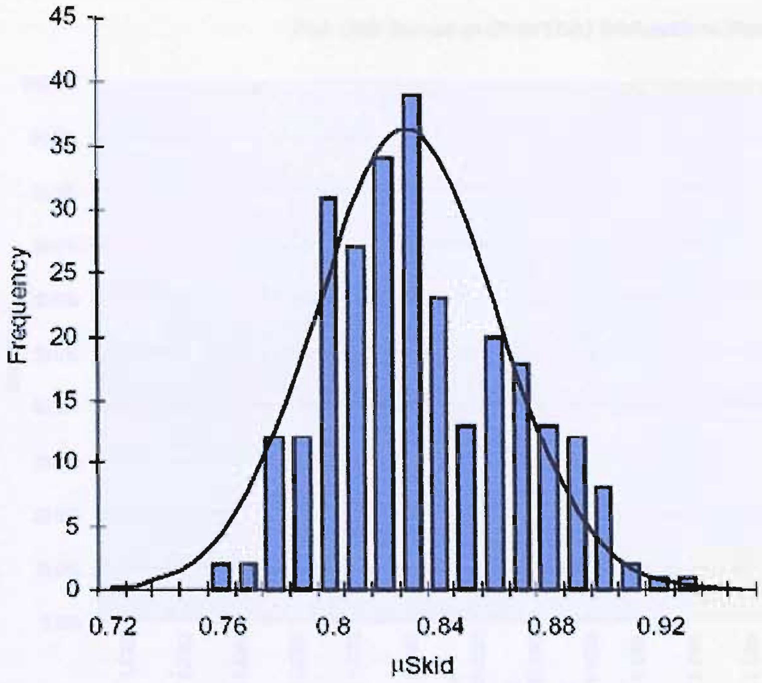
COEFFICIENTS OF FRICTION OF VARIOUS ROADWAY SURFACES								
DESCRIPTION	DRY				WET			
OF	Less than		More than		Less than		More than	
ROAD SURFACE	30 mph		30 mph		30 mph		30 mph	
	From	To	From	To	From	To	From	To
PORTLAND CEMENT								
New, Sharp	.80	1.20	.70	1.00	.50	.80	.40	.75
Travelled	.60	.80	.60	.75	.45	.70	.45	.65
Traffic Polished	.55	75	.50	.65	.45	.65	.45	.60
ASPHALT or TAR								
New, Sharp	.80	1.20	.65	1.00	.50	.80	.45	.75
Travelled	.60	.80	.55	.70	.45	70	.40	.65
Traffic Polished	.55	.75	.45	.65	.45	65	40	.60
Excess Tar	.50	.60	.35	.60	.30	60	.25	.55
GRAVEL								
Packed, Oiled	.55	85	.50	.80	.40	.80	40	.60
Loose	40	.70	.40	.70	.45	.75	.45	.75
CINDERS								
Packed	.50	.70	.50	.70	.65	.75	.65	.75
ROCK								
Crushed	.55	.75	.55	.75	.55	.75	.55	.75
ICE								
Smooth	.10	25	07	.20	.05	.10	.05	.10
SNOW								
Packed	.30	.55	.35	.55	.30	.60	.30	.60
Loose	.10	.25	.10	.20	.30	.60	.30	.60

Reproduced from: Baker, J.S., Traffic Accident Investigation Manual, The Traffic Institute, Northwestern University, 1975

Average Sliding and Peak Friction Coefficients For Passenger Car Tires		
Surface Condition	Sliding Friction	Peak Friction
Concrete/Asphalt, polished to new, dry	0.65 – 0.90	0.80 – 1.00
Concrete/Asphalt, polished to new, wet	0.45 – 0.70	0.60 – 0.75
Gravel, loose to packed	0.40 – 0.70	---
Gravel, some grass	0.35 – 0.40	0.40 – 0.50
Meadow, wet	0.15 – 0.20	0.20 – 0.25
Meadow, dry, firm, short grass	0.35	0.45
Off-road shoulder, firm dry	0.35	0.45
Soil, loose, moist, Tires sink down appr. 2 in.	0.60	0.70
Asphalt, wet leaves	0.60	0.70
Road, snow covered	0.30	0.30
Ice	0.15	0.15
Mud on wet pavement	0.2 – 0.3	—
Diesel fuel on wet asphalt	0.25 – 0.3	—
Diesel fuel on wet, polished asphalt	0.05 – 0.12	---

Reproduced from: Motor Vehicle Accident Reconstruction and Cause Analysis. 5th Edition. Rudolf Limpert

Table 7 Typical co-efficients of friction for a range of surfaces of various types and states (wet or dry) along with average sliding and peak friction levels on a range of surfaces from Marks (Marks, 2005)



Distribution of μSkid values for all three tire sets under dry road conditions with a superimposed normal distribution (0.828 ± 0.033).

Figure 17 Distribution of dry Mu skid values (Goudie et al., 2000)

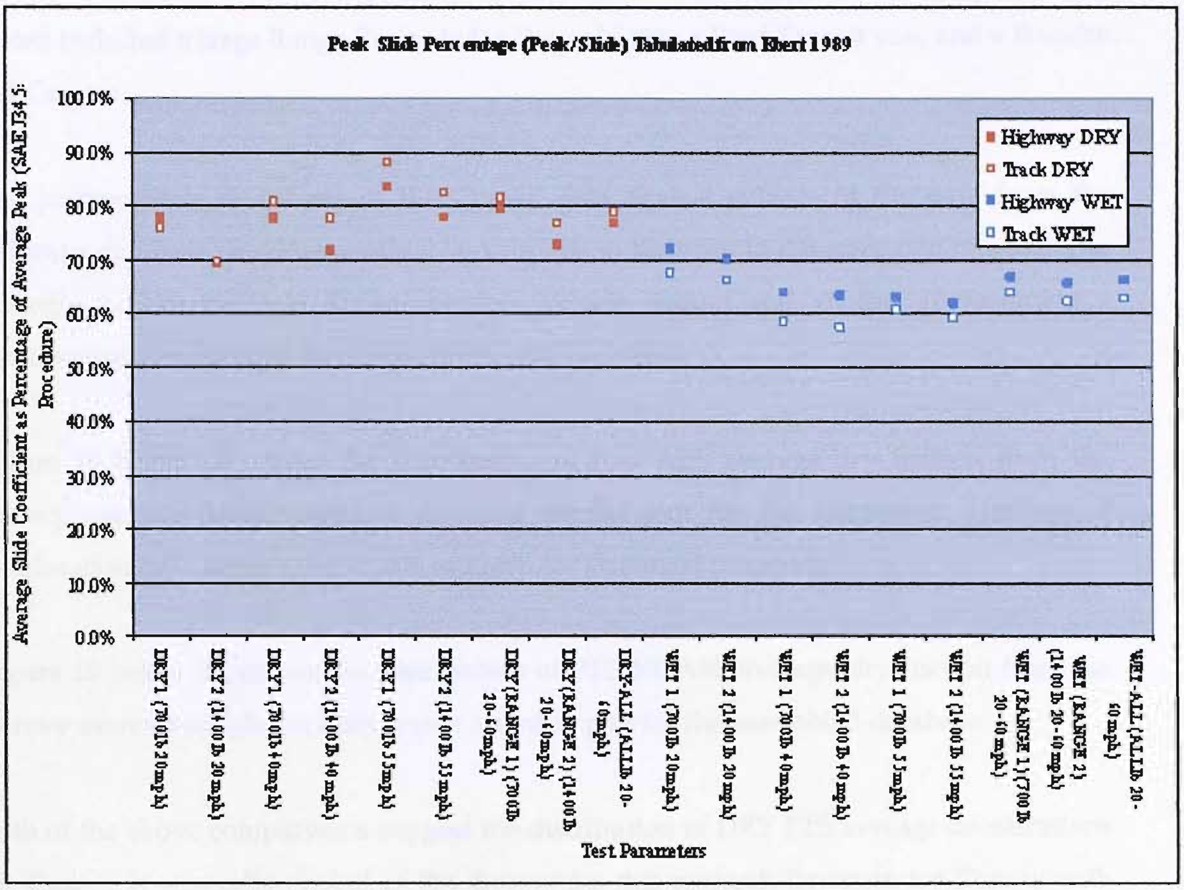


Figure 18 Data Tabulated from Ebert (Ebert, 1989)

2.5.19 A UK Based Dry Friction Benchmark Exercise

An exercise undertaken at Conwy on the 22nd of April 2006 provided a valuable local benchmark for DRY PTS performance. Twenty vehicles (cars, 4x4's and MPVs) were impounded by North Wales Police under their legal powers of seizure, the vehicles were tested for safety and repeatedly skid tested on a closed length of well textured old HRA (the classic NTS). Specific details of the vehicles tested and more detailed test data is provided in Appendix 1.

The data collection exercise was being undertaken by Constable Diane Mann of the North Wales Police as part of an MSc dissertation and the author was kindly invited to participate and share the data in return for the provision of test equipment. The vehicle tested included a large Range Rover 4x4, a Rover Metro, a Ford Transit van, and a Porsche 911 Carerra.

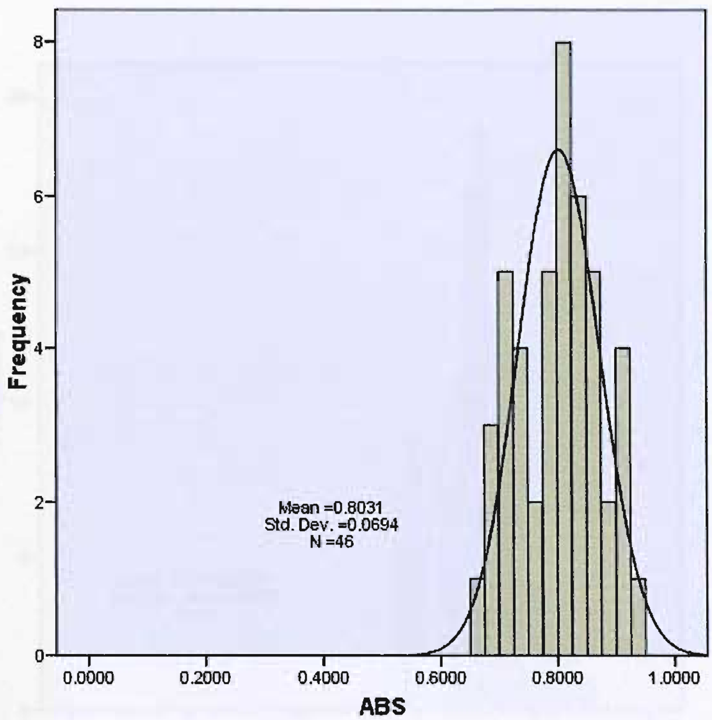
The juxtaposition of subsets of the Conwy data against subsets of the data from the Skidman database provides a valuable comparison between to datasets: one representing a single surface multiple device multiple vehicle dataset and another representing a multiple surface multiple device multiple vehicle dataset.

Figure 19 below illustrates the distribution of PTS ABS average dry friction from the Conwy exercise (single surface) versus a similar plot for the assembled database of deceleration time series used in this research for statistical purposes.

Figure 20 below illustrates the distribution of PTS NOABS average dry friction from the Conwy exercise (single surface) versus a similar plot for the assembled database.

Both of the above comparisons suggest the distribution of DRY PTS average decelerations for Conwy is generally typical of the dataset for this research however for Conwy with one surface tested; the variation is directly attributable to variations between the testing vehicles and devices rather than differences in the dry friction. (Ebert, 1989) presented a distribution of dry sliding values friction, this has also been reproduced in Figure 21 and in Figure 22 juxtaposed against the equivalent plot for the Conwy data (single surface) and the database respectively.

The above comparisons suggest the distribution of DRY PTS average decelerations for Conwy and the research database is generally lower than the average dry friction reported by Ebert and similar to that reported for the South East of England by Lambourn (Lambourn, 2004).



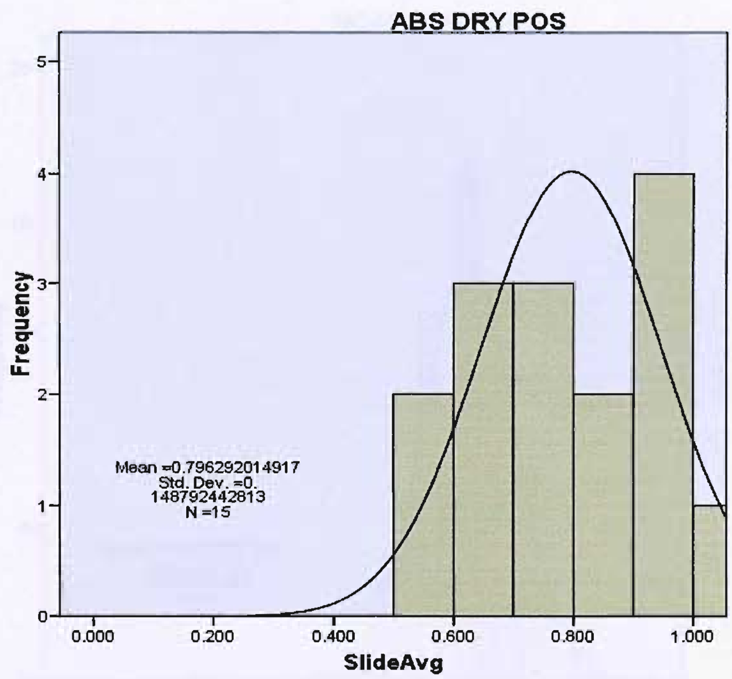


Figure 19 Top: Conwy (single surface) ABS DRY POS versus Bottom: Database ABS DRY POS

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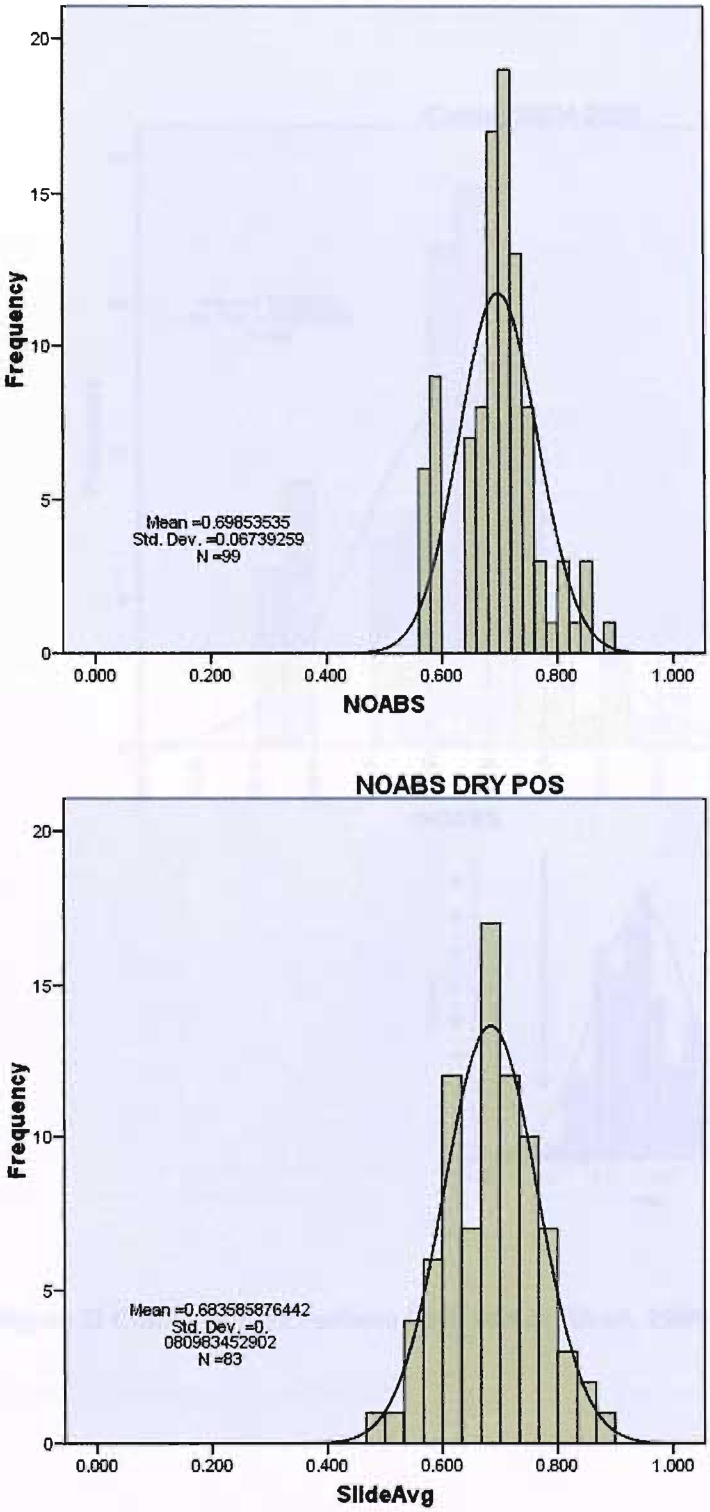

Figure 20 Top: Conwy (single surface) NOABS DRY POS versus Bottom: Database NOABS DRY POS

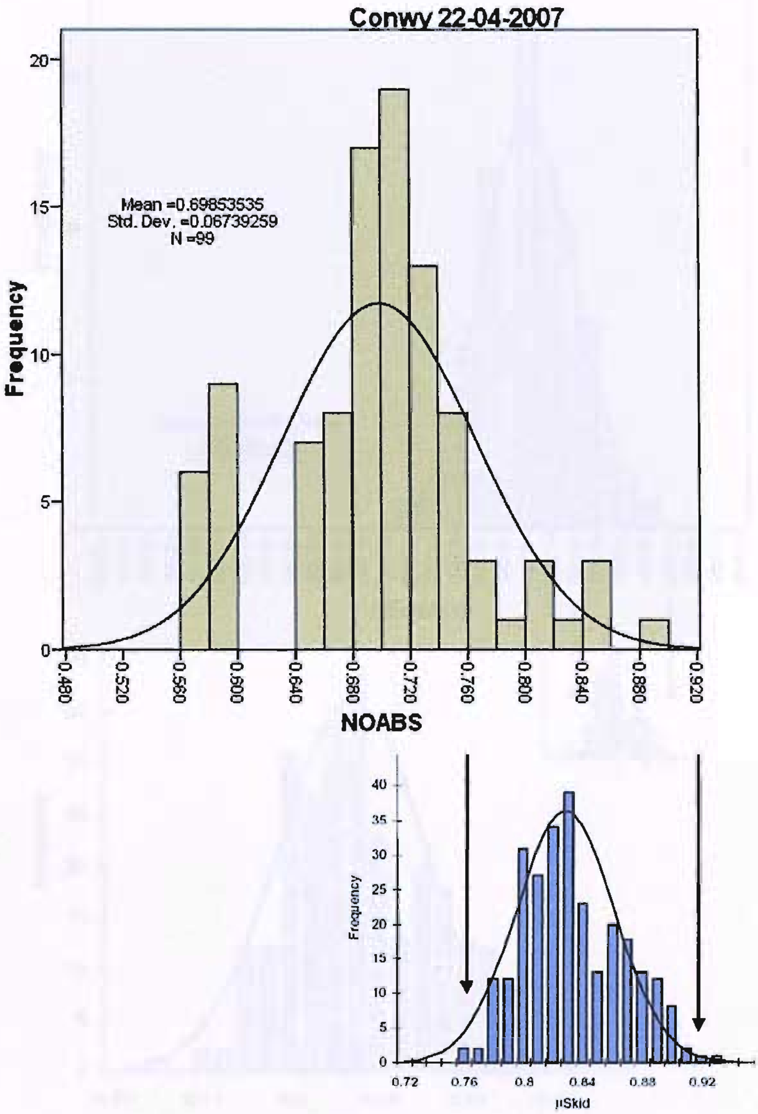

Figure 21 Conwy (single Surface) (top) versus (Ebert, 1989)(bottom)

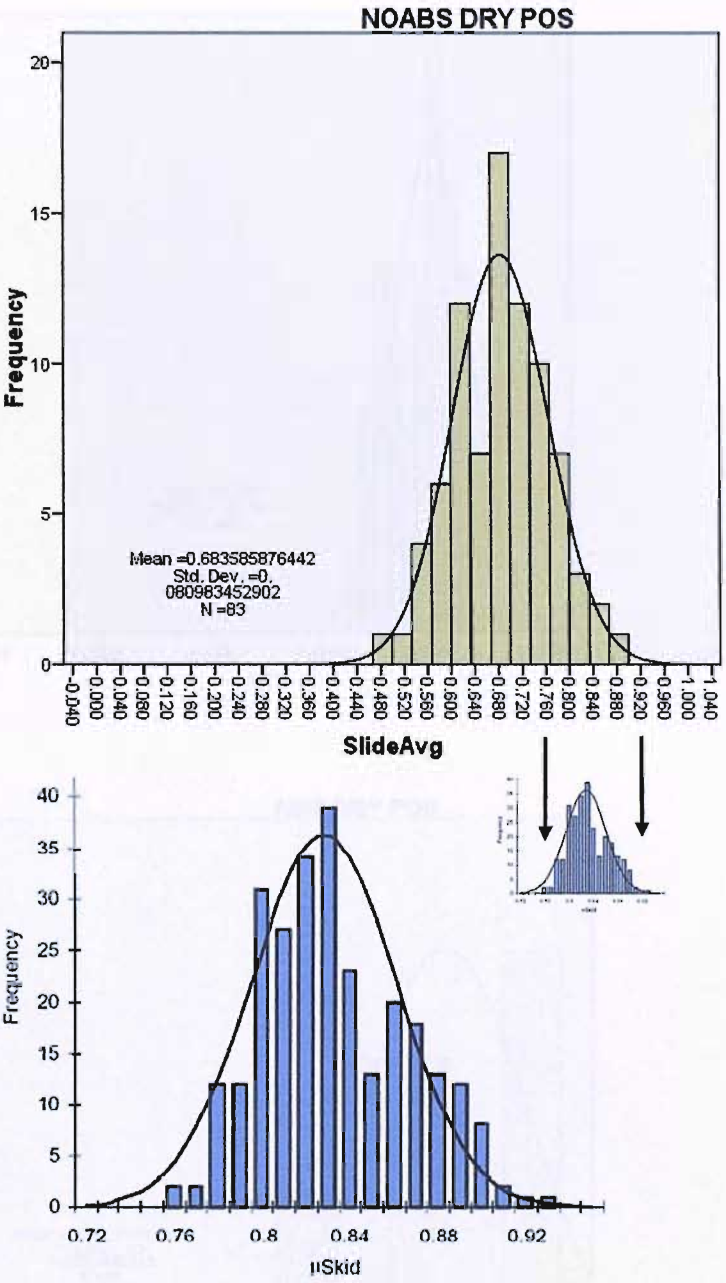

Figure 22 Database NOABS DRY POS (top) with Ebert juxtaposed versus (Ebert, 1989) (bottom).

2.5.20 The Reliability of a value for typical DRY road friction

When DRY friction is discussed, The uninformed Highway engineer is more likely to say "only wet roads are slippery", whereas the collision investigator calls on his or her years of testing dry roads with Skidman, chalk gun or drag sled (Hawthorne, 2000) testing devices. The range of values for typical dry friction observed in the literature, and described later also appear to suggest it is possible for a wide range of values to be encountered in relation the road surface conditions. Road surface conditions are commonly described in the literature as new, worn, polished etc. and as such the validity of a typical value of dry friction probably cannot be given any more value than a typical value for the wet other than the magnitude of values appears generally greater and the range of values commonly appears smaller.

Work by Lambourn (Lambourn, 2004) and Goudie (Goudie et al., 2000) give distributions for typical values of dry friction may be of use to collision investigators but fails to associate any range of values with specific surface conditions, however both Wallingford (Wallingford et al., 1990) and Marks (Marks, 2005) qualify their observations making the values stated far greater in significance.

2.5.21 Typical Wet Road Friction Values versus Typical Dry Road Friction Values

General reference to the figures above appears to confirm that the levels of DRY friction encountered during bituplaning events in the literature (generally below 0.50 Mu) appear to fall within the ranges of typical values of WET sliding friction stated in the literature, this issue has been highlighted by past workers (Manderson and Rudram, 1993, Roe, 2001) .

2.6 Material Interactions at the tyre/road interface

This section contributes towards addressing Question 4 in Section 1.4: What was the likely mechanism (or mechanisms) responsible for the generation of the low levels of dry friction observed on certain NTS surfaces?

An essential element of the understanding of the low dry friction phenomenon is an overview of the behaviour of the materials that interact at the tyre/road interface, in the case of a bituminous road surface where a film of bitumen (the "mastic") coats the rock aggregate at the tyre/road interface. This includes the behaviour of the bituminous mastic itself when exposed to the action of a loaded tyre passing over it.

Specific areas of interest exist encompassing the elements of the tyre/road interaction are:

- The mechanical elements of the tyre/road interface. The road aggregate, along with the bituminous materials (materials that may act as an intermediate layer between the tyre and aggregate).

- The methods by which the interaction between tyre and road stone (and potentially the intermediate bituminous material) are either modelled or measured in practice.

The following sections represent a synthesis of a number of limited literature reviews to provide the researcher with a basic understanding of the major processes in operation during the tyre/road interaction as relevant to the simulated emergency braking manoeuvres undertaken in the research testing described elsewhere in this work.

2.6.1 The generation of Friction between the tyre and the road

Evidence has been established from the analysis of results from the experimental work undertaken in this research that statistically substantiate the claim that the 'bituplaning' DRY NOABS behaviour of NTS surfaces is significantly different to that of DRY NOABS PTS surfaces. The ability to provide possible mechanisms for the bituplaning phenomenon requires an understanding of the basic mechanisms whereby friction is generated between tyre and road. The following text is taken from: http: //en.wikipedia.org/ wiki/Coefficient_of_friction and summarises the key frictional principles.

"The resistance to lateral motion when one attempts to slide the surface of one object over another surface is called friction or traction. The force of friction depends on the normal force, which is the force pressing the two surfaces together. It also depends on the types of materials from which the surfaces are formed--some materials are more slippery than others are.

- *The **coefficient of friction** is a measure of the slipperiness between two surfaces: the larger the coefficient of friction, the less slippery the surfaces. For example, pulling a heavy wooden block (large normal force) across the floor requires more force than does pulling a light one (small normal force); and pulling the wooden block along on a surface of rubber (large coefficient of friction) requires more force than pulling the same block along on a surface of ice (small coefficient of friction).*

- ***Static friction and kinetic friction:** For a given pair of surfaces, there are two types of friction coefficient. The coefficient of static friction, μs, applies when the surfaces are at rest with respect to one another, while the coefficient of kinetic friction, μk, applies when one surface is sliding across the other.*

- *The **maximum possible friction force(F max)** between two surfaces before sliding begins is the product of the coefficient of static friction and the normal force:*

Fmax = μsN.

μs= Static Friction, N = Normal force

It is important to realize that when sliding is not occurring, the friction force can have any value from zero up to Fmax. Any force smaller than Fmax attempting to slide one surface over the other will be opposed by a frictional force of equal magnitude and opposite direction. ***Any force larger than Fmax will overcome friction and cause sliding to occur.***

- ***Sliding Friction (Fs)***

When one surface is sliding over the other, the friction force between them is always the same, and is given by the product of the coefficient of kinetic friction and the normal force:

Fs = μkN.

μk= Kinetic Friction, N = Normal force

The coefficient of static friction is larger than the coefficient of kinetic friction*: it takes more force to make surfaces start sliding over each other than it does to keep them sliding once started.*

These empirical relationships are only approximations: they do not hold exactly. For example, the friction between surfaces sliding over each other may depend to some extent on the contact area, or on the sliding velocity. The friction force is electromagnetic in origin: atoms of one surface "stick" to atoms of the other briefly before snapping apart, causing atomic vibrations, and thus transforming the work needed to maintain the sliding into heat. However, despite the complexity of the fundamental physics behind friction, the relationships are accurate enough to be useful in many applications.

- ***The normal force (N)***

If an object is on a level surface and the force tending to cause it to slide is horizontal, the normal force N between the object and the surface is just its weight, which is equal to its mass multiplied by the acceleration due to earth's gravity, g. If the object is on a tilted surface such as an inclined plane, the normal force is less because less of the force of gravity is perpendicular to the face of the *plane. Therefore, the normal force, and ultimately the frictional force, is determined using vector analysis, usually via a free body diagram. Depending on the situation, the calculation of the normal force may include forces other than gravity.*

In the case of a road vehicle driving on pneumatic tyres, *the generation of friction between the tyre and the road surface is essential to enable the vehicle to manoeuvre, accelerate and brake in a controlled fashion.*

The force of friction arises from the interaction of two surfaces. The direction of the frictional force lies in the plane of the two surfaces and always opposes the direction of motion (kinetic friction) or attempted motion (static friction).

Thus, a common parameter to consider when studying the frictional interaction between surfaces is the surface friction co-efficient also expressed as Mu or the Greek symbol of the same name: μ

- **Tyre/road friction**

The interaction between tyre and road surface is a complex one as the tyre can deform and the coefficient of friction (μ) between tyre and road can exceed 1.0 when the tyre is in contact with a clean hard surface (Bird and Scott, 1936), conversely , μ can approach zero on ice near 0°c (Veith, 1998).

As a road vehicle relies on the friction developed between tyre and road to enable the safe completion of braking, acceleration or other manoeuvres, a relationship between the low coefficient of friction of road surfaces and the increased risk of accidents was soon established.

Investigations into the frictional properties of road surfaces date back to the early 1930s (Bird and Miller, 1937, Bird and Scott, 1936) with reference being made to a link between low values of wet μ and accident black spots as early as 1956 ((Hosking, 1992). Minimum levels of skidding resistance for Trunk Roads (as determined using the SCRIM device) being introduced into the UK in 1988 (Rogers and Gargett, 1991).

2.6.2 The Friction Generated between Tyre and Road

- General Friction Modelling

On close examination, the road is a highly irregular surface even at high magnification. This makes it difficult to model accurately the road surface in terms of its interaction with the tyre. The literature includes a number of relevant works from outside of tyre/rubber/highways industries but their effective transfer from the uniform laboratory test specimen to the real world of real road surfaces may not be a simple one.

The estimation, calculation, and understanding of friction between sliding and rotating bodies are as important in industry as it is in the study of the tyre/road interaction. However a comprehensive review of this area was unnecessary as the physics and mathematical modelling used were beyond the scope of this work and the subject of many studies was not relevant to the tyre/road interface problem. However, as the area of study of this work relates to a phenomenon whereby a relatively rigid surface (the dry road) is separated from a flexible one (the tyre) by a thin layer (the bitumen/mastic which may contain fibres and/or polymers); research examining the frictional properties of thin films, polymers and dry friction in isolation were investigated separately.

By means of an example, research undertaken by Linck et al (Linck et al., 2005), describes the finite element analysis of a contact with friction between an elastic body and a thin soft layer (on a scale of approximately 10μm). Work such as this could offer potential applications to the task of modelling the behaviour of the thin bituminous layer between tyre and road surface aggregate thought to be approximately the same thickness (Richardson, 1999).

2.6.3 Modelling and Measuring the Friction Generated between Tyres and the Road

A number of models exist which attempt to rationalise the generation of the friction developed between the tyre and the road. The environment of the tyre/road interface is both dynamic and complex and assumption and simplification are commonly employed to assist in its modelling.

Veith and Williams

Veith (Veith, 1983, Veith, 1998) subdivided the tyre/road contact in the wet into three zones:

Squeeze film Lubricated Contact (Hydroplaning)
Elasto- hydrodynamic Lubricated Frictional Contact
Boundary Layer Lubricated Frictional Contact

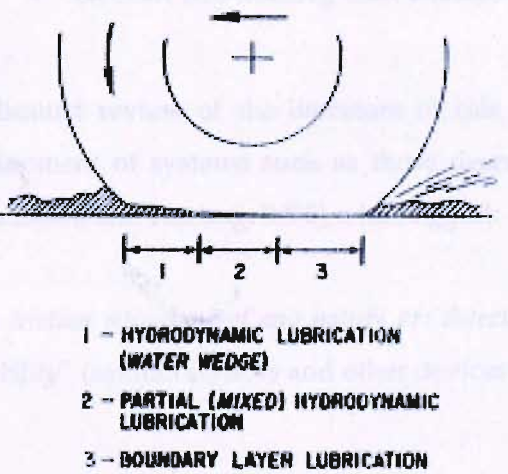

FIG. 6—Three-zone concept

Figure 23 The Three Zones (Veith, 1998)

The role of the level of macrotexture and/or tyre tread depth in improving wet tyre adhesion was also noted by Veith. This has been supported by workers such as Mancosu et al ((Mancosu et al., 2000) and Roe, Cenek and Viner ((Cenek et al., 2005, Roe et al., 1998, Viner et al., 2000)

The form of the Figure shown above may also be valid when a mobile bitumen film (rather than a water film) exists between tyre and road: Williams (Williams, 1992) rationalised Veiths model in terms of the water flow and water film thicknesses present between tyre and road with rolling and locked tyres (Figure 31 & Figure 32), effectively , illustrating the marked change in the characteristics of the behaviour of the water film between tyre and road when a tyre locks having previously been rolling. Heubner et al (Huebner et al., 1997) working in the civil engineering domain developed a predictive model for water film thickness and potential for hydroplaning independent of tyre characteristics. The flow dynamics observed in Williams may also be relevant when a mobile bitumen film (rather than a water film) exists between tyre and road because of some process reducing its viscosity.

- Recent Modelling and Measurement of the tyre/road interaction

The limited review of the literature in this area has attempted to review the ongoing development of systems such as those described (**Figure 24**) by Kendziorra & Harting (Kendziorra and Harting, 2005) who suggest:

"Low friction situations of any nature are detectable by the side slip detection system with high probability" (rainfall sensors and other devices were also part of the system).

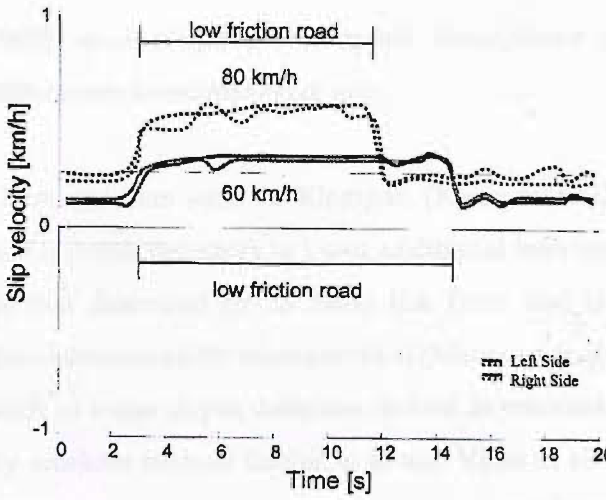

Figure 24 Low Friction Detection (Kendziorra and Harting, 2005)

With the increasing adoption of ever more complex suspension and braking control systems since the introduction of ABS in the last quarter of the 20th Century, there has been a need to provide such systems with an accurate model of the frictional properties of the road surfaces they are traversing to ensure that wheel lock is addressed or prevented.

Other recent developments in the area of ABS system development include the dynamic modelling of tyre friction. Velenis (Velenis et al., 2005), Gustafsson (Gustafsson et al., 2003) analysed wheel slip and torque data from instruments on the vehicle and compared it with classic tyre models to estimate road friction. Gou (Guo et al., 2005) appears to have established a typical tyre rubber behaviours using a simulation model fed with laboratory friction test data.

Research has also extended into the creation of monitoring and control technologies (such as that developed by Saito et al (Saito et al., 2004) to prevent drivers exceeding the frictional constraints of slippery roads. Low friction conditions can already be dynamically detected using wheel rotation sensors as illustrated in Kendziorra & Harting (Kendziorra and Harting, 2005) however this type of system may not warn of a low friction level resulting from the braking manoeuvre itself (as in the case of "bituplaning") only of low friction encountered during passage over a surface. Kanekawa et al (Kanekawa et al.,

2005) used single wheel speed fluctuations rather than between wheel rotational differences to estimate tyre grip.

Other workers such as Klempau (Klempau, 2001, Kanekawa et al., 2005) have utilised water depth detectors to input additional information into friction prediction models such as that described by La Torre (La Torre and Domenichini, 2001). Tyre models such as those developed by Mancuso et al (Mancuso et al., 2001) equally accept input from sensors such as water depth detectors to feed in relevant parameters shown to influence tyre grip by workers such as Gothié et al and Viner et al, (Gothié et al., 2001, Viner et al., 2000). A macrotexture measurement device for input into vehicle dynamics systems was known to be under development by The Ford Motor Company as early as 1999 (Reff, 1999b, Reff, 1999a).

The tyre industry has responded to the increasing number of potential inputs in to tyre predictive modelling by investigating the potential for simplified but still broadly effective models of tyre cornering and braking behaviour based on a few standard tests, since testing large tyres is expensive and testing facilities are rare (Schuring et al., 1996). Real time frictional measurement is also a desirable ability in manufacturing applications and the work undertaken in this area by workers such as Ramasubramanian & Jackson (Ramasubramanian and Jackson, 2003) though not directly applicable to the tyre/road interface at this time may contribute to this arena in the future.

Though complex in nature, the work carried out by Vacherand and Robert (Vacherand and Robert, 2005) at the nano-roughness scale of surfaces provides a useful concept to be applied to the low dry friction "bituplaning" phenomenon. They describe the manner in which the tyre/road contact can de-wet by nucleation and growth of a dry patch, this de-wetting phenomenon may be suppressed for NTS surfaces where:

1. Points of nucleation in the contact patch are masked by remnant binder/mastic

and/or

2. Fewer potential nucleation points exist by virtue a "face-up" rather than "edge up" alignment of the aggregate particles dominating the contact patch (NTS surfaces typically exhibit this face-up morphology).

- This work is particularly relevant to the environment between tyre and road surface on a DRY NTS surface. Here the fine micro texture of the coarse aggregate in the mixture is inferred to be completely or partially masked by the bituminous mastic, such a binder film may well perform the same role as Vacherand and Robert's water film in preventing the development of what would otherwise be a dry patch between unmasked aggregate and tyre rubber.

- The work of Persson (Persson et al., 2005, Persson et al., 2004b, Persson et al., 2004a) (summarised by Weiss ((Weiss, 2004)) opens up another area of potential application of wet friction theory to the low dry friction phenomenon where again the role of water in sealing the texture of the aggregate from the tyre (**Figure 27**) may be taken by the bituminous film (though potentially in a form far more resistant to displacement by the tyre).

- Despite the increasing complexity of the models used in ABS braking, at least in the tests documented in this research, the systems in place for cannot prevent the development of wheel slip of a magnitude that can not only be observed in deceleration time series but also in the manifestation of atypically noticeable ABS skid marks (dashes).

2.6.4 The Important Balance between Hysteresis and Adhesion

It is most important to observe that two of the fundamental processes responsible for the generation of friction between tyre and road are not uniformly represented as the speed between the tyre and the road surface increases (as would occur over an extended period during a skid or momentarily when slip occurs and is reduced as an ABS system operates) .

The two frictional forces, Hysteresis and Adhesion are generated in two very different ways:

1) Adhesion friction is generated by the establishment of chemical bonds between the rubber in the tyres of the vehicle and the immediate surface of the aggregate in the road surfacing that directly interfaces with the tyre (known as its microtexture). On dry road surfaces, adhesion is by far the greater component in tyre-road friction. However, in wet conditions (or where the surface of the aggregate interfacing with the tyre is smooth or polished); the adhesion component decreases, and can tend towards zero.

2) Hysteresis generated friction is caused by the deformation of the tyre by the projections of the road surface (known as its profile or macrotexture); this allows dissipation of heat and energy into the tyre and the road surface.

- In the case of NTS surfaces the macrotexture appears to generate less VISIBLE movement of the tyre during locked wheel braking (as determined by examination of high-speed video footage from the A428 Madingley trial, (See Chapter 3.5.2 and linked video footage).

NTS surfaces may generate less grip from hysteresis than PTS surfaces and more reliance being placed on the adhesion component of friction, Williams (Williams et al., 1976) very effectively illustrates the lack of hysteresis between tyre and road on a tyre passing over a smooth glass plate (adhesion will also be reduced by the presence of the water film).

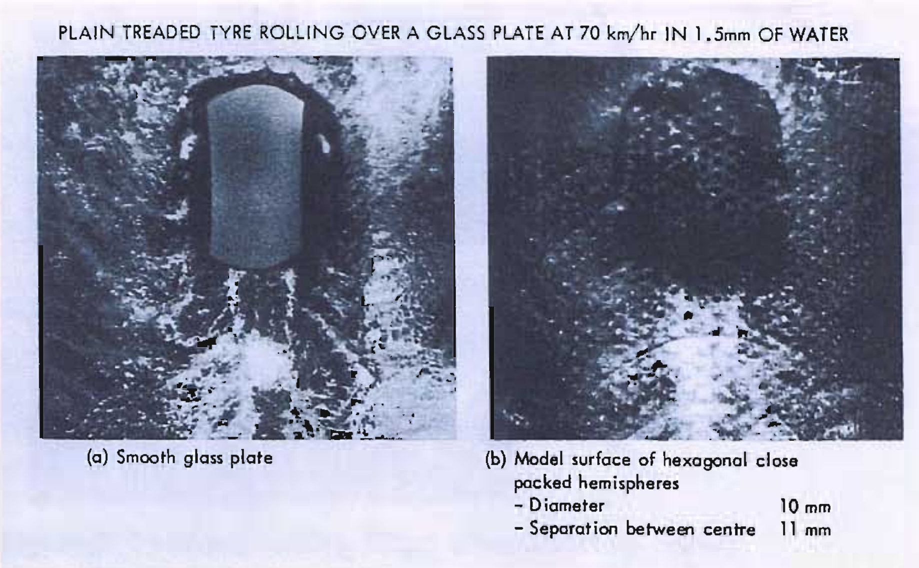

Figure 25 Effect of a model surface on water dispersal (Williams et al., 1976)

If an intermediate layer prevented contact of the tyre rubber with the road stone chipping (in a manner similar to how a water film might do), there is a likelihood that the adhesion component (compromised by the speed of passage of the tyre over the road surface) would not be offset against the increase in hysteresis with speed typically observed (Figure 26). Hysteresis has been noted as decreasing with temperature so with increasing temperature AND decreasing speed the point of lowest total friction may represent a complex interplay of tyre versus road speed and temperature.

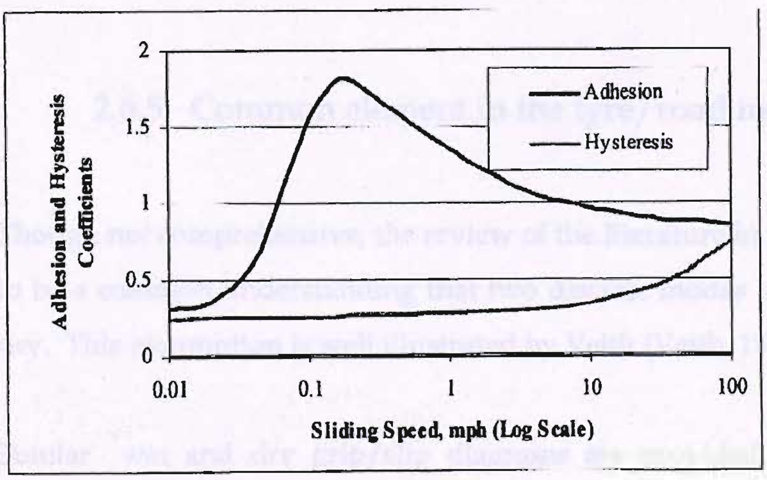

Figure 26 The influence of sliding speed on Adhesion and Hysteresis (Li et al., 2003)

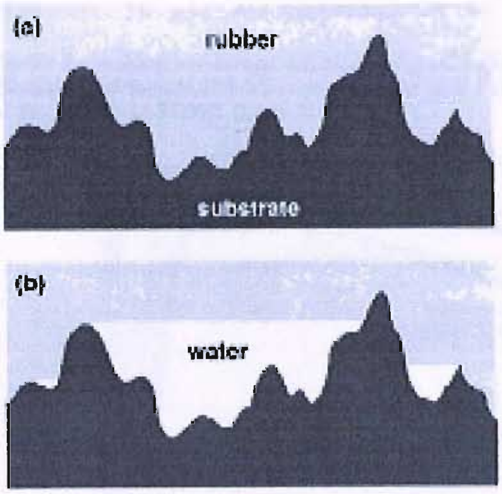

Figure 27 Perssons sealing Effect (Persson et al., 2004a)

Thus the role of the thin layer of water resulting in the "sealing effect" (Persson et al., 2005) on the texture of the wet road surface (Figure 27) may well be able to be replaced wholly or in part by the binder film present in low friction on dry NTS surfacing.

Friction between tyre rubber and ice represents another unique model to consider Gou et al (Guo et al., 2005) identified atypical behaviours of the tyre rubber when in contact with ice. There may be some similarity between the plane of low friction developed between ice and tyre and that developed between tyre and NTS at the friction minima.

2.6.5 Common element in the tyre/road interaction modelling

Though not comprehensive, the review of the literature in this area suggests there appears to be a common understanding that two discrete modes of behaviour exist: either wet or dry. This assumption is well illustrated by Veith (Veith, 1998) in Figure 28.

Similar wet and dry grip/slip diagrams are provided in other works such as those by(Kendziorra and Harting, 2005), Kulakowski et al (Kulakowski et al., 1992) and Delanne et al (Delanne et al., 2001) in Figure 29

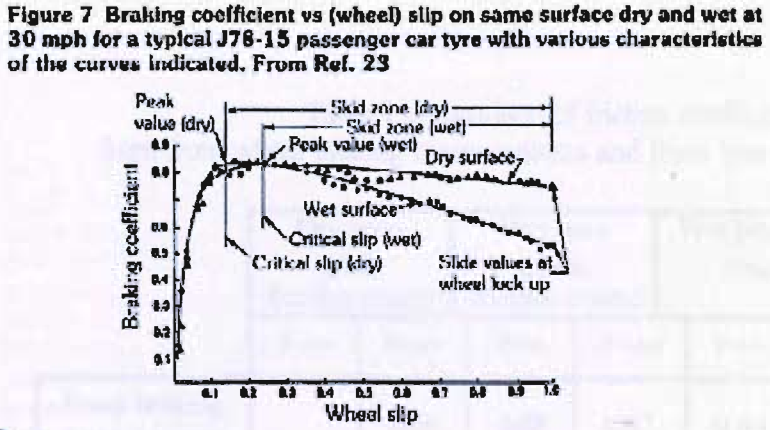

Figure 28 Braking co-efft. Versus Wheel Slip (Veith, 1998)

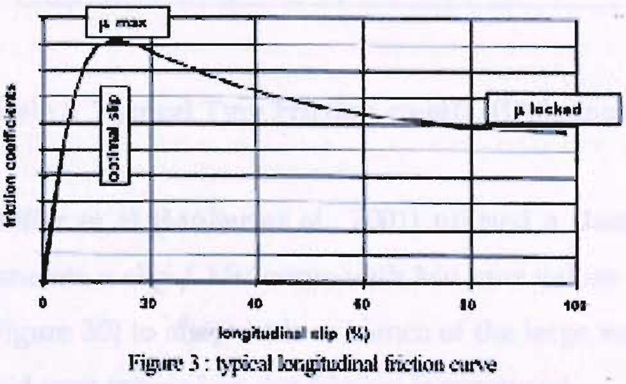

Figure 29 Friction co-efficients versus longitudinal slip (Delanne et al., 2001)

Table 1 comparison of friction coefficient obtained
from front wheel braking measurements and from tyre manufacturer measurements

	Dry open grade friction course		Wet open grade friction course		Wet bituminous concrete		Wet polished bituminous concrete	
	μ_{max}	μ_{locked}	μ_{max}	μ_{locked}	μ_{max}	μ_{locked}	μ_{max}	μ_{locked}
Front braking measurements		0,69	0,88	0,67	0,84	0,60	0,51	0,43
Tyre manufacturer Measurements	1,02	0,75	0,92	0,69	0,87	0,64	0,55	0,39

Table 8 Typical Tyre Friction co-efts. (Delanne et al., 2001)

Műller et al (Műller et al., 2001) utilised a standard tyre model (Bakker et al., 1995) to generate a slip / Mu curve with Mu max values of 0.9 and 0.65, these curves can be seen (Figure 30) to show little evidence of the large magnitude changes in MU observed in dry skid tests where low dry friction is measured.

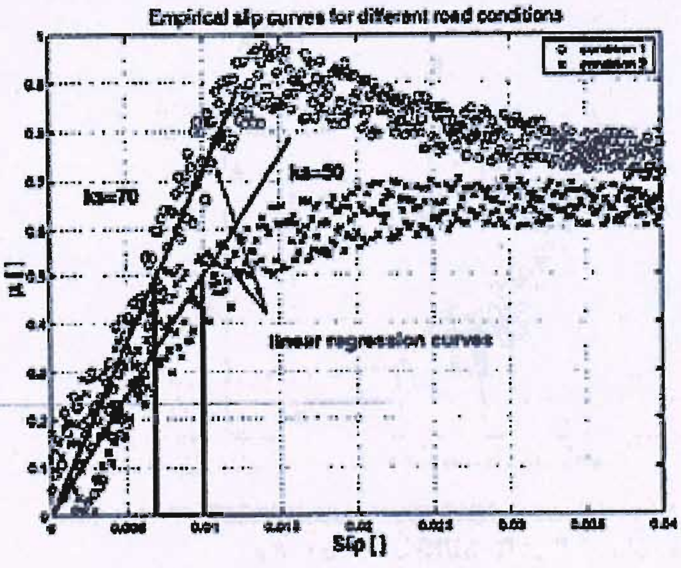

Figure 30 Slip/Mu curves (Műller et al., 2001)

Delanne et al also includes a table providing typical dry friction coefficients (Table 8) which again are atypical of those obtained for thick film NTS surfaces.

Műller et al (Műller et al., 2001, Műller et al., 2003) investigated the estimation of maximum levels of tire road friction and compared the various values for the slope of the linear part of dry-road slip curves from the literature against their own findings. Comparison of similar results from a comprehensive study of dry NTS materials would be a valuable exercise.

Tyre-road friction models are commonly utilised in the simulation of braking control systems. One such modelling exercise was undertaken by Alvarez et al (Alvarez et al., 2005), if the behaviour of NTS surfaces does not follow these models there may be opportunities for wheel lock to occur over and above the momentary deceleration that may occur prior to ABS activation. Tyre-road friction models are commonly utilised in the simulation of braking control systems. One such modelling exercise was undertaken by Alvarez et al (Alvarez et al., 2005).

- If these tyre/friction ABS models are found ultimately not to accommodate the bituplaning phenomenon, there may be a need to review them.

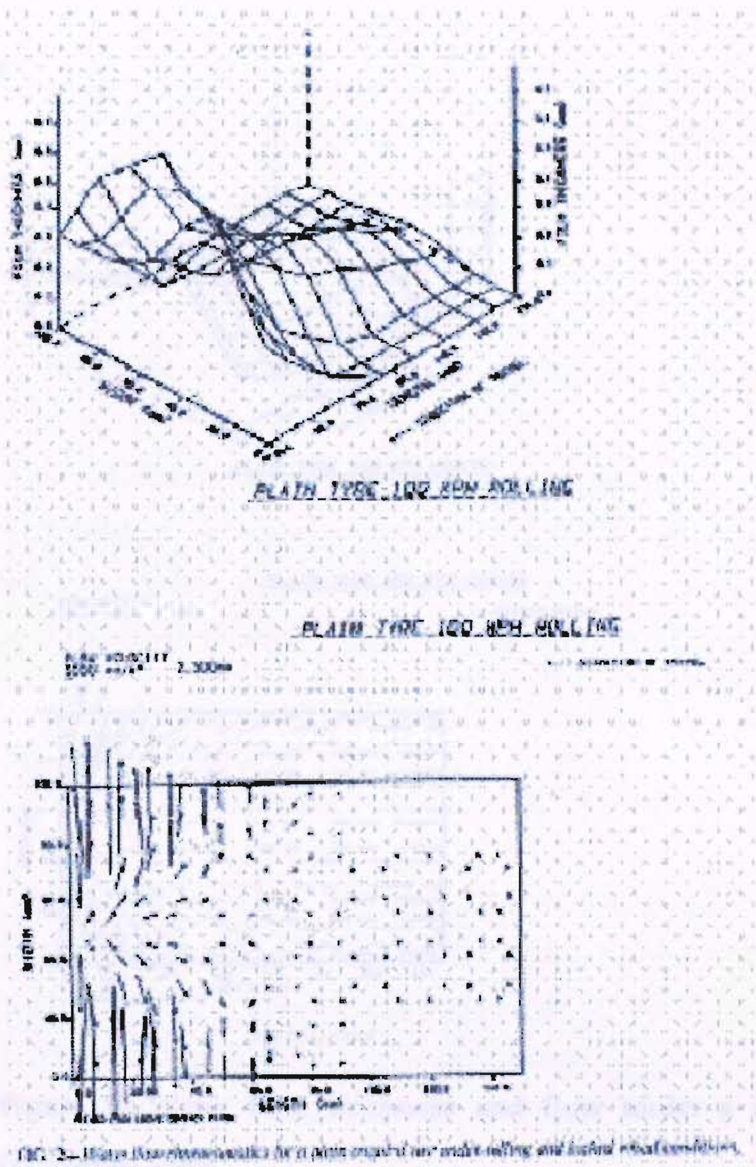

Figure 31 Water Film thickness and flow under a locked smooth tyre at 100kph (Williams, 1992)

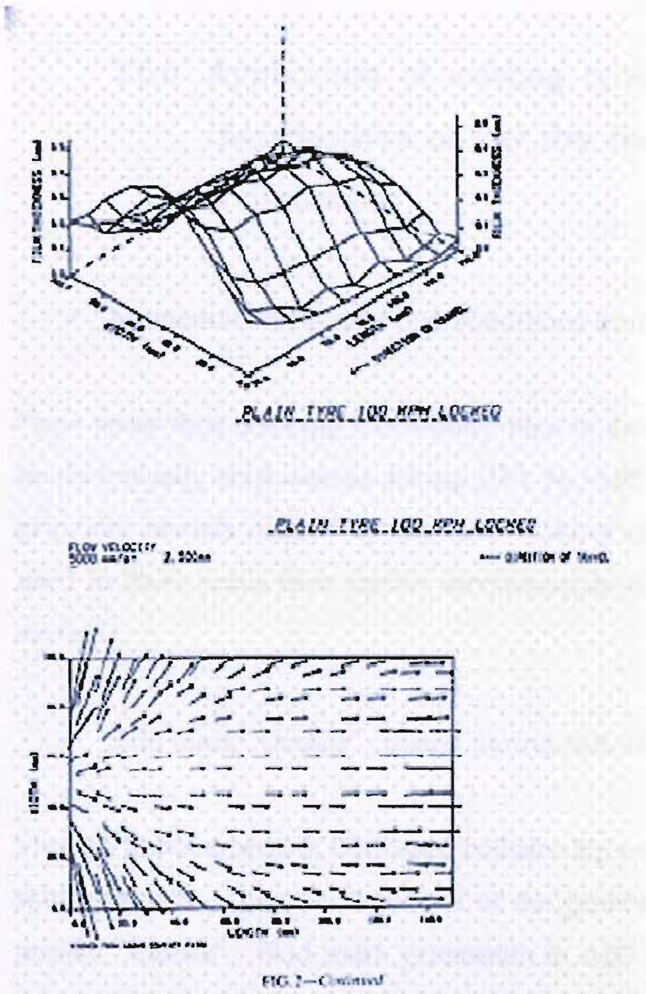

Figure 32 Water Film thickness and flow under a rolling smooth tyre at 100kph (Williams, 1992)

2.6.6 Application of existing tyre/road interaction models to the characteristics of low dry friction events on thick binder film NTS surfaces

- Momentary lock/near lock conditions during ABS tests on DRY NTS

Time series data showing momentary dips in deceleration during DRY ABS down to the levels typically encountered during DRY NOABS tests (e.g. Figure 140), suggests that the grip/slip models utilised by the ABS braking control systems installed on the vehicles used in these brake tests cannot accommodate the grip/slip behaviour of the DRY NTS surfaces.

- Skid mark "Dashes" created during ABS skid tests on DRY NTS surfaces

Though undocumented, UK based collision investigators colloquially associate DRY ABS skid tests with a greater likelihood of the generation of clearly visible short skid marks termed "dashes". Skid mark generation in ABS testing/braking is uncommon but they are typically far more difficult to see but still can occur, but infrequently as wheel lock is suppressed by the operation of the ABS system.

The inability of the ABS control systems to prevent wheel lock is leading to the generation of low levels of dry friction and the associated "dashes" visible on the road surface. Momentary wheel lock during DRY ABS simulated emergency braking events on NTS was captured from the high-speed video experiments at Madingley; "ABS dashes" are commonly visible where simulated ABS emergency braking manoeuvres are undertaken on NTS surfaces with a visible bituminous film on the surfacing aggregates.

The production of these "dashes" (which are probably indicative of near-locked or locked wheel conditions during ABS braking) suggests the fundamental models used in the development of ABS systems cannot accommodate the behaviour of NTS surfaces whose characteristics lead to the generation of low levels of dry friction. The idealised grip/slip curves discussed, and those shown in other works not referenced) appear very different in form to those few obtained when the low dry friction phenomenon is known manifests itself and the grip/slip curve could be recorded (as was documented at Smeatharpe in Devon).

- Grip/Slip Ratios in the Literature for dry roads

Low dry friction events have been characterised in the literature (Jutte and Siskens, 1997) by a 40%-50% or more reduction in friction between the peak and sliding phases. The magnitude of change between these phases in the existing DRY grip/slip models is commonly represented in the literature as being of a level more akin to 10-20% as illustrated in the grip/slip models.

2.6.7 Conclusions

- Limited measurements of deceleration versus slip undertaken on the low macrotexture Gripclean binder course surface in Devon (Smeatharpe), may provide the first evidence for those surfaces exhibiting bituplaning possessing a hybrid grip/slip curve not corresponding to those seen in the literature.

- The presence of momentary dips in deceleration during ABS tests on Dry NTS may also suggest that the existing tyre/road interaction models and ABS control systems cannot be able to accommodate the rapid transition between the high and low friction states inherent in the tyre/road interaction characteristics of the low dry friction event.

- There is some evidence based on the difference in grip slip ratios seen on NTS surfaces compared against traditional surfaces (and the literature) along with limited evidence to suggest the grip/slip characteristics of DRY NTS surfaces depart from those considered typical in the literature to warrant detailed research into the typical grip/slip characteristics of NTS surfaces in general.

2.7 Bitumen Rheology

This section contributes towards addressing Question 4 in Section 1.4: What was the likely mechanism (or mechanisms) responsible for the generation of the low levels of dry friction observed on certain NTS surfaces?

The environment that exists between the tyre and the road surface during extreme braking manoeuvres is one of high energy as it represents the interface through which the energy transfer takes place to bring potentially several tonnes of vehicle to a halt. The temperatures and stresses the bituminous materials are exposed to at this interface may be akin to those experienced by the same materials during their manufacture (during their combination with crushed rock aggregate and other components of the final mix in a mixing plant)).

To the road surfacing contractor, the manufacturers, and the client alike, the acceptable behaviour of bituminous materials during the manufacturing process and during installation and subsequent service is paramount; these behaviours are reflected in the rheological properties of the bituminous materials.

"Rheology is the study of the deformation and flow of matter. The term rheology was coined by Eugene Bingham, a professor at Lehigh University, in 1920, from a suggestion by Markus Reiner, inspired by Heraclitus's famous expression panta rhei, 'everything flows'".

From http://www.en.wikipedia.org/wiki/Rheology

"The science of deformation and flow of matter. Rheological descriptions usually refer to the property of viscosity and departures from Newton's law of viscosity."
From: http://www.ucalgary.ca/~schramm/visc.htm

"The branch of physics that studies the deformation and flow of matter"

From: http://www.wordnet.princeton.edu/perl/webwn

Rheological testing and the understanding of the behaviour of materials in relation to their rheological characteristics has been applied to the design and development of bituminous materials for decades, with modern developments in rheological testing being increasingly applied to this field as technological advances are made.

"Rheology. Concepts, Methods and Applications." (Malkin and Isayev, 2006) provides a comprehensive text covering the majority of rheological concepts and methodologies.

The application of rheological study and testing has extended to many areas where non-quantitative (subjective) testing was commonly the norm; a good example of such a change in assessment methods is that of the characterisation of food products. Rheological assessment is being used even to quantify properties as diverse as "creamy mouthfeel" in yoghurts and similar food properties (Jellema et al., 2005, Stenz et al., 2006, Tarrega and Costell, 2005, Telis-Romero et al., 2006) .

The rheological behaviour of bitumen materials in the tyre/road interaction zone may be viewed as akin to that of the rheological behaviour of bitumen materials during their installation as a hot mass rather than in service (Figure 71) since:

1. The temperatures generated between tyre and road surface observed at Madingley are more representative of temperatures in the region commonly experienced during the laying of bituminous surfacing rather than those typically encountered post-installation (**Figure 71**).
2. The shear stresses potentially generated between tyre and road surface moving at a potential relative speeds of up to 13m/sec (50 kph) are more likely to be representative of the shear stresses commonly experienced during the laying of bituminous surfacing rather than those typically encountered post-installation for which the bituminous designs are carried out to address. No evidence exists in the

literature of routine testing undertaken at the shear inferred to exist in the realm of NOABS skid tests.

3. Study of the higher temperature / higher shear behaviour of bitumen during the installation process may provide information of value regarding their behaviour if exposed to such temperatures as a result of the action of a sliding tyre.

4. Rheological behaviours of other materials under high strain/shear and/or at high temperatures where such materials contain components such as polymers found in certain bituminous materials may provide valuable models for bituminous materials.

The literature includes works of value both specifically addressing this area as well as work addressing rheological problems generally encountered with polymers, rubbers and bitumens outside of the tyre/road interface but valuable in contributing to the wider understanding of their behaviour during extreme conditions at the tyre/road interface .

2.7.1 Bitumen Rheology in practice

The latest equipment to be utilised in rheological studies this is the Dynamic Shear Rheometer (DSR) as used by Collop et al (Collop et al., 2002) and (Soenen et al., 2006) whose testing regime is illustrated in
Figure 33.

The rheological properties of the bituminous material surrounding the fine particles and additives in the mastic (which itself coats the coarse aggregate fraction in negative textured surfacing) are designed by the manufacturers to produce an end product capable of being transported to site (without loss [drain down] of the mastic), capable of being rolled or compacted (high temperature workability) and able withstand the action of traffic during service (in service performance).

An important observation to be made is that the presence of solid particles in a medium can have a significant effect on the Rheology of the mass, in this case the mastic described above, may have significantly different rheological properties in-toto than for the non solid bituminous components. Hill (Hill and Carrington, 2006) provides a graphical summary (Figure 34) of the effect of the percentage of particles and on the behaviour of a suspension however the influence of zeta potential (electrostatic bonds) illustrated may be less for bituminous mastics than for lower viscosity suspensions. Similarly, the shear thinning resulting from the presence of a large number of particles leading to weak structure failure at high shear may not necessarily apply to bituminous mastics. The bondings between fine non-bituminous particles in the bituminous mastic may well be an influence on the bulk behaviour of the mastic.

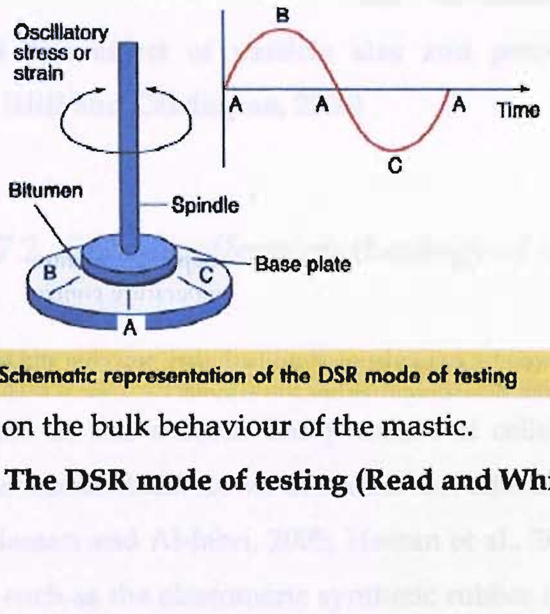

Fig. 7.21 Schematic representation of the DSR mode of testing

Figure 33 The DSR mode of testing (Read and Whiteoak, 2003)

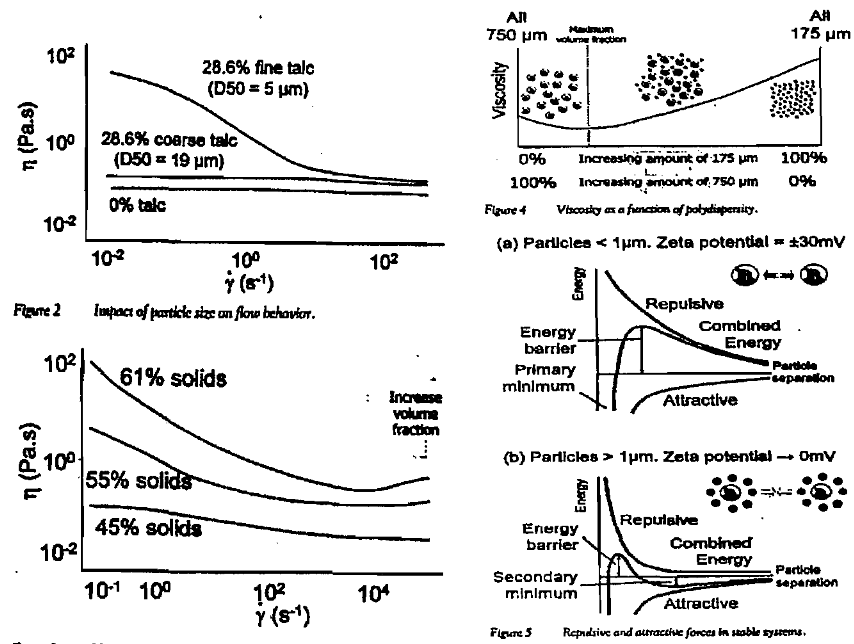

Figure 34 The effect of particle size and percentage solids on viscosity and zeta potential (Hill and Carrington, 2006)

2.7.2 Specific effects on rheology of additives

The Shell Bitumen Handbook (Read and Whiteoak, 2003) contains a wealth of background information on this subject. The presence of cellulose fibres in the mastic primarily to reduce the mastic drain down in transit can effects on the performance of the material in service (Hassan and Al-Jabri, 2005, Hassan et al., 2005). The use of chemical and polymer additives such as the elastomeric synthetic rubber in the Olexobit 100 binder used on the A428 Madingley section (used for the high-speed video and infra-red study) delivers rheological characteristics which are more accommodating in terms of the acceptable range of temperatures each phase (from manufacture to installation and subsequent service) can successfully occupy.

The use of polymers has a proven ability to improve the durability and in-service performance of bituminous materials and is still the subject of research (Champion-Lapalu, 2000, Garcia-Morales et al., 2006, Glanzman, 2005, Hassan et al., 2005, Kumar et al., 2006, Rek et al., 2005).

2.8 Physical Stresses at the tyre/road interface

Anghelache & Moisescu (Anghelache and Moisescu, 2006) recently presented the results of research undertaken to measure the stresses generated between tyre and road. Part of their work has resulted in an output showing the stresses generated during braking, free rolling, and traction (acceleration). This work to a less or greater degree gives some measure of the minimum forces acting on an NTS during emergency braking (it was not established whether the forces related to locked wheel braking events).

Earlier unpublished work by Parry et al (Parry, 1998) (Abridged by Walsh (Walsh, 2002)) included measuring the pressure distribution between tyre and road however this information was delivered in terms of false colour contour maps (**Figure 35**) rather than objective measures.

Several workers have illustrated the theoretical modelling of the pressure distribution between the tyre and a contact surface including Merzouki et al (Merzouki et al., 2004) in their estimation of the frictional force at the tyre/road interface (**Figure 36**)

If the tyre/road stresses can be adequately quantified it may be possible to consider the influence of these confining and normal pressures between tyre and road when studying the potential for the viscosity characteristics of the bituminous mastic to be modified by the increases in confining pressure during wheel lockup.

If data then existed relating to the pressure /viscosity properties of the bituminous binders or mastics (and for pressures of a suitably high magnitude) , the introduction of a value for confining pressure may be of value in the better modelling the contribution of pressure to the manifestation of the low dry friction phenomenon.

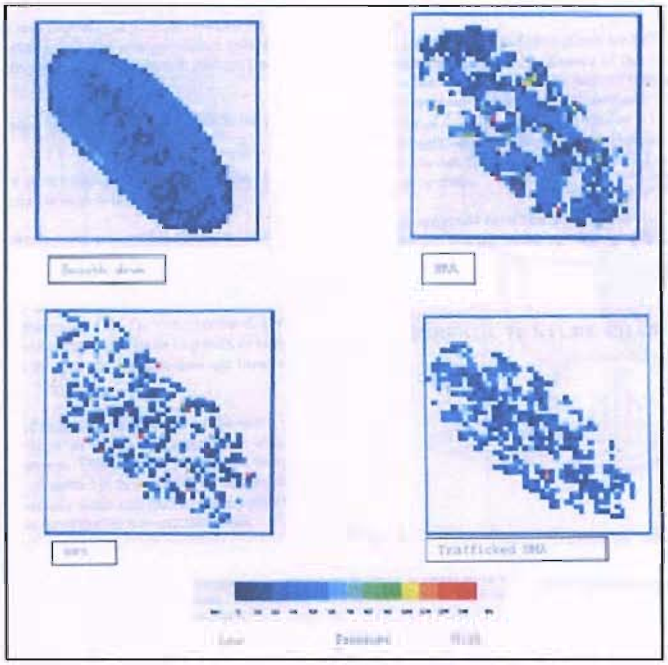

Figure 35 Pressure pad figures from the MARS report (Parry, 1998)

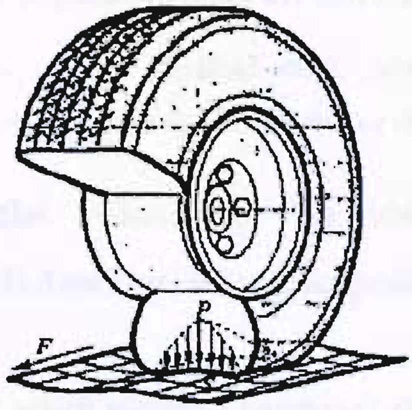

Fig. 1. Tire-Road Contact with pressure distribution

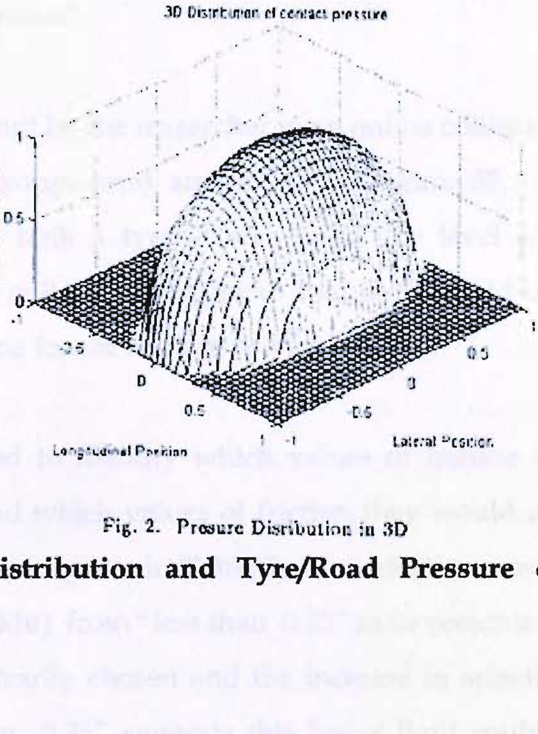

Fig. 2. Presure Distribution in 3D

Figure 36 3D pressure distribution and Tyre/Road Pressure contact distribution (Merzouki et al., 2004)

3. Investigations Undertaken in this Study

Following the main literature review, original desk, laboratory, and field based investigations were undertaken, this section details a number of these activities

3.1 Establishing the values for "typical" friction used in practice by collision investigation professionals

Following the literature review, which yielded a number of alternative values for typical friction on the road surface, it was important to establish the collision investigators' understanding of "typical friction".

The results of a poll carried out by the researcher in an online collision investigators forum (RTA_Investigators@yahoogroups.com) are shown in **Figure 37**. As can be seen, the collision investigators have both a typical wet AND dry level of surface friction co-efficient in mind. A similar poll among highway engineers would be equally interesting; however, an equivalent online forum remains to be found.

The respondents were asked to identify which values of friction they would consider "typical" for wet friction and which values of friction they would consider "typical" for dry friction (questions asked are given in **Table 9**. The selection was made from values of surface friction co-efficient (Mu) from "less than 0.35" in increments of 0.05 to "more than 1.1", these limits were arbitrarily chosen and the increase in selection for "typical wet" between 0.35 and "less than 0.35" suggests this lower limit could have been reduced further.

The mean values for wet and dry friction (scoring "less than 0.35" as 0.3 and more than 1.1" as 1.15) were calculated from the raw data as 0.51 and 0.73 respectively.

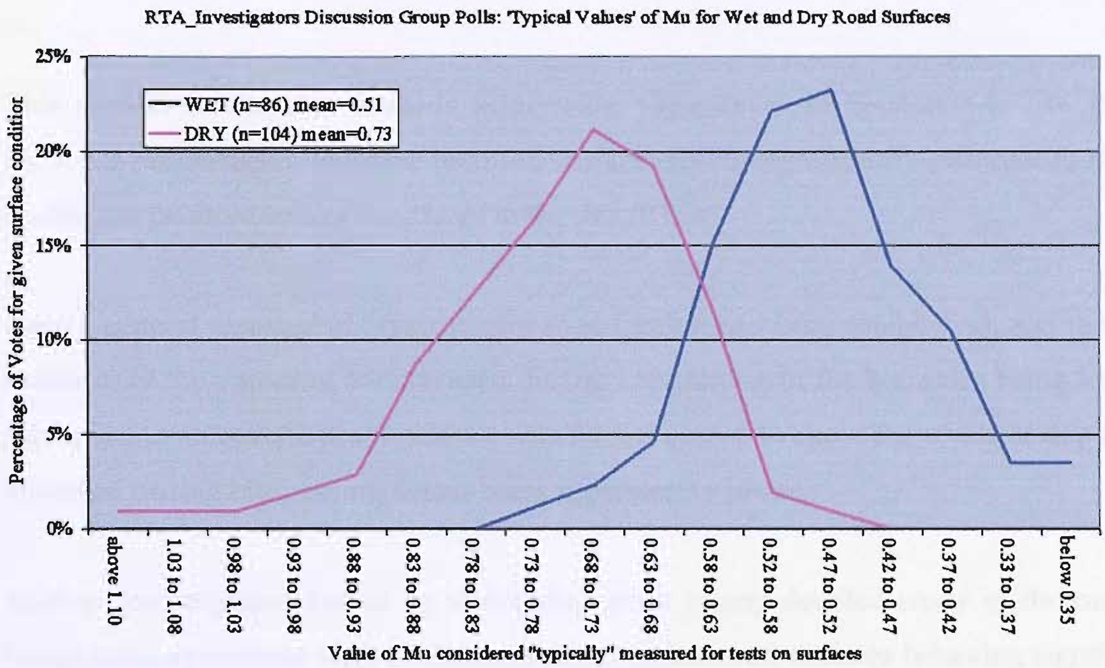

Figure 37 Distribution of values for MU considered by collision investigators to be "representative" of wet or dry road surfaces

POLL QUESTION: What would you consider to be reasonable levels of Mu (from test devices) on a level length of DRY road surface (bituminous or concrete surfacing).

Please, tick ALL the values that fall within your perception of a "normal" and commonly encountered range for the above.

POLL QUESTION: What would you consider to be reasonable levels of Mu (from test devices) on a level length of WET road surface (bituminous or concrete surfacing).

Please, tick ALL the values that fall within your perception of a "normal" and commonly encountered range for the above.

Table 9 Survey texts (bottom) and Breakdown of choices for "typical "wet and dry friction (top) for the RTA_Investigators @yahoogroups.com online survey

3.2 Assembly of the Deceleration Time series database

This section contributes towards addressing Question 1 in Section 1.4: Are the dry frictional properties of negative textured surfaces (NTS) significantly different to those of traditional positive textured surfaces in the dry (PTS)?

Once a general measure of "typical" dry road friction had been established, and there was evidence of the values of friction seen during bituplaning in the literature being less than this typical value, statistical evidence was then required to show the levels of dry friction observed during bituplaning events were significantly lower.

Such an investigation had to be undertaken prior to any detailed study of the causes of bituplaning as without such evidence of negative textured surfaces behaving significantly differently it would be impossible to disprove that the measurements made for such bituplaning events were only representative of the extremes of behaviours still considered to be representative of typical road surfaces.

Key performance differences between surfaces capable of delivering bituplaning and other surfaces were already established from the literature review.

A difference between levels of dry friction achieved on NTS and lack of use of ABS braking (Jutte and Siskens, 1997, Swart, 1997, van der Zwan et al., 1997).

A similarity in the levels of deceleration in the dry and in the wet for NTS surfaces without the use of ABS (Leusink and Bennis, 2000, Veldhuis, 2004, Manderson and Rudram, 1993, Roe, 2004) and in New Zealand (tests from 2005).

Differences between PTS and NTS surfaces with respect to their ratios of peak to sliding deceleration in the dry could exploit a database of information already collected in the USA (Ebert, 1989).

Thus, there was a need to prove statistically if these interactions and behaviours were reflected in significant differences in the measured decelerations recorded for each group during skid tests recorded in the course of this work over a range of surfaces and conditions.

The key things to establish were:

If a significant difference existed between levels of dry friction achieved on NTS where ABS braking was not used (NOABS).

A lack of significant difference existed between levels of deceleration in the dry and in the wet for NTS surfaces without the use of ABS (NOABS).

A significant difference in the ratio of peak to sliding deceleration existed between NTS and PTS surfaces in the dry either where ABS was not used or in both ABS and NOABS cases.

To this end, the deceleration time-series database (assembled from data collected from SkidMan/Vericom tests undertaken at the investigation of fatal or near fatal collisions) was analysed using MiniTab 14 and SPSS 15 to support or reject the existence of above inter-relationships.

The braking systems used on the vehicle carrying out the test (ABS or NOABS), the surface condition of the road (DRY or DAMP or WET), the surface material type (POSITIVE texture (PTS surfaces) or NEGATIVE texture (NTS surfaces)) may or may not influence the resulting level of deceleration recorded.

3.2.1 Justification for the use of skid test decelerometer data from collision investigations

The UK Design Manual for Roads and Bridges (Highways Agency, 2003a) states:

"Police skid tests are carried out in differing conditions and are used at accident sites to assist in accident reconstruction. They are frequently made in dry conditions. The measurements are not suitable for assessing whether a road surface is substandard or in need of remedial treatment."

The Manual continues:

"However, if a dry skid test indicates a lower than expected dry road skid resistance, this should be drawn to the attention of the highway authority so that the cause can be investigated"

The Skidman was thus considered a suitable tool for investigating dry skid resistance and for identifying any occurrences of bituplaning.

It should be noted that statistical evidence from a past study of police collision recording practices suggests that very few collisions (approx. 4%) are contributed to ONLY by the surface conditions of the road where they occurred (Broughton et al., 1998).

The collection of data from collision sites therefore should reasonably be viewed as sampling from a non-representative population of road surfaces in general.

3.2.2 Collection and verification of decelerometer data collected by the Police in the course of collision investigation of fatal and near fatal crashes

Following a number of presentations to senior collision investigators, requests were made to work closely with Police Forces nationwide to obtain decelerometer data collected during ALL tests executed pursuant to collision investigations, along with additional details of the braking system used, surface conditions and broad surfacing type. The surfacing type being determined using both the experience of the investigating officer and with reference to a photographic identification guide with the assistance of the Hampshire County Council Technical advice Group (TAG).

This activity was undertaken in an attempt to provide:

- A body of detailed time series data relating to a range of road surface types, road surface conditions and braking systems to establish whether the bituplaning deceleration events seen by the Researcher in the UK were typical of those reported by earlier workers (Shelshear, 1993, Shelshear, 1986a, Roe and Lagarde-Forest, 2005, Roe, 2004, Roe, 2003, Roe, 2001, Jutte and Siskens, 1997).

- A data source for the statistical work that identified the statistical significance of a number of characteristics thought typical of the bituplaning events described in the literature.

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The level of Police interest in contributing varied between forces, very few were unwilling to assist, many actively sought to submit data and a small number offered to carry out regular testing of specific sections, as a surrogate for SCRIM and PFT testing. .

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3.2.3 Deceleration Data Collection Methodology.

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This data collection exercise was focussed around visits to various police collision investigation units, to download data from their SkidMan test devices used to record skid tests.

Data collection commenced in late 2003, using an MS-DOS SIMRET package running under the Windows 98SE operating system on a Dell Latitude Laptop linked to the SkidMan device with a SKIDCALC cable (kindly provided by Turnkey Instruments the manufacturer of Skidman). Typically the Skidman devices were downloaded by the Researcher at the offices of the individual police units but exceptionally this downloading was done by Turnkey Instruments during routine servicing or by the police themselves, using SIMRET and the forces own data transfer cable.

The use of Vericom data was limited to recordings by the Researcher of deceleration events forming part of the experimental activities as at no force involved in the data submission process was using such a device. Data retrieval from the Vericom VC3000DAQ device was facilitated using the PROFILE 3 software downloadable from the Vericom website and the Vericom to PC cable provided with the device.

Stage 1: Data Download from the SkidMan Device

The raw ASCII format data files were downloaded from the SkidMan via the SIMRET MSDOS package using the SIMRET DOS application and download cable.

Stage 2: Combination of the Individually Downloaded Deceleration Events

Multiple raw column format ASCII files downloaded from the SkidMan device were combined and transposed into multi row spreadsheet worksheets using a Microsoft Excel spreadsheet running a Visual Basic macro procedure (see Appendix 4, the final spreadsheet was based on a procedure scripted for the researcher by L. Vosslamber in the Netherlands).

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Additional information was added to the spreadsheet holding the deceleration data. The additional data related to the following:

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- The braking system used on the vehicle carrying out the test (ABS or NOABS)
- The surface condition of the road (DRY or DAMP or WET),
- The surface material type (POSITIVE or NEGATIVE texture)
- The vehicle used in the test (free text field)

This additional data was added as and when this information was available from the police force in question.

The combined test data streams were then imported into a Microsoft Excel spreadsheet augmented with a number of macros (see Appendix 3) which enabled points within each time series to be identified and marked as additional values in the database.

Stage 3: Test inclusion/exclusion process

It was important to apply a reasoned judgment as to whether a test recorded by a device was in fact a "correct" test rather than one that would be classified as invalid for some reason. Tests which are not completed (and considered void) owing to an obstruction to the safe progress of the vehicle (test stopped short) , poor driving leading to incorrect speed or brake application, along with those tests undertaken on goods vehicles, trams and other exotica, need to be excluded from the database. Tests not undertaken in cars were excluded once identified.

Excluding tests recorded but considered by the police as unsuitable, was more problematical: since the police do not normally examine the detailed time series data, no assistance in identifying "invalid runs" was provided.

Figure 38 provides annotated valid deceleration test plots, these are annotated to identify the following phases:

- The periods of the initial deceleration up to the momentary MAXIMUM (PeakG): 14A & 43A.
- The periods of locked wheel sliding or ABS activation respectively (SlideG): 14B & 43B.
- The period of the test when the vehicle comes to rest and when suspension bounce occurs: 14C & 43C.

NOTE the transition period between the MAXIMUM deceleration and the sliding deceleration for Test 14.

The following conditions for rejecting a test were applied:

- Tests where the ABS state and/or Road Surface condition and/or Surface type or other key identify was missing were rejected.
- Tests that showed an incomplete time series, i.e. lacking in a suspension bounce phase (shown in periods 14C and 43C), were rejected.
- Tests that did not illustrate the "typical" rectangular or rhomboidal form (as illustrated in the tests below) were also arbitrarily rejected.

The reasons behind this last rejection criterion were:

1) The majority of tests regardless of whether ABS is applied or not tend to show an initial peak, after the onset of deceleration (as illustrated by the ends of periods 14A and 43A)
AND
2) In the case of ABS tests: a maintained second phase of seemingly randomly variable deceleration averaging just below the peak initially encountered deceleration (illustrated by the period 43B below)

OR

2.1) In the case of NOABS tests: a period of relatively stable but slowly increasing deceleration following a rapid drop from the initial peak (illustrated by the period 14B below)
AND
2.2) In the case of tests undertaken on WET surfaces, a "softening" of the deceleration curve around the peak (which will be reduced) and less "detail" in the deceleration variation for the secondary phase with the lubrication of the road by surface water.

Thus with these defined prerequisites the database was scanned visually test-by-test and those tests not complying with these "typical" requirements (as illustrated below) were removed since there was no means to confirm whether the deceleration profile shown had resulted from poor test process or were a real response to the road surface conditions. It was decided to err on the side of caution.

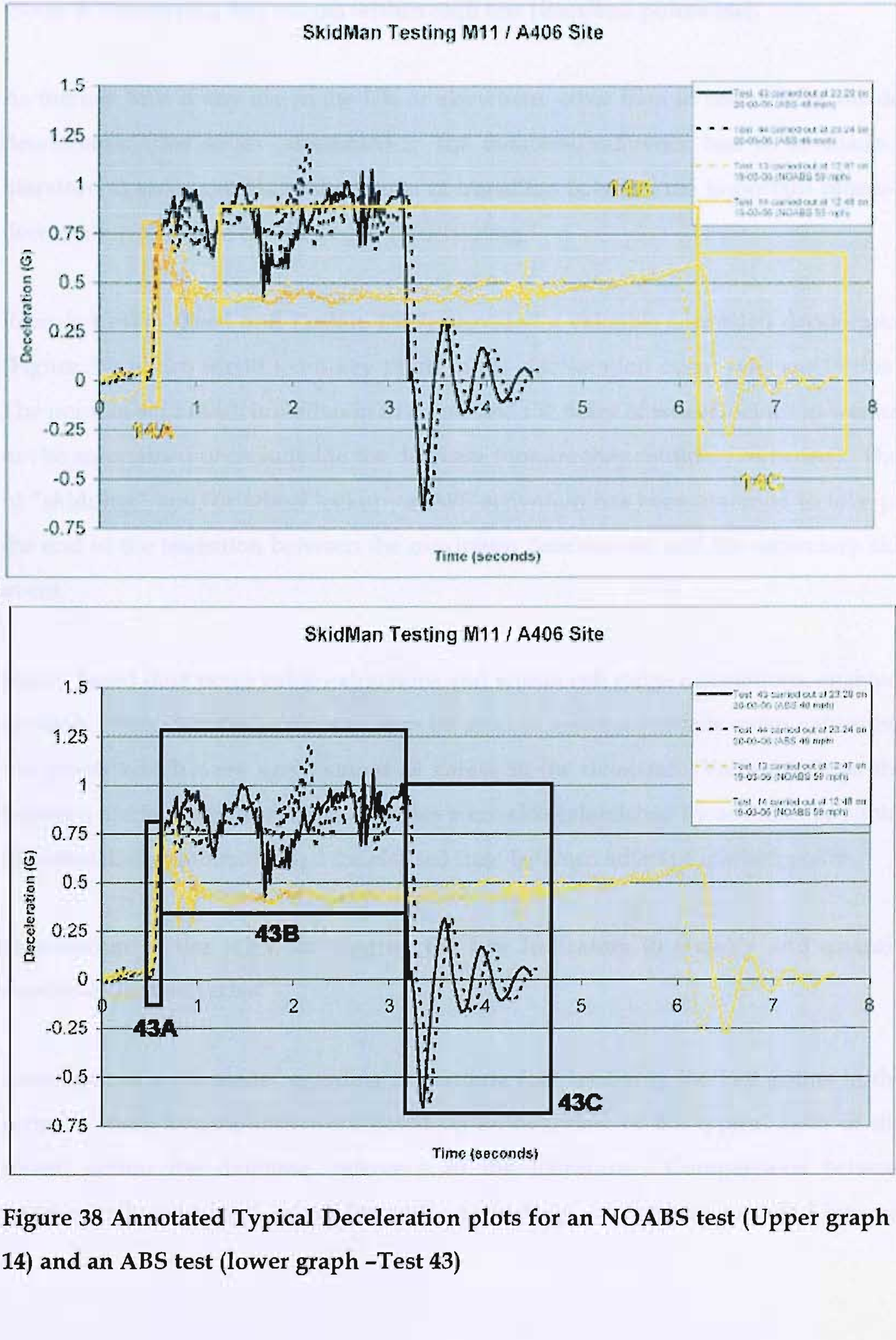


Figure 38 Annotated Typical Deceleration plots for an NOABS test (Upper graph – Test 14) and an ABS test (lower graph –Test 43)

Stage 4: Identifying key events within each test (start/end points etc).

As there is little if any use in the UK or elsewhere, other than in research, of the detailed deceleration time series' assembled in the database, reference had to be made to the literature to ascertain where the points of transition between the important phases of the deceleration test were considered to be occurring.

Reed & Keskin (Reed and Keskin, 1989) provided a valuable annotated deceleration plot (Figure 39) which identified a key point in the deceleration event relevant to this work. The point of skid mark initiation in dry tests and the point of wheel lockup in wet tests has not be ascertained or included in the database (nor are they routinely recorded). The onset of "skidding" and/or wheel lockup or ABS activation has been assumed to take place at the end of the transition between the maximum deceleration and the secondary skidding event.

Macro based data point value extractions and within cell range calculations, enabled these (x=time, y=deceleration) points to then be used to generate further mean values between the points which were again stored as values in the database. Values such as the time between marked points in the data series were also established by addition or subtraction of cumulative combinations of the elapsed time between adjacent marked points.

Description of the rules for tagging the key indicators to classify and quantify the deceleration time series'

Assumptions were made regarding the criteria for classifying the key points in the time series'. These assumptions were based on an overview of the typical form of the time series' within the database, reference to the literature. Comparisons between the automatically calculated values for peak and average deceleration recorded internally by the SkidMan and those extracted from the database using the key indicators assisted further.

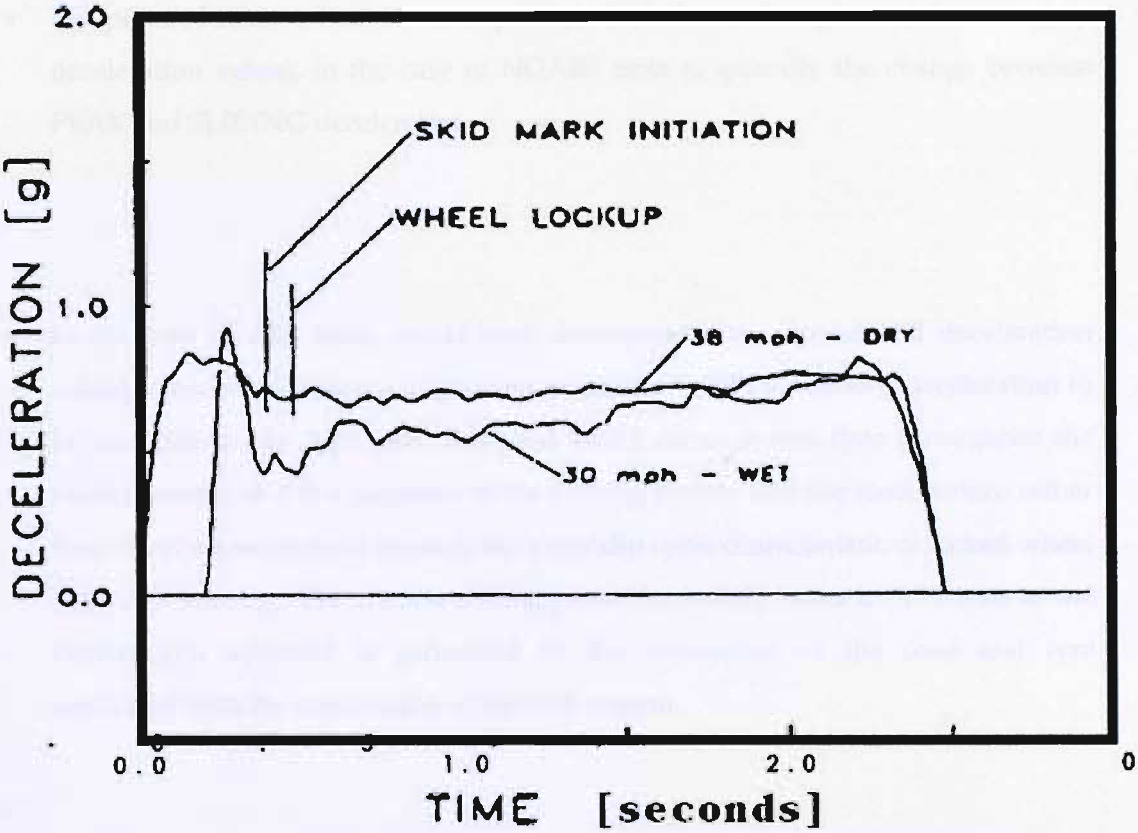


Figure 39 Figure from Reed & Keskin (Reed and Keskin, 1988, Reed and Keskin, 1989)

Turnkey Instruments will not release the algorithms used for the internal calculations, however the values generated are accepted in collision investigation as the device was developed by a Police collision investigator.

The following points were identified as delineating key points in the deceleration time series':

- Start of braking deceleration following acceleration up to test speed (identified as the data point in the series marking the transition between forward or neutral acceleration and the onset of deceleration (braking)

AND

- The point of achievement of initial peak (recorded as a time point and momentary deceleration value), in the case of NOABS tests to quantify the change between PEAK and SLIDING deceleration.

OR

- In the case of ABS tests, actual peak deceleration (time point and deceleration value) to enable a measure of greatest momentary ABS influenced deceleration to be established. In ABS tests, this peak could occur at any time throughout the braking event, as it is a response of the braking system and the road surface rather than simply a recognised point in the grip/slip cycle characteristic of locked wheel (NOABS) braking. No discrete sliding phase commonly exists in ABS tests as the deceleration achieved is generated by the interaction of the road and tyre combined with the moderation of the ABS system.

AND

- In the case of NOABS tests, commencement of the sliding phase (time point and deceleration values)

AND

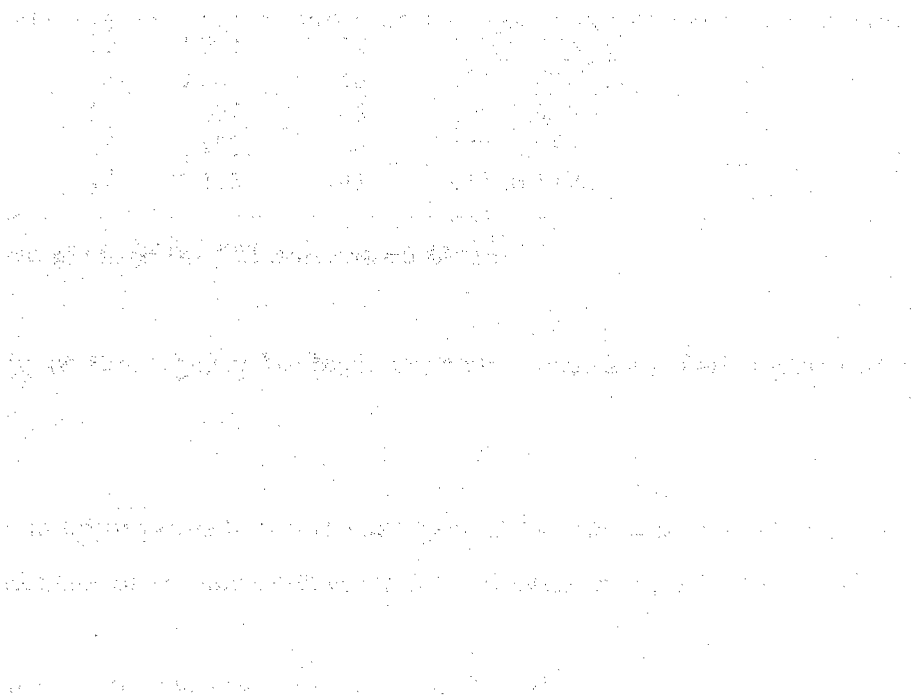
In the case of NOABS tests, the end of sliding phase / End of deceleration (ABS tests) / Start of post slide suspension bounce (time point and deceleration value when zero forward velocity occurs).

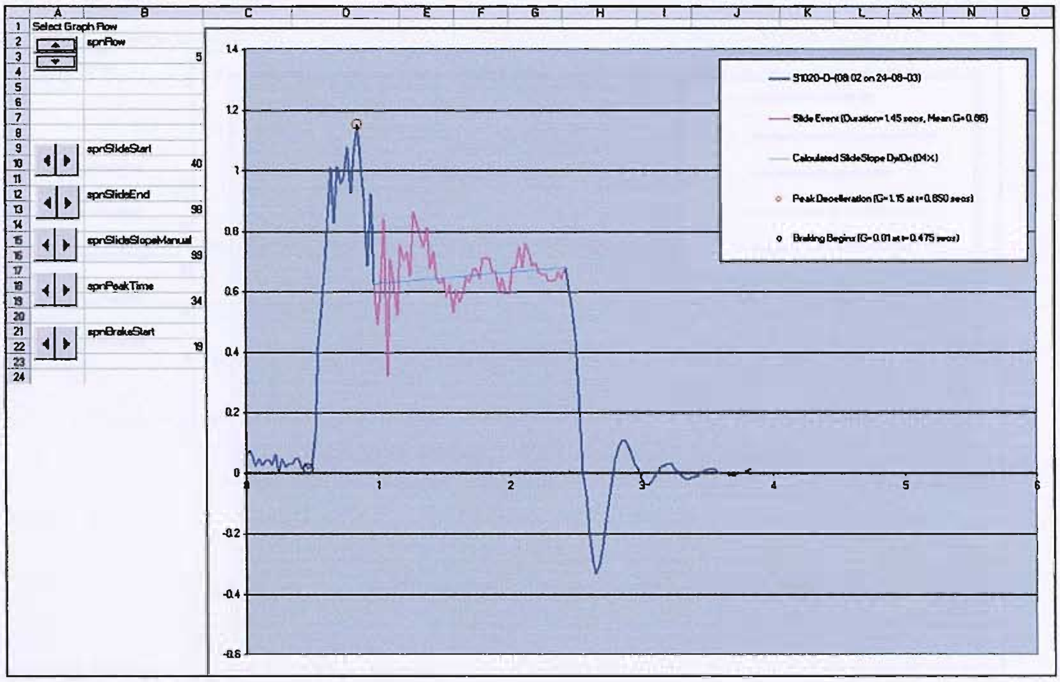
Stage 5 Tagging Process for the Deceleration Database

See Appendix 4 DVD \SOFTWARE DEMO SCREEN CAPTURES\DECELERATION DATABASE TAGGING.avi for a video capture of this software in operation.

Multiple macros embedded in a Microsoft Excel worksheet (Appendix 3) enabled the key points in each deceleration time series to be identified (tagged") and the values to be extracted from the time series database to a database or use in the subsequent statistical analysis. The macros enabled a point on the time series to be identified, this value copied to a database, used in calculations and for this value to be recalled in order to be visible when the same time series was viewed later.

The functionality of the "Tagging" worksheet is shown in Figure 40. The start of skid, end of slide and peak deceleration were tagged using the spin box functionality of Microsoft Excel (spin boxes shown on the left), data generated by the use of the macro is written to the spreadsheet (bottom) to enable the use of visually selected parameters in later analysis. It was possible to add additional modules to the macro to extract other parameters as and when required.





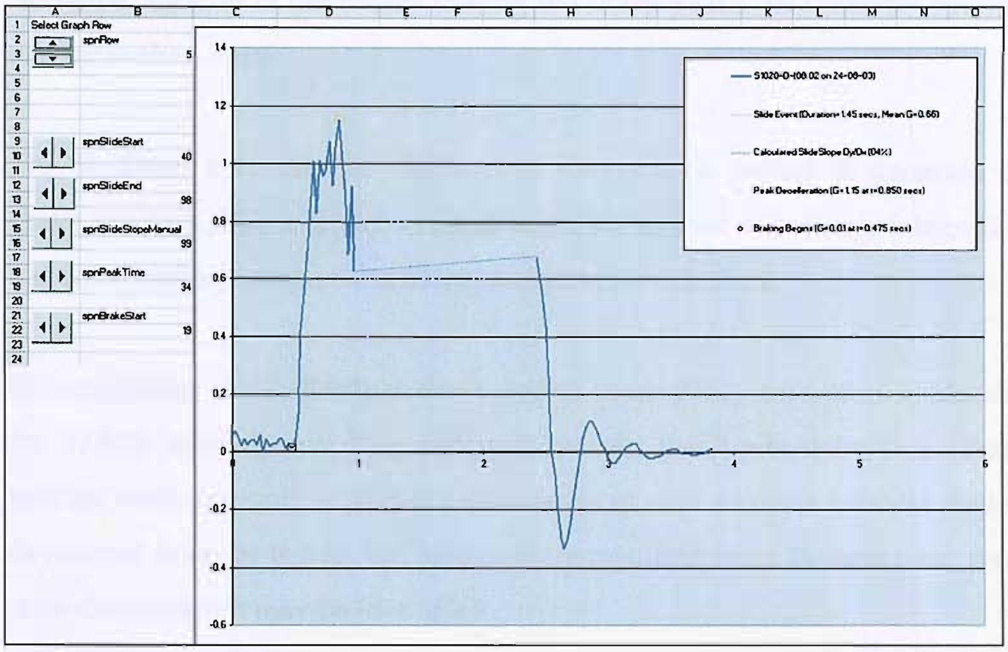
IO	IP	IQ	IR	IS	IT	IU	IV
BrakeStartFound	PeakTime	PeakTime G	SlideStart Time	SlideEnd Time	SlideAvg	SlideDur	SlideSlope
17	35	1.021	42	123	0.616098		
19	33	0.961	40	123	0.621119		
19	36	1.027	48	101	0.687648		
19	34	1.152	40	98	0.663576		
10	47	1.133	61	116	0.605696		

Figure 40 Screen shots of the "Classification Macro"

Cross checking of the tagging by back analysis: Secondary Test inclusion/exclusion process

It was considered appropriate to test the accuracy of key fields in the downloaded data by reference to estimates of the same values from the deceleration calculated data stream.

Initial work using the Turnkey Instruments SkidCalc software package deemed it unsuitable for analysis purposes. SkidCalc transferred a smoothed version of the



IO	IP	IQ	IR	IS	IT	IU	IV
BrakeStartFound	PeakTime	PeakTimeG	SlideStartTime	SlideEndTime	SlideAvg	SlideDur	SlideSlope
17	35	1.021	42	123	0.616098		
19	33	0.961	40	123	0.621119		
19	36	1.027	48	101	0.687648		
19	34	1.152	40	98	0.663576		
10	47	1.133	61	116	0.605696		

Figure 40 Screen shots of the "Classification Macro"

Cross checking of the tagging by back analysis: Secondary Test inclusion/exclusion process

It was considered appropriate to test the accuracy of key fields in the downloaded data by reference to estimates of the same values from the deceleration calculated data stream.

Initial work using the Turnkey Instruments SkidCalc software package deemed it unsuitable for analysis purposes. SkidCalc transferred a smoothed version of the deceleration dataset (**Figure 42**), this fact was established by the visualisation of the same deceleration events using both the SkidCalc and SIMRET forms, SkidCalc delivered a 'softened' version of the events loosing the sharp peaks, and troughs present in the 40 Hz non-smoothed data.

The SkidMan may use the momentary deceleration values to generate the distance to brake to a halt, time to brake to a halt and time at start of braking, integrating between the test start, braking start, and braking end points in the data.

By integrating the individual downloaded momentary measures of deceleration during the 1/40th second recording intervals (within the limits defined as braking start and braking end), not only would the robustness of data analysis methodologies to be further developed later, be tested, but also outliers resulting from incorrect test recording and/or miss-classification may be identified.

3.3 Interpretation of the Deceleration Time series database

This section contributes towards addressing Question 1 in Section 1.4: Are the dry frictional properties of negative textured surfaces (NTS) significantly different to those of traditional positive textured surfaces in the dry (PTS)?

Once the database had been assembled and vetted, the dataset could then be analysed with a view to establishing the significance of the inter-relationships between surface types and braking systems of the key indicators already identified.

The comparisons were undertaken in sequence:

- Identification of outliers and extremes within the dataset.

- Verification of the integrity of parameters calculated post-test against those calculated internally by the Skidman device itself.
- Verification of the Validity of the Wet / Damp / Dry criteria.
- Comparison between the relative performance of NTS and PTS materials under different braking regimes (ABS and NOABS).

3.3.1 Identification of outliers and extremes within the dataset

SPSS 15 automatically tags outliers and extreme values within datasets when generating error bar plots. The output from SPSS for bar plots generated from the deceleration database enabled extremes and outliers to be identified an investigated.

The definition of an Outlier used by SPSS 15 is:

"An outlier is an observation whose value is distant from the values of the majority of observations. It is sometimes more technically defined as a value whose distance from the nearest quartile is greater than 1.5 times the interquartile range."

It was important for these outliers and extremes to be investigated to ensure than they resulted from tests likely to be representative of extremes within the correctly classified groups rather than through incorrect test processes (as identified earlier) or as a result of the miss-classification of tests (i.e. An ABS test classified as NOABS).

Box plots were generated for the values of interest in the data set (**Figure 41**).

Box plots allowed the comparison of each group using five indicators: the median, the 25th and 75th percentiles, and the minimum and maximum observed values that are not statistical outliers. Outliers and extreme values are given special attention in SPSS. The heavy black line inside each box marks the 50th percentile, or median, of that distribution. The lower and upper hinges, or box boundaries, mark the 25th and 75th percentiles of each distribution, respectively. Whiskers appear above and below the hinges. Whiskers are vertical lines ending in horizontal lines at the largest and smallest observed values that are not statistical outliers.

Outliers are identified with an O. Label refers to the row number in the SPSS 15 Data Editor where that observation is found. Extreme values are marked with an asterisk (*).

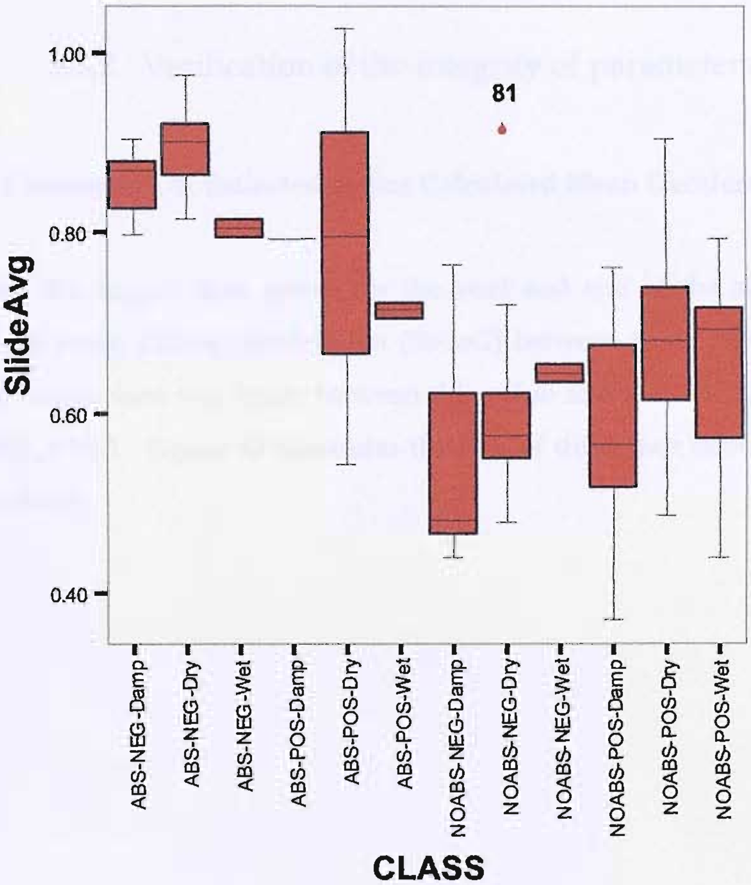


Figure 41 Box plot of Derived Average Sliding G against classification by ABS/TEX/SURF

Examination of the individual time series deceleration graphs for the marked outliers and extremes identified on the relevant box plots failed to provide any valid reasoning for removing any of these tests from the database. No external reference dataset existed to use as a filter for such acceptance/rejection and the general form of the individual deceleration curves corresponded with the general model described earlier.

The box plots generated, graphically illustrate a number of characteristics within the dataset which may be significant and are allied to the influence of surface state and/or braking system type and/or surface type on the characteristics decelerations recorded.

3.3.2 Verification of the integrity of parameters

Comparison of Extracted versus Calculated Mean Decelerations

Using the tagged data points for the start and end of the sliding phase to extract the overall mean sliding deceleration (SlideG) between these points the following Paired T Test comparison was made between this value and that recorded by the Skidman device (SMO_AVG). Figure 43 illustrates the lack of difference between the two variables very effectively.

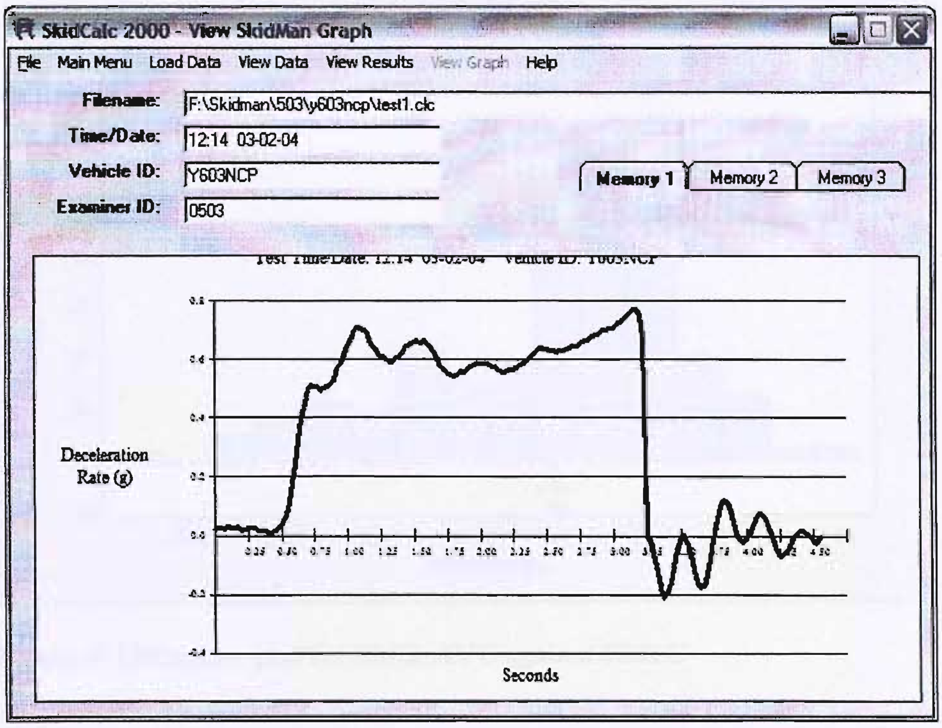


Figure 42 SkidCalc generated image from SkidCalc download

```
Paired T for Mean_EFFORT - SlideAvg

               N      Mean     StDev   SE Mean
Mean_EFFORT  270   0.661136  0.114316  0.006957
SlideAvg     270   0.662242  0.131263  0.007988
Difference   270  -0.001106  0.027713  0.001687

95% CI for mean difference: (-0.004427, 0.002215)
T-Test of mean difference = 0 (vs not = 0): T-Value = -0.66  P-Value = 0.513
```

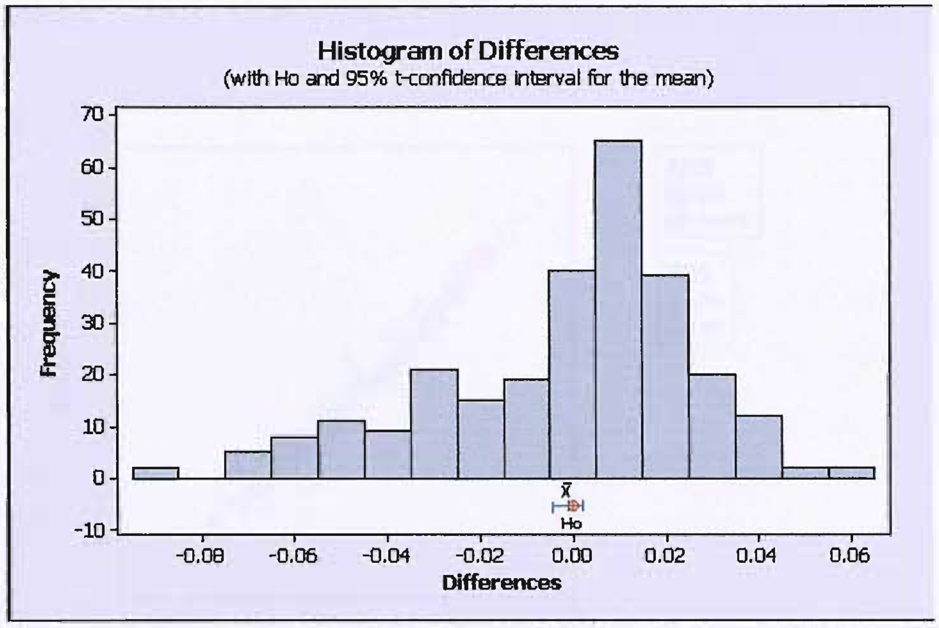


Figure 43 Difference plot for SMO_AVG against SlideG

Observation

The internally estimated SMO_AVG and the derived SlideG agree well (See Figure 44 top) however the tagged data output SlideG is a measure of only average sliding deceleration within the limits of the sliding phase and SMO_AVG is the average through the majority of the whole deceleration event.

Without knowing the precise algorithm used by the Skidman the limits used for the generation of the SMO_AVG value it is difficult to identify the source of the error.

Conclusion

Slide G and SMO_AVG agree well however the reason for this is not entirely understood as they represent different sections of the same deceleration event.

Recorded MEAN deceleration versus Extracted MEAN OVERALL deceleration

The internally estimated SMO_AVG and the derived SMO_AVG_EQUIV correlate well but not as well as between SMO_AVG and SlideG well (See Figure 44 bottom).

SMO_AVG_EQUIV may deliver a more precise measure of the overall average deceleration than the internally calculated SMO_AVG because of using non-smoothed data in its generation.

Overall Conclusion

Both SMO_AVG and the derived SMO_AVG_EQUIV appear to be relative indicators of the overall average deceleration, the reason for the SlideG being better correlated to SMO_AVG than the derived SMO_AVG_EQUIV has not be established.

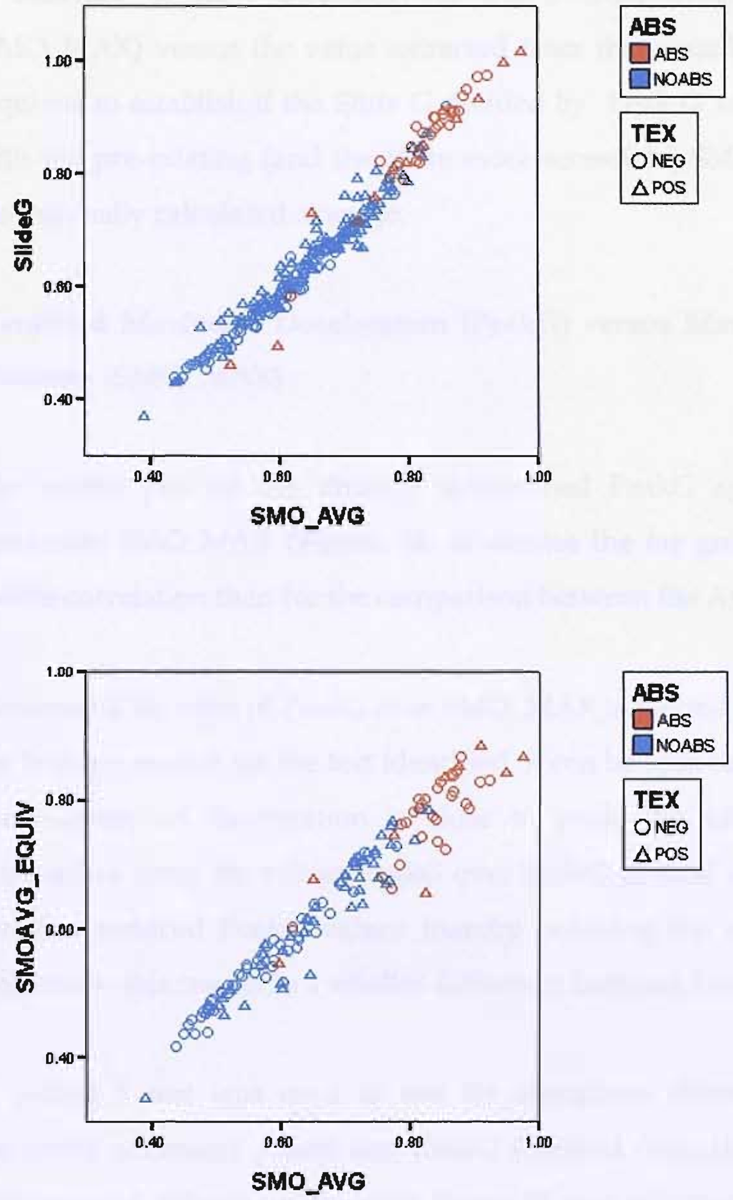


Figure 44 Internally versus analytically calculated average values compared, Derived Slide G versus Skidman calculated SMO_AVG (top), Derived overall average deceleration (SMOAVG_EQUIV) versus SMO_AVG (bottom)

Recorded MAX deceleration versus Extracted MAX deceleration

A measure of the sensitivity of the internal measurement of peak deceleration (SMO_MAX) versus the value extracted from the visually tagged database (PeakG) was required to establish if the Slide G divided by Peak G value could be replaced in future with the pre-existing (and therefore more accessible) SMO_MAX divided by SMO_AVG the internally calculated average.

Identified Maximum Deceleration (PeakG) versus Maximum value generated by the Skidman (SMO_MAX)

The scatter plot of the visually determined PeakG against the internally calculated maximum SMO_MAX (**Figure 46**) illustrates the far greater spread of data and poorer visible correlation than for the comparison between the Average values.

However if the ratio of PeakG over SMO_MAX is plotted against PeakG over SlideG, with the braking system for the test identified, it can be seen that in the case of ABS tests where the majority of deceleration is close to peak, the ratio of PeakG over SMO_MAX approaches unity for values PeakG over SlideG around unity. Wet surfaces are likely to produce reduced PeakG values thereby reducing the magnitude of the peak to slide difference- this results in a smaller difference between PeakG and SMO_MAX.

A paired T test was used to test for significant difference between SMO_MAX (the internally generated value) and PeakG (derived from the data sets): The MINITAB 14 histogram of differences shown in Figure 45 very effectively illustrates the very significant difference between the two variables.

```
Paired T for Peak_Value - PeakG

              N       Mean     StDev   SE Mean
Peak_Value  269   0.781370  0.109482  0.006675
PeakG       269   0.976078  0.127964  0.007802
Difference  269  -0.194708  0.094435  0.005758


95% CI for mean difference: (-0.206045, -0.183372)
```

```
T-Test of mean difference = 0 (vs. not = 0): T-Value = -33.82  P-Value = 0.000
```

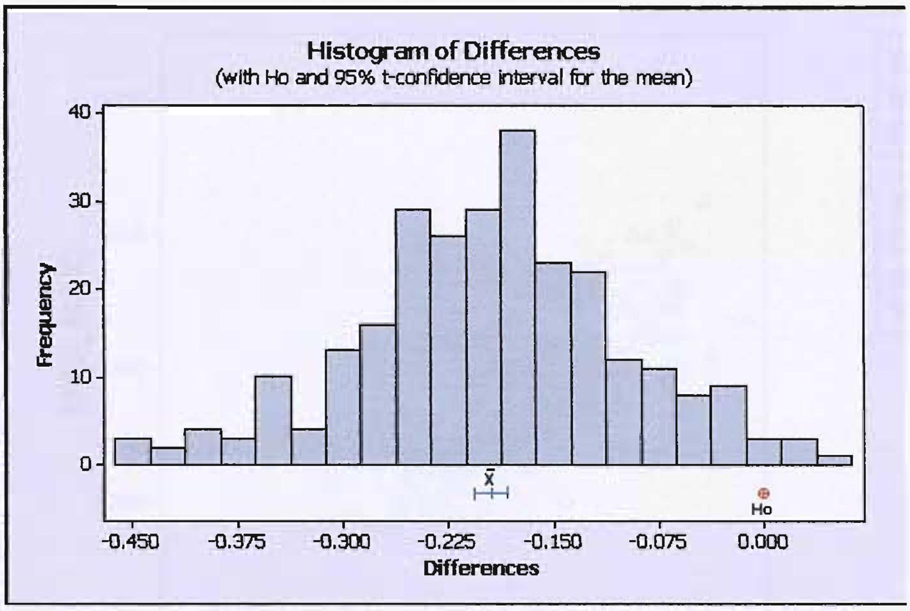


Figure 45 Histogram of differences between Peak_Value and PeakG

In this comparison, the difference between SMO_MAX and PeakG is very significant, for purposes of comparison the mean difference here of - 0.19 represents nearly 20% of the mean value for the tests.

Peak over average deceleration/friction has been identified as a key parameter in the literature (Ebert, 1989) and as such, the use of the internally calculated values in any research had to be compared with the same parameter generated from the extracted peak and sliding decelerations.

From the scatter plot of the slide / peak ratios for the internally calculated and spreadsheet-derived values (**Figure 46**) it can be seen that where PeakG and SMO_MAX are closest are for tests where PeakG and SlideG are also likely to be closest: in ABS tests. For tests in the WET, PeakG (**Figure 46**) appears to exceed consistently the internally calculated SMO_MAX apart from where the subsequent levels of SlideG are closer to PeakG (ABS tests).

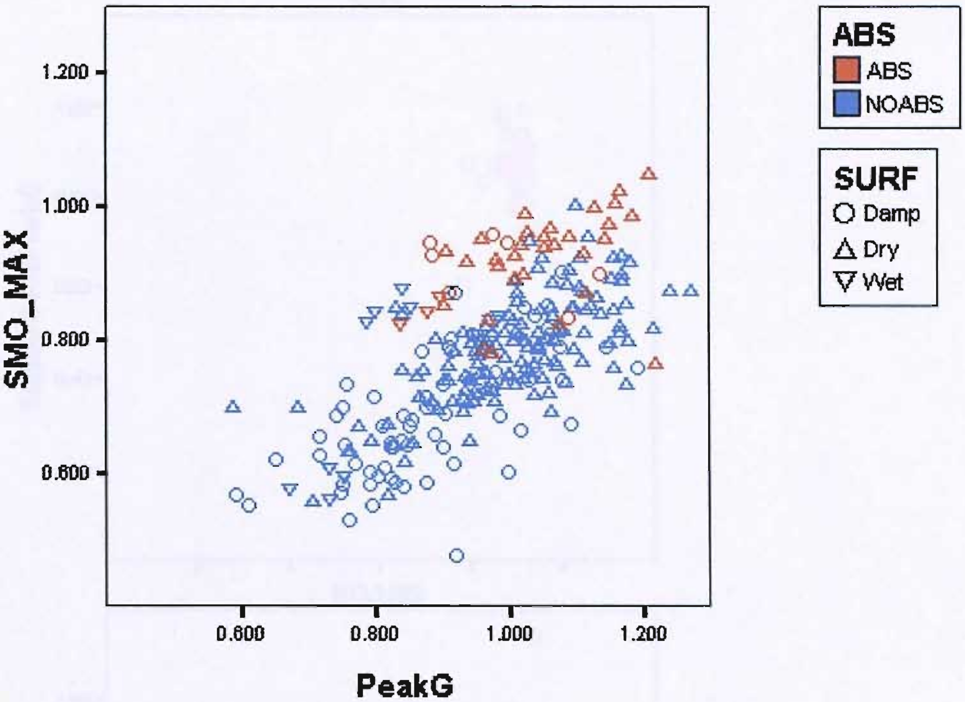


Figure 46 Derived PeakG versus internally calculated SMO_MAX

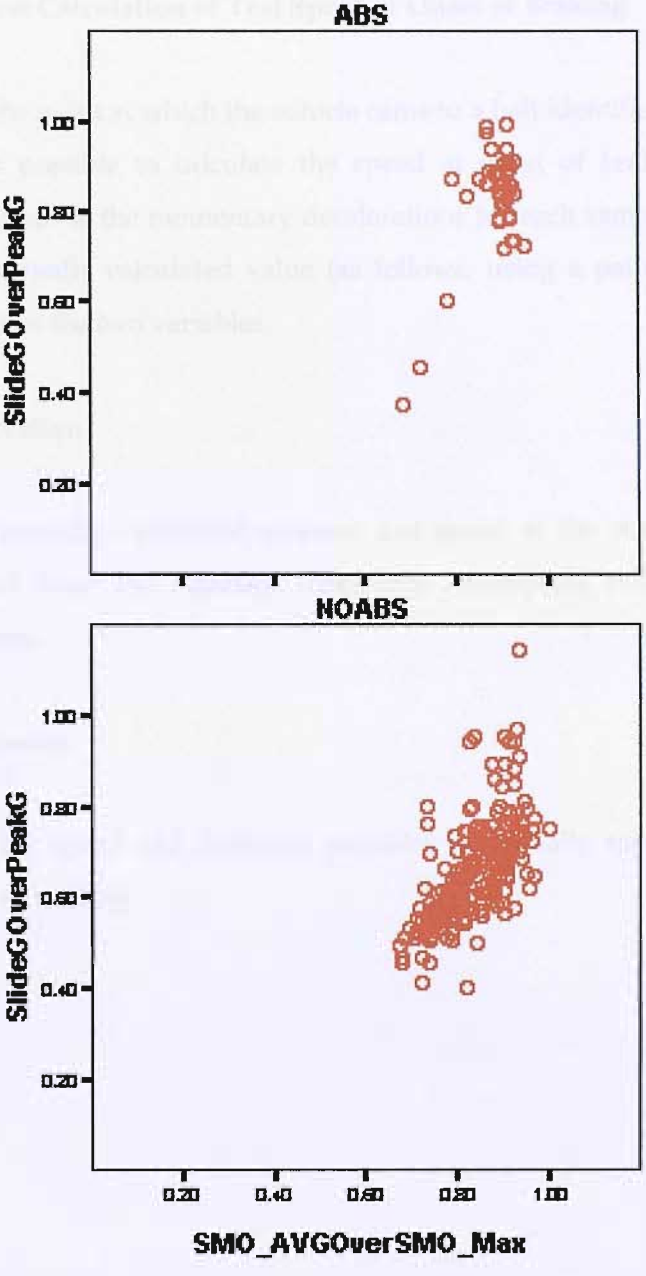


Figure 47 Derived SlideGoverPeakG versus braking state

Post-test Calculation of Test Speed at Onset of Braking

With the point at which the vehicle came to a halt identified tabulated within the database, it was possible to calculate the speed at onset of braking of the test vehicle by the integration of the momentary decelerations for each sampling period and test this against the internally calculated value (as follows, using a paired T test). Figure 48 graphical compares the two variables.

Observation

The internally calculated measure test speed at the onset of braking (Speed) and that derived from the database (EstSpeed) correspond closely and are not significantly different.

Conclusion

Both the Speed and EstSpeed variables are equally representative of the true speed at onset of braking.

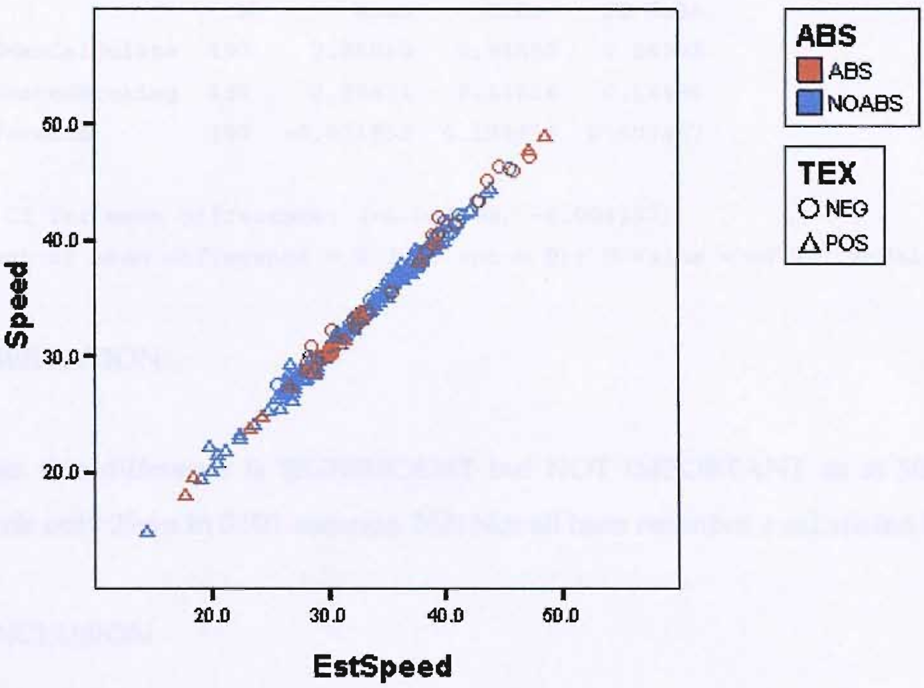


Figure 48 internally calculated speeds (Speed) versus derived speeds (Est. Speed) for speed at onset of braking

Post-test Calculation of BRAKING Time to Stop

By marking the onset and completion of the simulated braking manoeuvres, an estimate of the braking time for the test was calculated from their difference (EstimatedBrakingTime).

The SkidMan device uses the decelerometer output to calculate internally a time to stop from onset of braking (SkidManCalculatedBrakingTime). It should be noted not all tests recorded included this information. Figure 49 graphically illustrates the distribution of the two variables. A Paired T-Test confirmed a significant difference between the two variables.

Paired T for SkidManCalculatedBrakingTime - EstimatedBrakingtime

	N	Mean	StDev	SE Mean
SkidManCalculate	197	2.36685	0.61655	0.04393
EstimatedBraking	197	2.38871	0.63016	0.04490
Difference	197	-0.021853	0.109996	0.007837

```
95% CI for mean difference: (-0.037308, -0.006397)
T-Test of mean difference = 0 (vs. not = 0): T-Value = -2.79  P-Value = 0.006
```

OBSERVATION

Again this difference is SIGNIFICANT but NOT IMPORTANT as at 50km/h a vehicle travels only 29cm in 0.021 seconds. NB: Not all tests recorded a calculated braking time.

CONCLUSION

The Internally Calculated Braking Time appears suitable for use in subsequent analyses as its values correspond closely to values of braking time derived from the momentary decelerations in the time series.

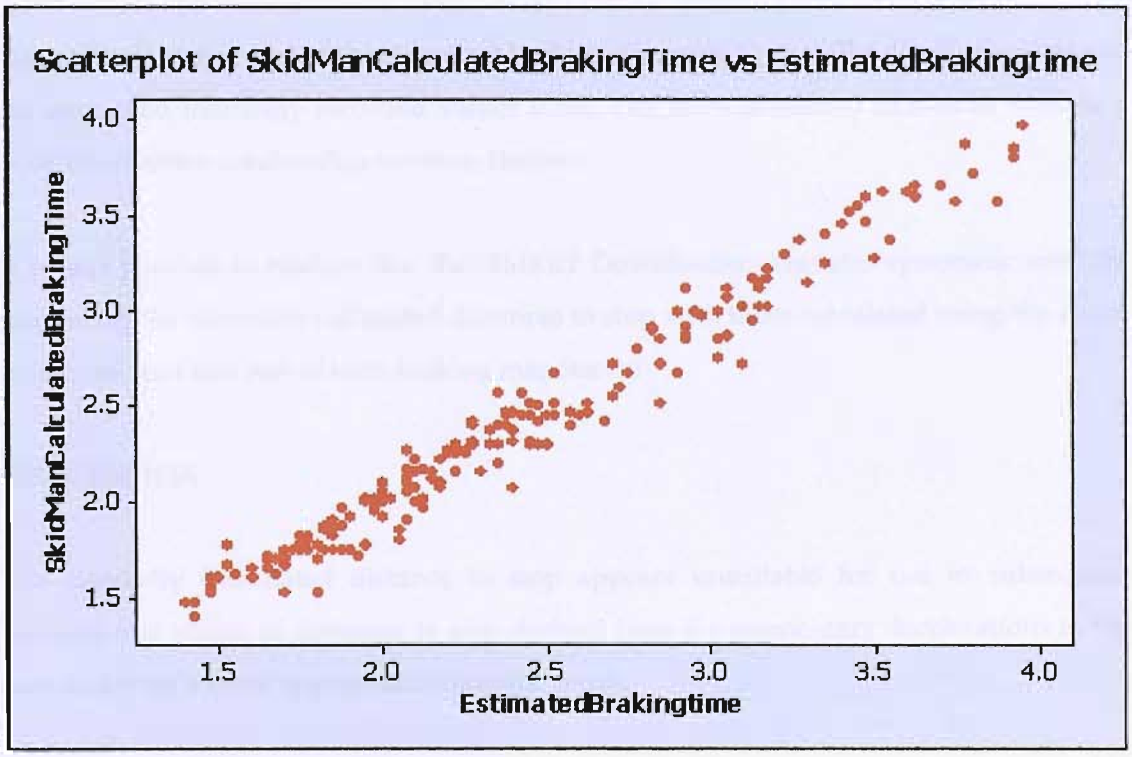


Figure 49: Scatter plot of internally calculated braking time versus braking time estimated from database

Calculation of Braking Distance to stop in metres

Since this comparison is independent of the classification process (ABS/NOABS, surface state, surface type) any errors in this classification are not relevant at this stage as here we are simply comparing internally recorded measurements against derived values from the deceleration time series).

The SIMRET downloader corrupts the recorded BRAKING distance to stop as the legacy SIMRET device the downloader application was written for and the SkidMan device use different memory registers to store this information.

An alternative measure of the distance to stop was derived from the summation of the incremental deceleration multiplied by the SkidMan sampling rate (1/40th second or 0.025 seconds) to sum the distances travelled for each of the momentary decelerations, between the limits of the braking manoeuvre already marked in the time series data.

Figure 50, A scatter plot of these derived braking distances to stop (Est_DistToStop) versus the corrupted internally recorded values (Calc_dist_from_skidman) illustrates there is a poor but positive relationship between the two.

It is thus possible to confirm that the SIMRET Downloader generates systematic error by comparing the internally calculated distances to stop with those calculated using the limits set for the start and end of each braking manoeuvre .

CONCLUSION

The Internally Calculated distance to stop appears unsuitable for use in subsequent analyses and values of distances to stop derived from the momentary decelerations in the time series are a more appropriate measure to use.

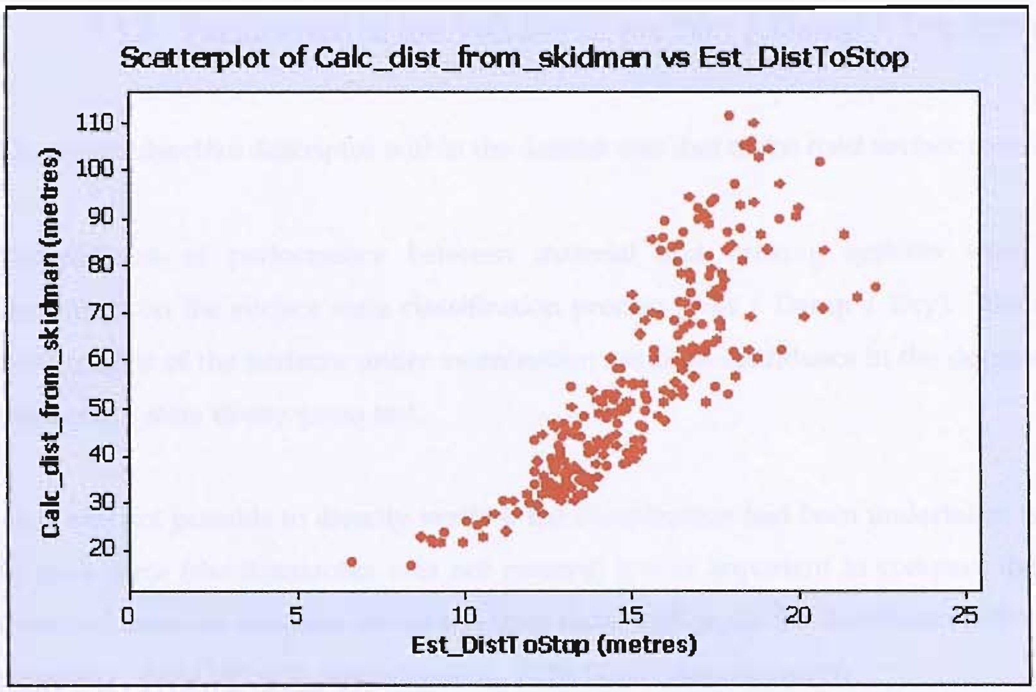


Figure 50 Internally calculated braking distance to stop versus value derived from database

3.3.3 Verification of the Validity of the Wet / Damp / Dry criteria

The most subjective descriptor within the dataset was that of the road surface condition.

Comparisons of performance between material and braking systems were highly dependent on the surface state classification process (Wet / Damp / Dry). The relative performance of the surfaces under examination required confidence in the designation of this surface state to any given test.

As it was not possible to directly verify if the classification had been undertaken correctly by each force (the Researcher was not present) it was important to compare the values extracted from the database for each surface classification via the distributions of the other classifiers (ABS/NOABS (Brake System), POS, NEG (Macrotexture)).

The use of the DAMP classifier was not consistent throughout the forces submitting data to the deceleration database (see **Table 10**). It was therefore desirable to establish whether all three descriptors were each associated with different responses in terms of deceleration values (PeakG SlideG) as would be expected from the findings of the literature search. The researchers own experience of tests carried out on dry and wet surfaces suggested an "intermediate" or "damp" state could actually exist in practice or it could be equivalent to either the WET or DRY state.

For the purposes of comparison the distribution of values by the classifiers Wet, Dry and Damp were compared for the key variables recorded in the database. The issue remained whether the DAMP classification corresponded to WET or DRY and whether it was permissible to combine WET and DAMP or DRY and DAMP to reduce the dataset to two rather than three possible surface states.

With the understanding of the "softening" of the maximum peak deceleration in response to surface water, the fact that "damp" surfaces made up the "middle distance" with respect to values of PeakG was worthy of note.

It can be easily discerned (see **Figure 51**) that there is an overlap between the Damp, Dry and Wet groups but no apparent consistent mirroring of the spread of Damp values as more approximating either the Wet or the Dry group, thus it was concluded that:

The three surface state descriptors could not be combined into two

AND

Only the DRY and the WET tests should be analysed, as these two surface states are more readily understood and more likely to be correctly identified.

Force * SURF Crosstabulation

			SURF			
			Damp	Dry	Wet	Total
Force	Derbyshire	Count	12	70	2	84
		% within Force	14.3%	83.3%	2.4%	100.0%
		% within SURF	16.7%	42.4%	11.8%	33.1%
		% of Total	4.7%	27.6%	.8%	33.1%
	Dorset	Count	35	57	9	101
		% within Force	34.7%	56.4%	8.9%	100.0%
		% within SURF	48.6%	34.5%	52.9%	39.8%
		% of Total	13.8%	22.4%	3.5%	39.8%
	Durham	Count	8	13	1	22
		% within Force	36.4%	59.1%	4.5%	100.0%
		% within SURF	11.1%	7.9%	5.9%	8.7%
		% of Total	3.1%	5.1%	.4%	8.7%
	Gwent	Count	17	15	0	32
		% within Force	53.1%	46.9%	.0%	100.0%
		% within SURF	23.6%	9.1%	.0%	12.6%
		% of Total	6.7%	5.9%	.0%	12.6%
	JB/Dorset	Count	0	10	5	15
		% within Force	.0%	66.7%	33.3%	100.0%
		% within SURF	.0%	6.1%	29.4%	5.9%
		% of Total	.0%	3.9%	2.0%	5.9%
Total		Count	72	165	17	254
		% within Force	28.3%	65.0%	6.7%	100.0%
		% within SURF	100.0%	100.0%	100.0%	100.0%
		% of Total	28.3%	65.0%	6.7%	100.0%

Table 10 Distribution of Wet, Dry and Damp classification between forces

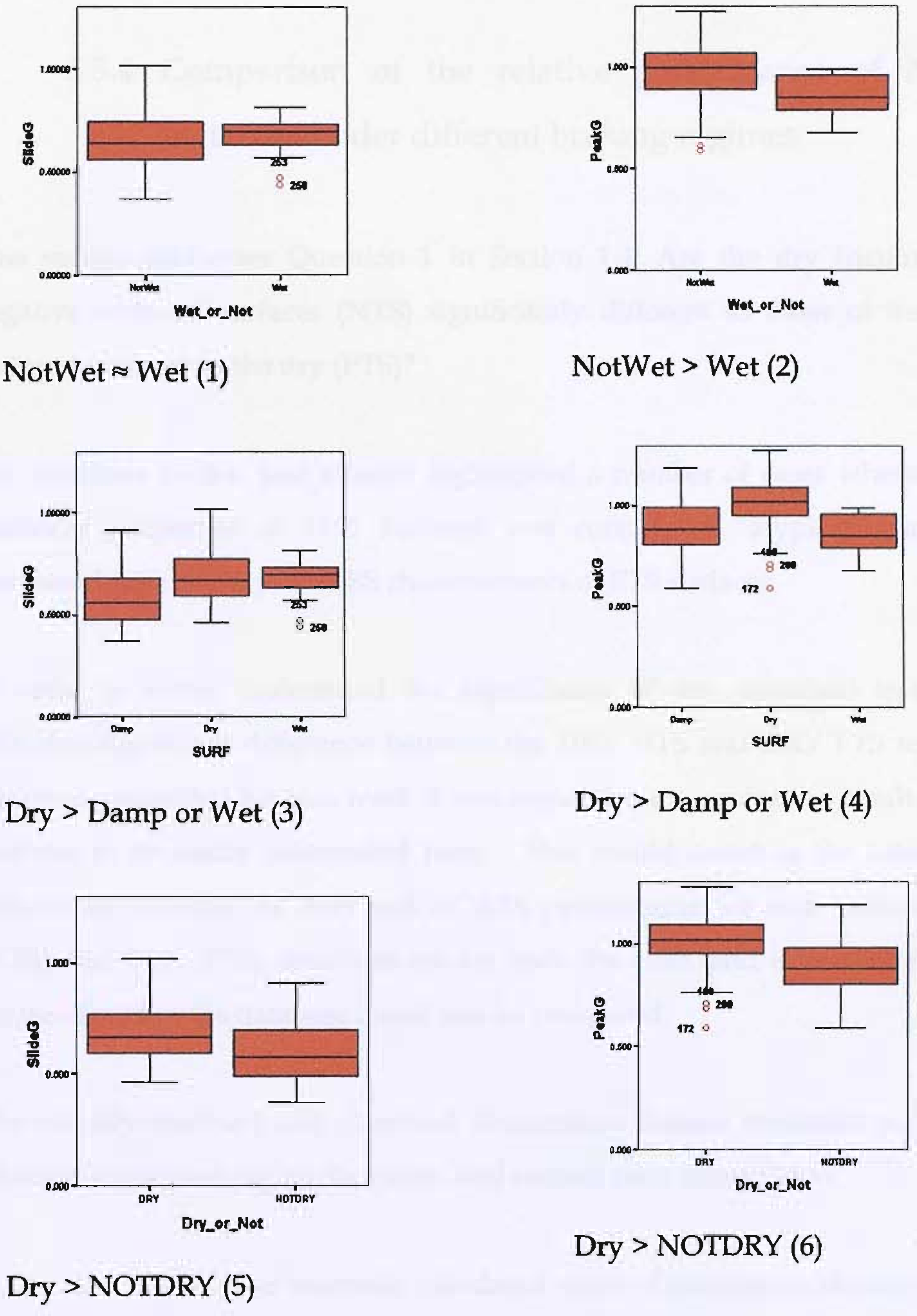


Figure 51 Combined ABS & NOABS datasets: DRY/Wet/Damp versus Dry or not versus Wet or Not for main data variables

3.3.4 Comparison of the relative performance of NTS and PTS materials under different braking regimes

This section addresses Question 1 in Section 1.4: Are the dry frictional properties of negative textured surfaces (NTS) significantly different to those of traditional positive textured surfaces in the dry (PTS)?

The literature review had already highlighted a number of cases where the dry NOABS frictional properties of NTS surfaces was considered "atypical" (and lower) when compared with the dry NOABS characteristics of PTS surfaces.

In order to better understand the significance of any statistical tests undertaken to establish significant difference between the DRY NTS and DRY PTS test results for the database assembled for this work it was important to present the results of the statistical analysis in an easily interpreted form. This would assist in the interpretation of the differences between the ABS and NOABS performance for each surface type. The NEG (NTS) and POS (PTS) distributions for both the peak and average deceleration values recorded within the database could also be compared.

The visually analysed and classified deceleration dataset contained six key variables in addition to the braking, surface type, and surface state information:

- SMO_AVG: The internally calculated value of average deceleration
- SMO_MAX: The internally calculated value of maximum deceleration
- SlideG: The value of average deceleration within the tagged limits in the dataset
- Peak G: The value of peak deceleration tagged in the dataset
- Slide G divided by Peak G

These variables were to be related to the three states of surface state (SURF: Wet or Dry), Surface Texture (TEX: POS or NEG) and braking system used in the test (ABS: ABS or NOABS).

It was proposed to establish where a significant difference existed between values derived from the deceleration database for discrete combinations of the classifying criteria for the tests: i.e. ABS NOABS, WET or DRY roads, NEGATIVE or POSITIVE texture.

Crash Investigation tests are typically undertaken in the dry without ABS (NOABS) and this is reflected in the uneven distribution of valid tests over the range of possible combinations, this inequality is shown in Figure 52.

The NULL hypothesis (Ho) in all cases was that the values derived from the database for one given combination of surface type/braking system and surface state were not significantly differently to those of any other combination under examination or their "equivalent"(i.e. ABS versus NOABS with TEX and SURF the same).

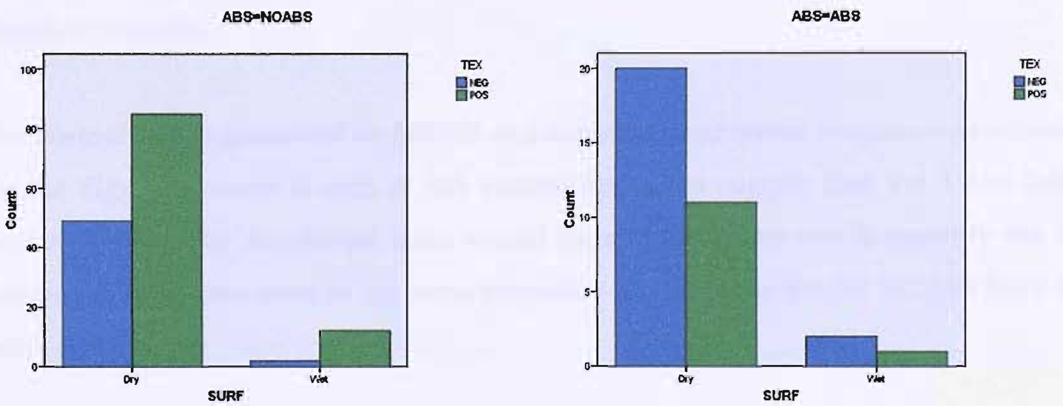


Figure 52 Unequally represented ABS and NOABS and Wet and DRY tests in the deceleration database (count = number of individual tests)

Specific Areas of interest to be addressed by the Analysis.

Dialogue with collision investigators and evidence from the literature review suggested that a difference in the levels of average deceleration generated between ABS and NOABS tests on DRY negative textured surfaces existed. A significant difference in the levels of average deceleration generated in NOABS tests may also exist between DRY NEGATIVE TEXTURED and DRY POSITIVE TEXTURED surfaces.

There may be also be evidence of the magnitude of the average to peak deceleration ratio for DRY negative textured surfaces being be greater than for the difference observed for other texture/surface state combinations.

T Tests of Significant Difference for SlideG and PeakG for dry roads and ABS/NOABS

Before T tests were undertaken, it was important to visualise the distribution of the data that was going to be compared, to this end, SPSS15 was used to generate histograms with the relevant normal distribution curve superimposed. Juxtaposing the histograms for the pairs of values being compared (e.g. ABS DRY NEGATIVE v NOABS DRY NEGATIVE) enables a simple comparison to be made supported or discredited by subsequent statistical analysis.

The normal curves generated by SPSS15 and superimposed on the frequency distributions for the Figures already shown in this section appear to suggest that the T test (which requires a normally distributed data) would be an appropriate test to quantify the very noticeable differences seen in the same frequency distributions for the NOABS DRY NTS tests.

Thus, the functionality of MiniTab 14 was used to undertake two sample T tests and simultaneously generate box plots of the distributions compared to assist in the interpretation of the T statistics.

In each case the null hypothesis (H_0) was that no significant difference existed between the datasets compared and a 95% confidence interval was chosen for the significance of the difference between the datasets tested. Table 11 summarises verbose descriptions for the T Test outputs of Minitab 14.

Average Deceleration (SlideG) DRY SURFACES

Sig. diff. (>99%)	ABS NEG	ABS POS	NOABS NEG	NOABS POS
ABS NEG	X	X	**ABS Higher**	X
ABS POS	**NEG Higher**	X	X	**ABS Higher**
NOABS NEG	X	X	x	X
NOABS POS	X	X	**NEG Lower**	X

Peak Deceleration (PeakG) DRY SURFACE

Sig. diff. (>99%)	ABS NEG	ABS POS	NOABS NEG	NOABS POS
ABS NEG	X	X	**ABS Lower**	X
ABS POS	**NO DIFF**	X	X	**ABS Lower**
NOABS NEG	X	X	X	X
NOABS POS	X	X	**NO DIFF**	X

Table 11 Summary of T Test results on DRY ROAD tests

Figures Figure 53

Verbose Summary of Average Deceleration (Slide G) T tests

H0: Average deceleration NOABS DRY NEGATIVE = NOABS DRY POSITIVE
Reject H0 at P=0.000 level NOABS DRY NEGATIVE < NOABS DRY POSITIVE
Conclusion: DRY NEGATIVE surfaces have a significantly lower level of average NOABS deceleration than DRY POSITIVE surfaces.

H0: Average deceleration ABS DRY NEGATIVE = ABS DRY POSITIVE
Reject H0 at P=0.025 level ABS DRY NEGATIVE > ABS DRY POSITIVE

Conclusion: DRY NEGATIVE surfaces have a significantly higher level of average ABS deceleration than DRY POSITIVE surfaces

H0: Average deceleration DRY ABS POSITIVE = DRY NOABS POSITIVE
Reject H0 at P=0.012 level DRY ABS POSITIVE > DRY NOABS POSITIVE
Conclusion: DRY POSITIVE surfaces have a significantly lower level of average deceleration with NOABS than with ABS.

H0: Average deceleration DRY ABS NEGATIVE = DRY NOABS NEGATIVE
Reject H0 at P=0.000 level DRY ABS NEGATIVE > DRY NOABS NEGATIVE
Conclusion: DRY NEGATIVE surfaces have a significantly lower level of average deceleration with NOABS than with ABS.

Verbose Summary of Peak Deceleration (PeakG) T tests

H0: Peak deceleration DRY NOABS POSITIVE = DRY NOABS NEGATIVE
Accept H0 at P=0.905 DRY NOABS POSITIVE = DRY NOABS NEGATIVE
Conclusion: DRY NEGATIVE surfaces do not have a significantly different level of NOABS peak deceleration than DRY POSITIVE surfaces (See Figure 57).

H0: Peak deceleration DRY ABS POSITIVE = DRY ABS NEGATIVE
Accept H0 at P=0.337 DRY ABS POSITIVE = DRY ABS NEGATIVE
Conclusion: DRY NEGATIVE surfaces do not have a significantly different level of ABS peak deceleration than DRY POSITIVE surfaces.

H0: Peak deceleration DRY ABS NEGATIVE = DRY NOABS NEGATIVE
Reject H0 at P=0.039 DRY ABS NEGATIVE < DRY NOABS NEGATIVE
Conclusion: DRY ABS NEGATIVE surfaces do have a significantly lower level of peak deceleration than DRY NOABS NEGATIVE surfaces.

H0: Peak deceleration DRY ABS POSITIVE = DRY NOABS POSITIVE
Reject H0 at P=0.036 DRY ABS POSITIVE < DRY NOABS POSITIVE

Conclusion: DRY ABS POSITIVE surfaces do have a significantly lower level of peak deceleration than DRY NOABS POSITIVE surfaces.

Complete MiniTab 14 T Test results

MiniTab 14 T Test results are reproduced with box plots (Figure 53 through Figure 61) individually below:

```
Two-sample T for SlideAvg

TEX   N    Mean    StDev   SE Mean
NEG  50  0.5884  0.0718     0.010
POS  83  0.6836  0.0810    0.0089


Difference = mu (NEG) - mu (POS)
Estimate for difference:  -0.095168
95% CI for difference:  (-0.121900, -0.068436)
T-Test of difference = 0 (vs. not =): T-Value = -7.05  P-Value = 0.000  DF = 113
```

Box plot of DRY NOABS SlideAvg by TEX

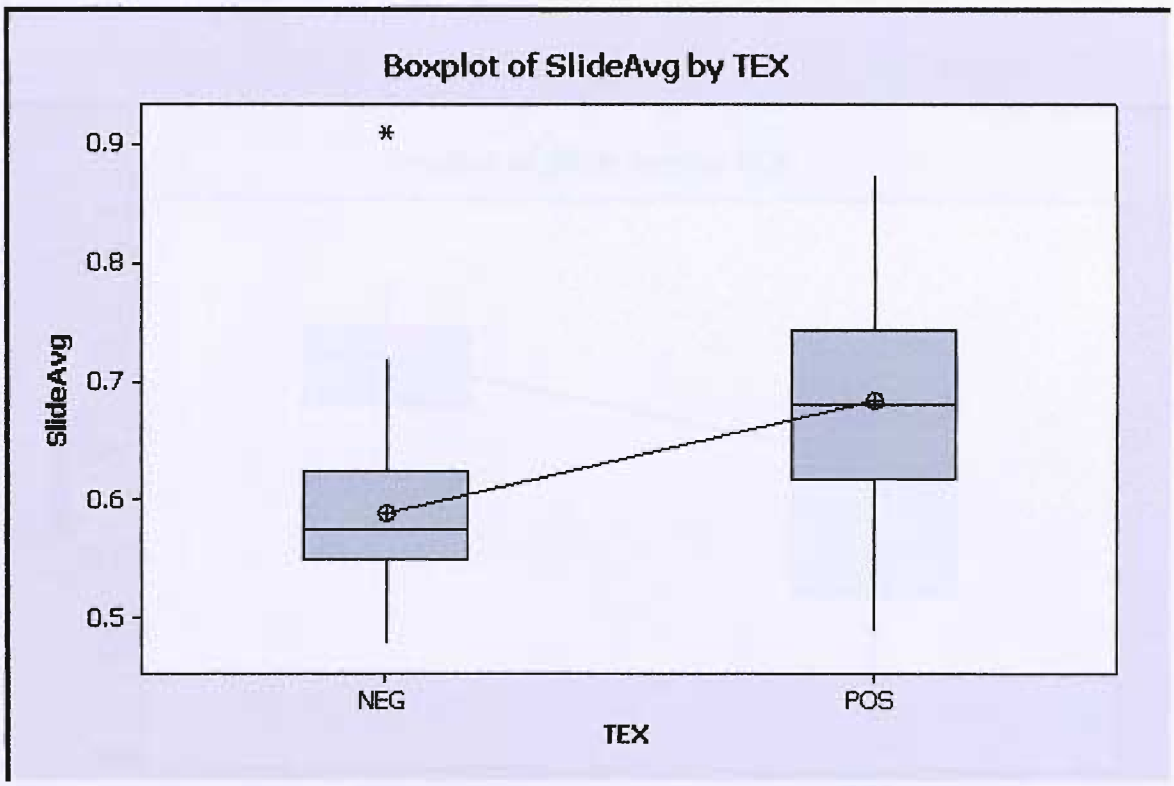


Figure 53 Two-Sample T-Test and CI: SlideAvg, NOABS DRY NEGATIVE versus DRY POSITIVE

```
Two-sample T for SlideAvg

TEX   N    Mean   StDev  SE Mean
NEG  19  0.8951  0.0460    0.011
POS  15   0.796   0.149    0.038


Difference = mu (NEG) - mu (POS)
Estimate for difference:  0.098839
95% CI for difference:  (0.014382, 0.183296)
T-Test of difference = 0 (vs. not =): T-Value = 2.48  P-Value = 0.025  DF = 16
```

Box plot of DRY ABS SlideAvg by TEX

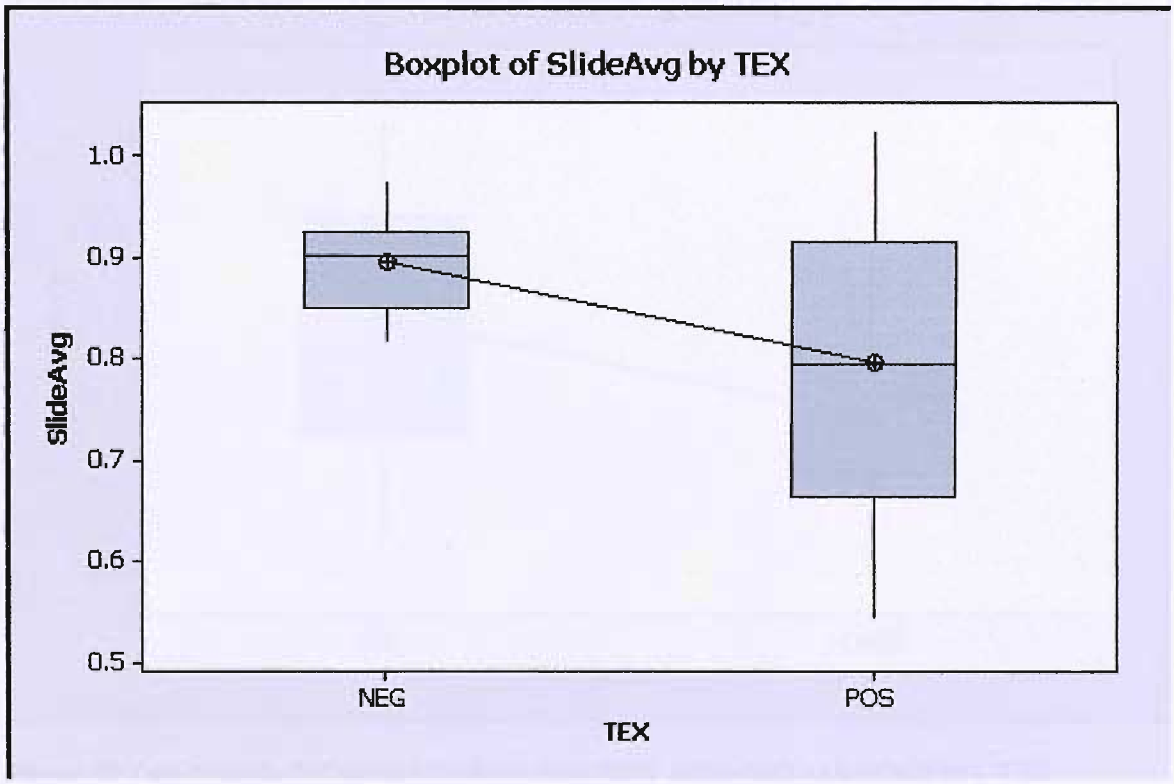


Figure 54 Two-Sample T-Test and CI: SlideAvg, ABS DRY NEGATIVE versus ABS DRY POSITIVE

```
Two-sample T for SlideAvg

ABS      N    Mean    StDev  SE Mean
ABS     15   0.796    0.149    0.038
NOABS   83  0.6836   0.0810   0.0089


Difference = mu (ABS) - mu (NOABS)
Estimate for difference:  0.112706
95% CI for difference:  (0.028657, 0.196756)
T-Test of difference = 0 (vs. not =): T-Value = 2.86  P-Value = 0.012  DF = 15
```

Box plot of DRY SlideAvg by ABS (POSITIVE TEX)

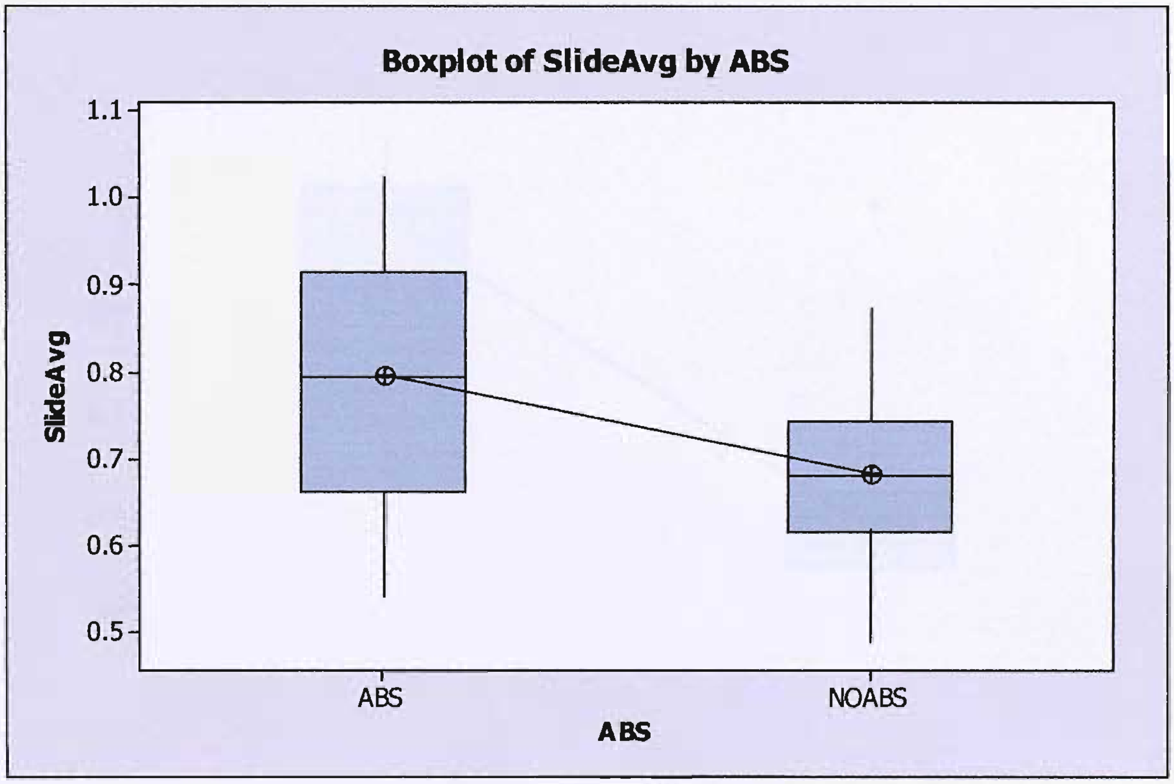


Figure 55 Two-Sample T-Test and CI: SlideAvg, DRY ABS v NOABS POSITIVE TEX

```
Two-sample T for SlideAvg

ABS      N    Mean   StDev  SE Mean
ABS     19  0.8951  0.0460    0.011
NOABS   50  0.5884  0.0718    0.010


Difference = mu (ABS) - mu (NOABS)
Estimate for difference:  0.306713
95% CI for difference:  (0.277308, 0.336119)
T-Test of difference = 0 (vs. not =): T-Value = 20.95  P-Value = 0.000  DF = 50
```

Box plot of DRY SlideAvg by ABS (NEGATIVE TEX)

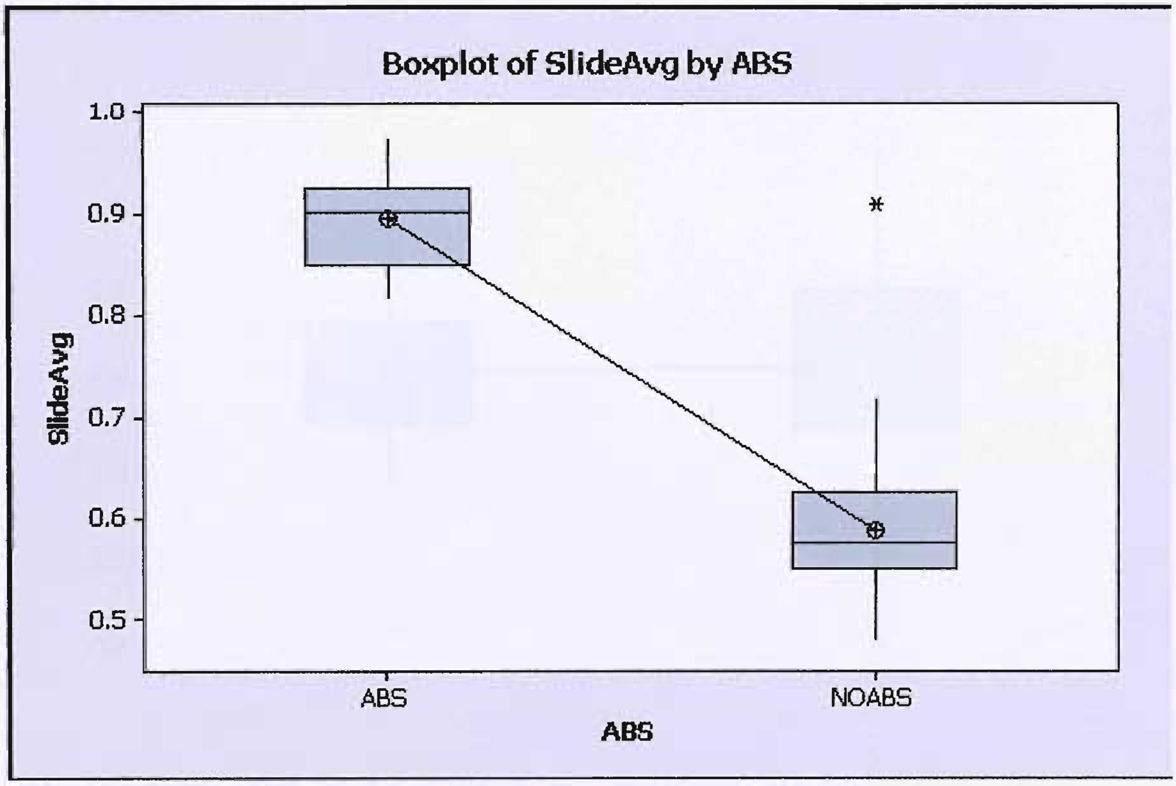


Figure 56 Results for: DRY ABS v NOABS NEGATIVE TEX Two-Sample T-Test and CI: SlideAvg, ABS

```
Two-sample T for PeakG

TEX   N    Mean   StDev  SE Mean
NEG  50  1.0128  0.0816    0.012
POS  83   1.015   0.120    0.013

Difference = mu (NEG) - mu (POS)
Estimate for difference:  -0.002095
95% CI for difference:  (-0.036746, 0.032555)
T-Test of difference = 0 (vs. not =): T-Value = -0.12  P-Value = 0.905  DF = 129
```

Box plot of DRY NOABS PeakG by TEX

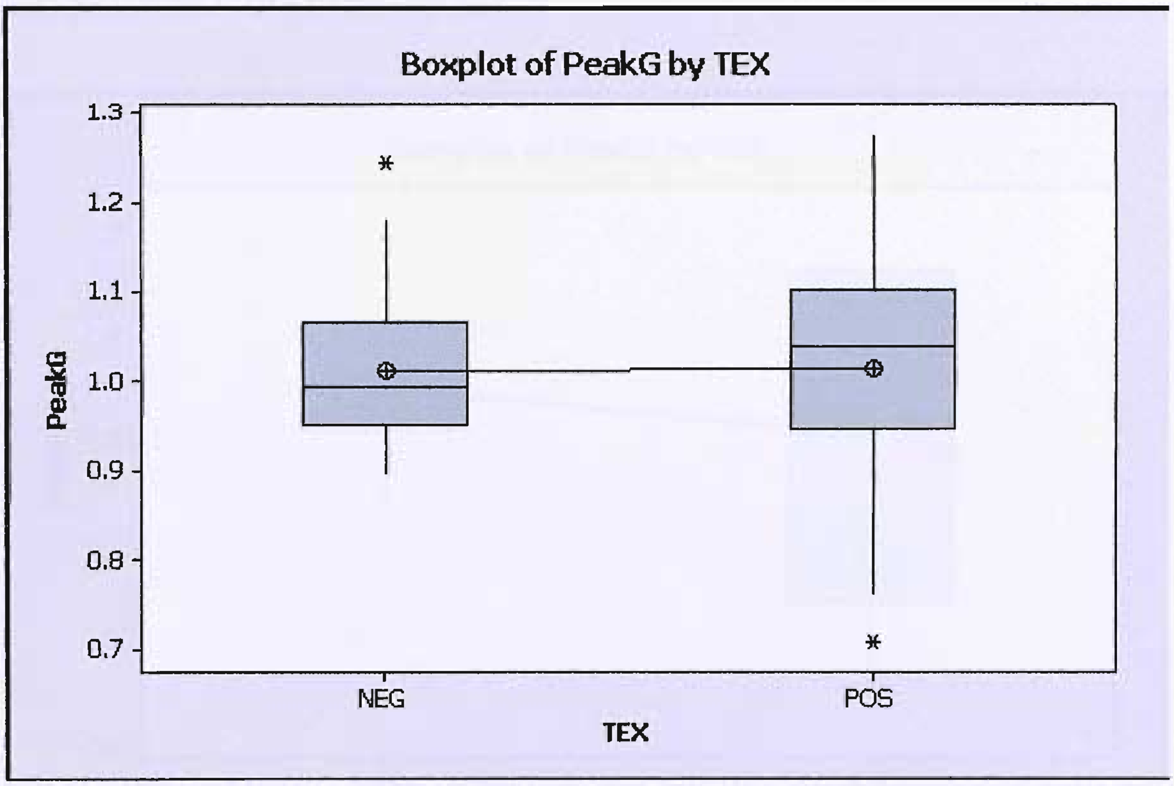


Figure 57 Results for: PeakG, NOABS POSITIVE v NEGATIVE TEXTURE Two-Sample T-Test and CI: PeakG, TEX

```
Two-sample T for PeakG

TEX   N    Mean   StDev  SE Mean
NEG  19  1.0522  0.0631    0.014
POS  15   1.008   0.165    0.043


Difference = mu (NEG) - mu (POS)
Estimate for difference:  0.044344
95% CI for difference:  (-0.050425, 0.139113)
T-Test of difference = 0 (vs. not =): T-Value = 0.99  P-Value = 0.337  DF = 17
```

Box plot of DRY ABS PeakG by TEX

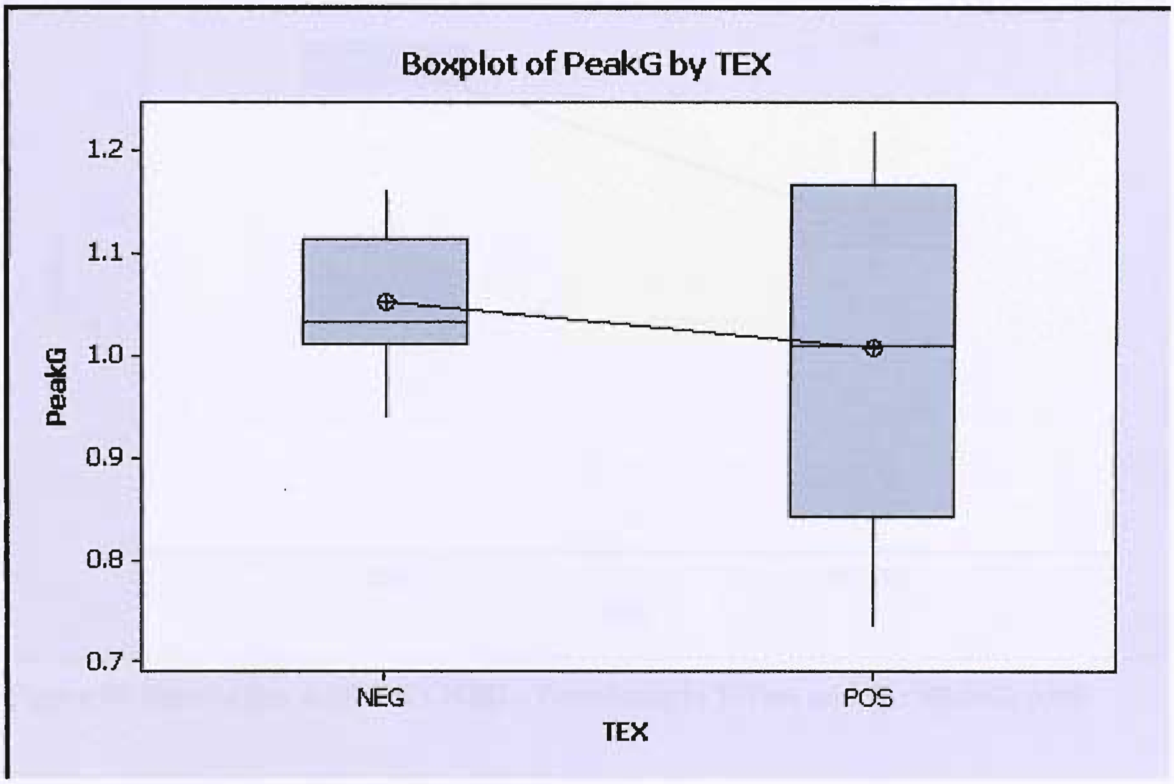


Figure 58 Results for: PeakG, ABS POSITIVE v NEGATIVE TEXTURE Two-Sample T-Test and CI: PeakG, TEX

Two-sample T for SlideG

ABS	N	Mean	StDev	SE Mean
ABS	20	0.8777	0.0838	0.019
NOABS	49	0.5888	0.0735	0.010

Difference = mu (ABS) - mu (NOABS)
Estimate for difference: 0.288929
95% CI for difference: (0.245112, 0.332745)
T-Test of difference = 0 (vs. not =): T-Value = 13.45 P-Value = 0.000 DF = 31

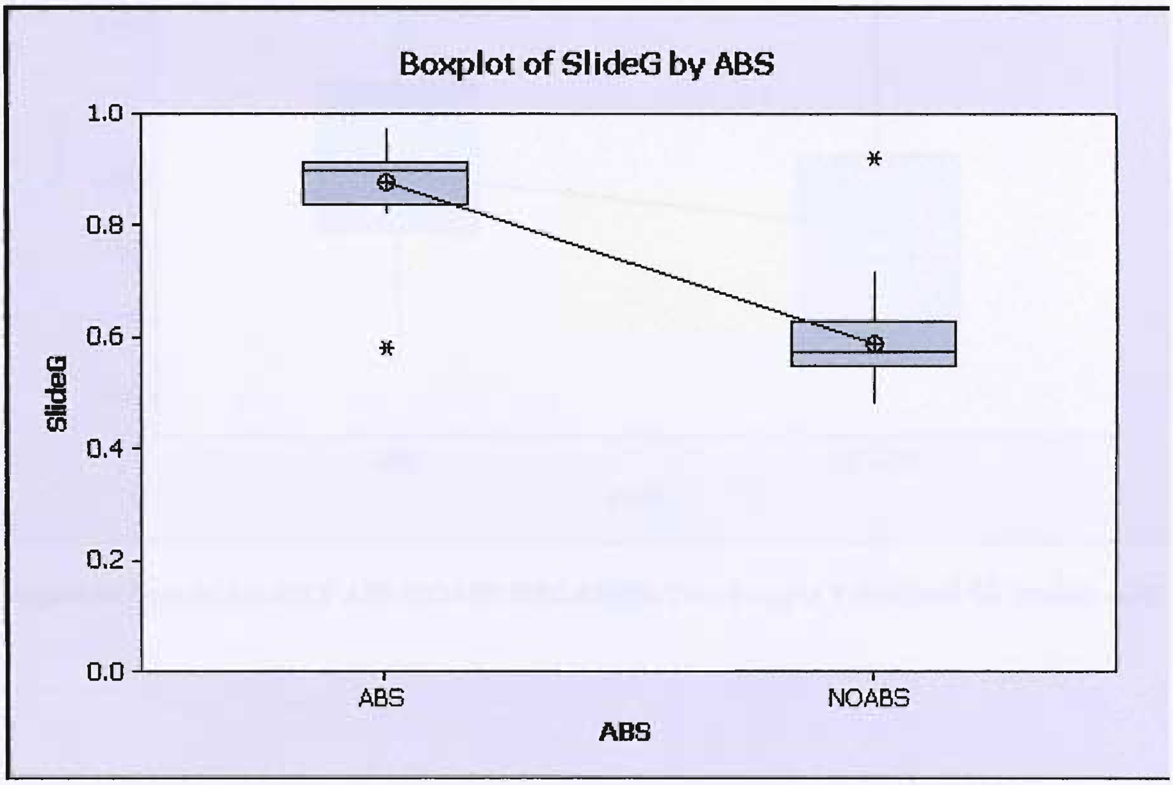


Figure 59 Results for: ABS DRY NEG - Two-Sample T-Test and CI: SlideG, ABS

```
Two-sample T for PeakG

ABS     N    Mean   StDev  SE Mean
ABS    19  1.0522  0.0631    0.014
NOABS  50  1.0128  0.0816    0.012

Difference = mu (ABS) - mu (NOABS)
Estimate for difference:  0.039451
95% CI for difference:  (0.002076, 0.076825)
T-Test of difference = 0 (vs. not =): T-Value = 2.13  P-Value = 0.039  DF = 41
```

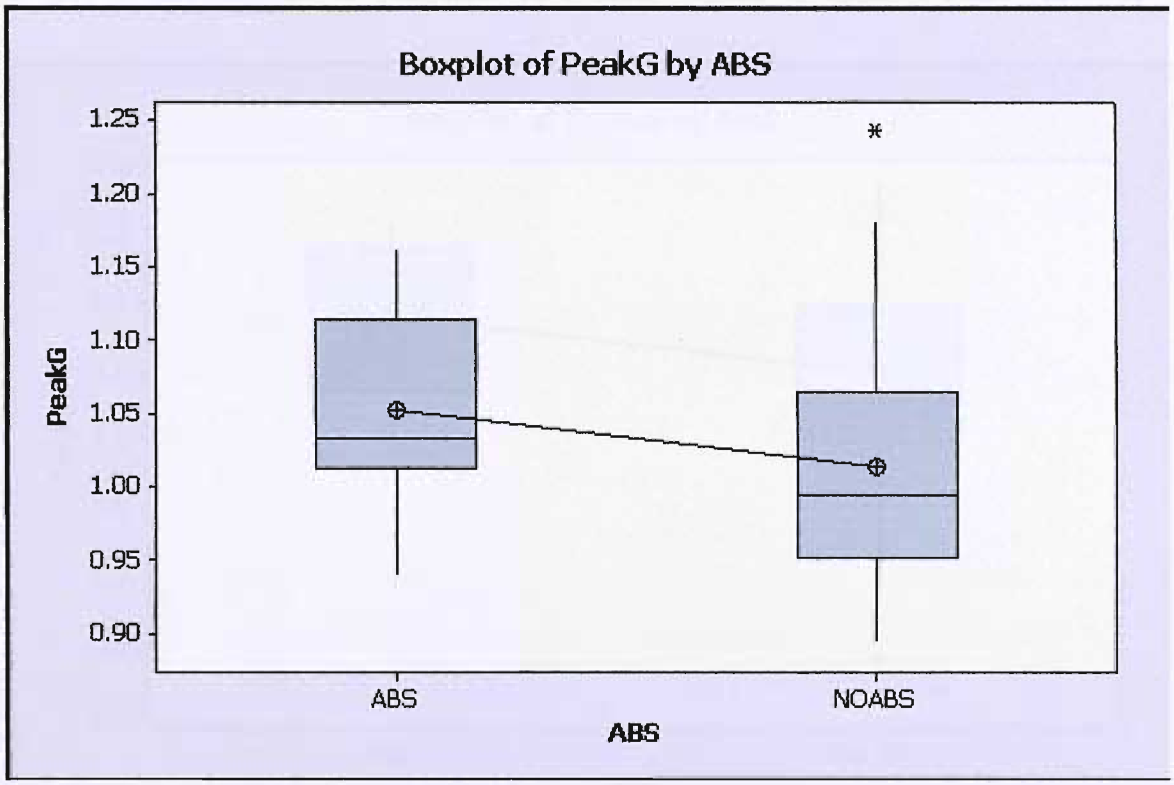


Figure 60 Results for: DRY ABS NOABS NEGATIVE Two-Sample T-Test and CI: PeakG, ABS

```
Two-sample T for PeakG

ABS      N   Mean  StDev  SE Mean
ABS     11  1.084  0.109    0.033
NOABS   85  1.001  0.136    0.015

Difference = mu (ABS) - mu (NOABS)
Estimate for difference:  0.083364
95% CI for difference:  (0.006250, 0.160478)
T-Test of difference = 0 (vs. not =): T-Value = 2.32  P-Value = 0.036  DF = 14
```

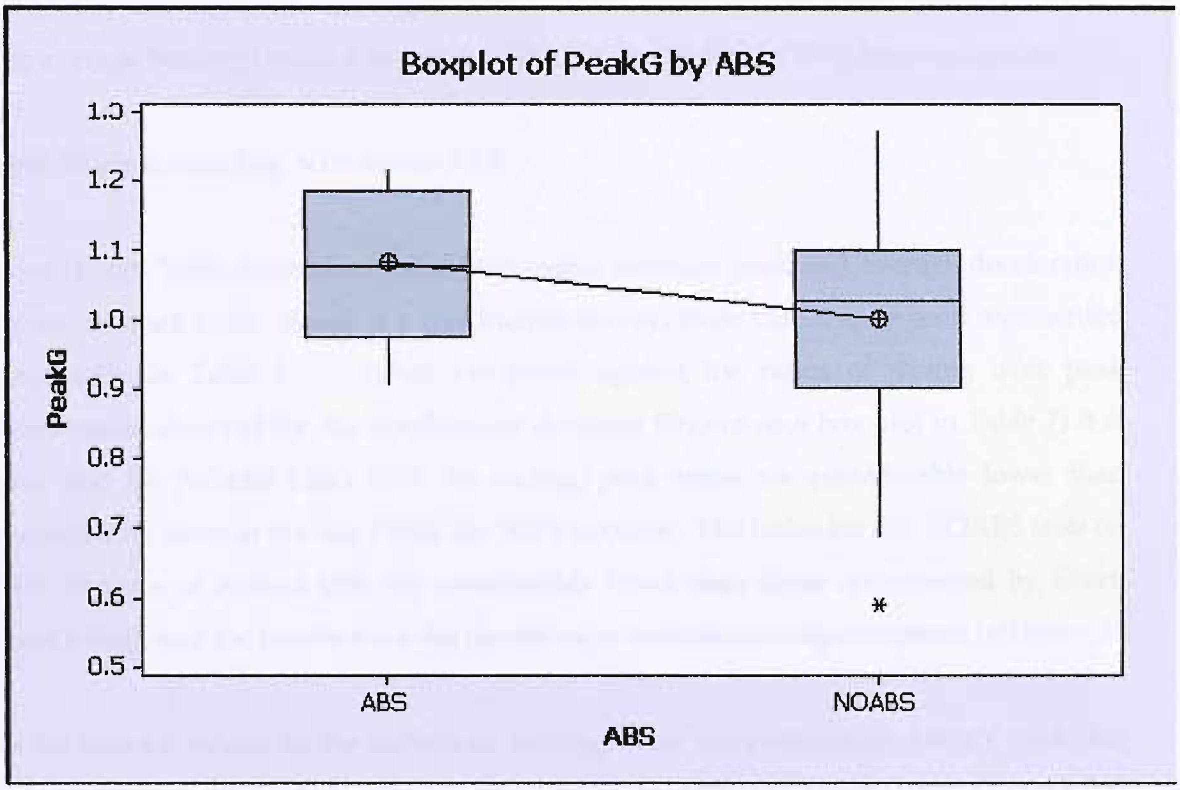


Figure 61 Results for: DRY ABS NOABS POSITIVE Two-Sample T-Test and CI: PeakG, ABS

T Tests of Significant Difference for Braking Distance to Stop between ABS and NOABS for NEG versus POS surfaces

A significant difference exists at better than the 5% (0.05) level for the Braking Distance to Stop between for DRY NOABS tests between POSITIVE and NEGATIVE surfaces.

The average Braking Distance to stop is LONGER for the NEGATIVE textured surface.

Peak/Slide Ratios: Dry NTS versus PTS

Ebert (Ebert, 1989) documented the relationship between peak and average deceleration values obtained in the course of a tyre friction survey, these values have been represented graphically in Table 6 . When compared against the ratios of sliding over peak deceleration observed for the deceleration database (Shown as a box plot in Table 7) it is clear that for NOABS NEG DRY the sliding/peak ratios are considerably lower than encounter by Ebert in the late 1980's for WET surfaces. The ratios for dry NOABS tests on NEG surfaces of around 60% are considerably lower than those documented by Ebert. Ebert's work and the results from the deceleration database are superimposed in Figure 64.

As the discrete values for the individual readings were not available for Ebert's work, the only direct comparison between peak slide ratios possible was between the wet and dry groups within the deceleration database; Figure 64 adequately illustrates the difference between dry NEG (NTS) and dry POS (PTS) tests.

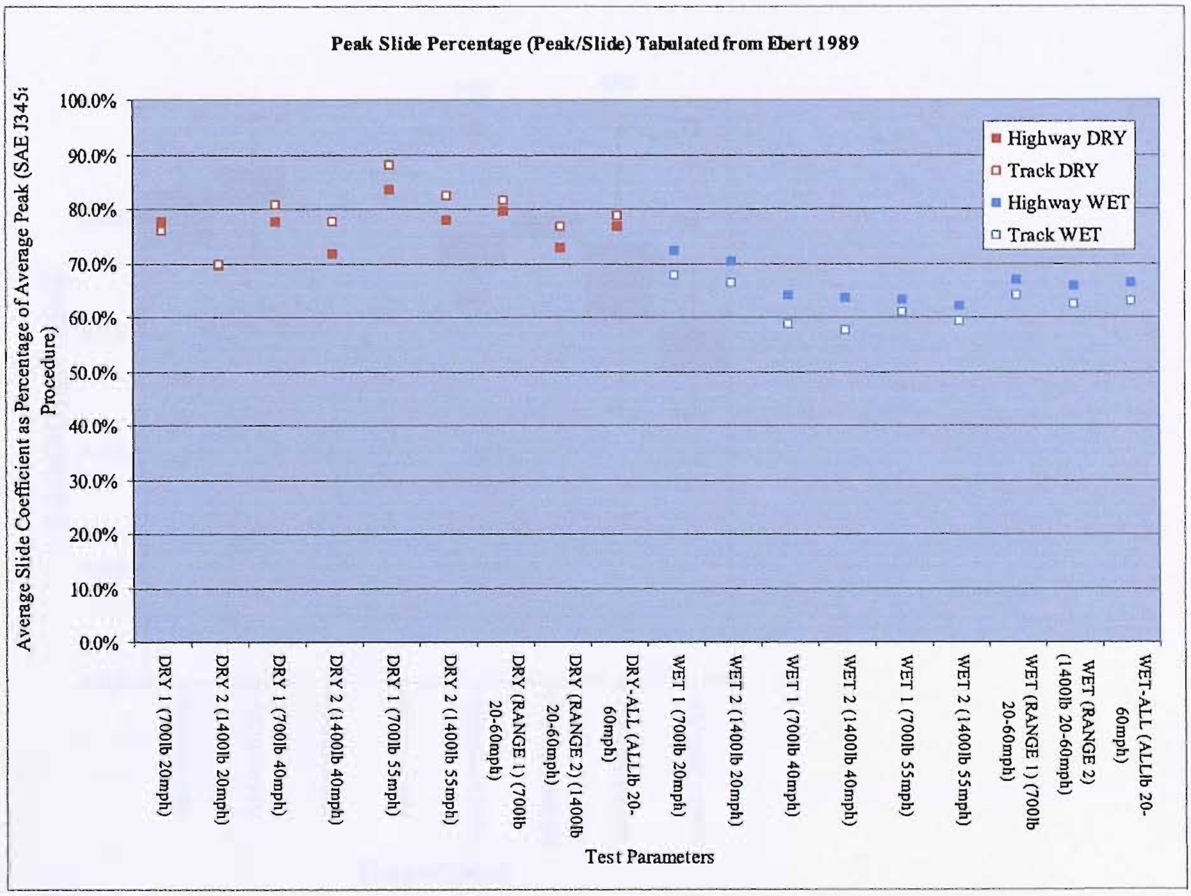


Figure 62 Existing tabulated sliding friction coefficients as a percentage of peak (Ebert, 1989)

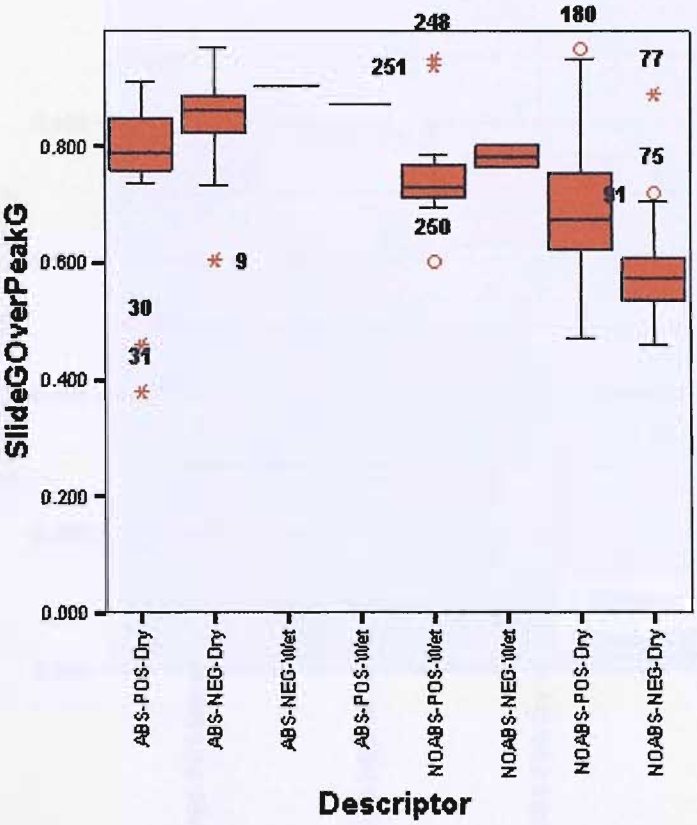


Figure 63 Box plot from SPSS of the sliding deceleration as a percentage of peak (Data from the deceleration database)

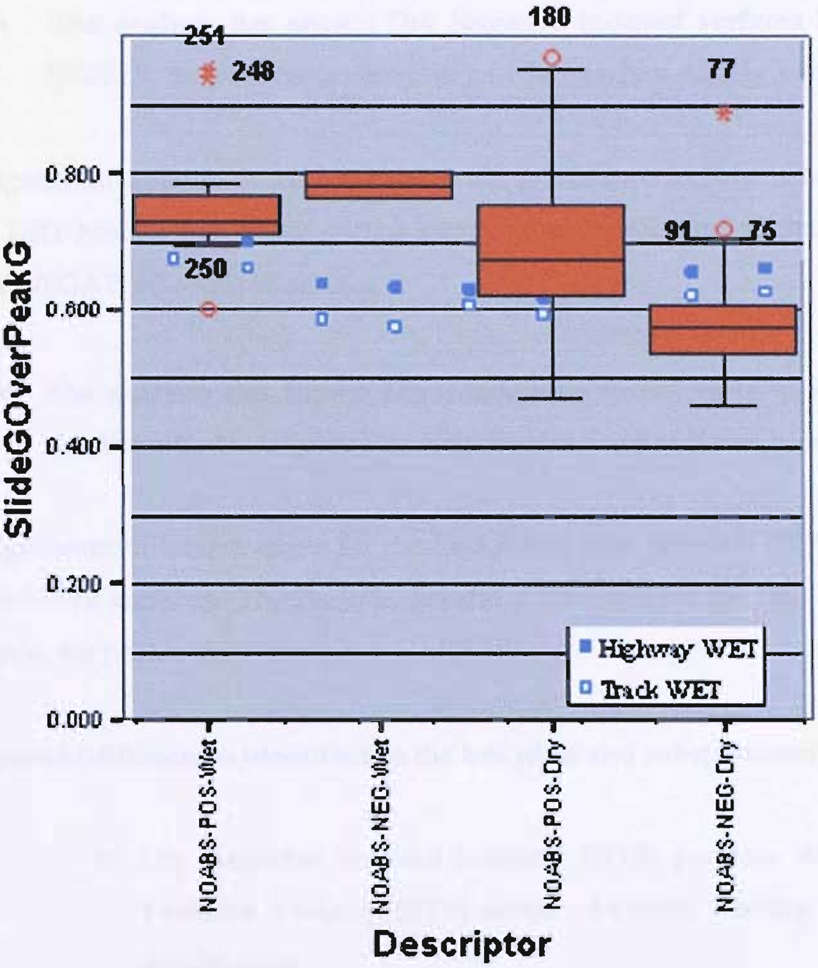


Figure 64 For the purpose of comparison Wet Track and Wet Road co-efficient data from Ebert juxtaposed with the same ratio derived for tests in the deceleration database

Summary & Observations on the T Tests

There is only a significant difference between the values of sliding friction (SlideG) between NEGATIVE and POSITIVE textured DRY surfacing with NOABS, no significant difference appears to exist elsewhere. The difference being a DECREASE in the average value of SlideG for the NEGATIVE textured surface in the DRY with NOABS.

- **The analysis has shown Dry Negative textured surfaces behave significantly WORSE to positive textured dry surfaces when ABS is not used**

- **The analysis has shown Dry Negative textured surfaces behave significantly BETTER to positive textured dry surfaces when ABS is used**

A significant difference exists for the Braking Distance to Stop between DRY POSITIVE and DRY NEGATIVE surfaces. The average Braking Distance to Stop is LONGER for the DRY NEGATIVE textured surface.

- **The analysis has shown Dry Negative textured surfaces in ABS tests behave significantly WORSE to Dry Negative textured surfaces in NO ABS tests**

A significant difference exists for the Peak/Slide ratio between DRY POSITIVE and DRY NEGATIVE surfaces. The Peak/Slide ratio is HIGHER for the DRY NEGATIVE textured surface; the peak slide difference is GREATER

Important differences identified in the box plots and substantiated by the T Testing

1) **Dry Negative textured Surfaces (NTS) perform WORSE than Positive Textured Surfaces (PTS) under NOABS braking with respect to dry deceleration**

The literature (Goudie et al., 2000, Manderson and Rudram, 1993, Rudram and Lambourn, 1981) points towards a level of dry friction / deceleration of approximately 0.7 to 0.8, this has been supported by feedback from the yahoogroups online questionnaire discussed earlier.

Figure 65 illustrates that the negative textured dry surfaces in NOABS tests returned an overall average level of sliding deceleration noticeably below that of positive textured dry surfaces with a visible longer distance to stop.

2) Negative textured surfaces (NTS) perform WORSE than positive textured surfaces with respect to estimated braking distances

3) ABS undoubtedly improves the effective level of deceleration achieved as can be observed from visual examination of the deceleration versus time plots where ABS and NOABS tests have been undertaken in parallel (Jutte and Siskens, 1997), however this difference appeared greatest between NO ABS And ABS tests on dry negative textured surfaces and this difference has been statistically proven.

4) Negative textured surfaces (NTS) perform WORSE than positive textured surfaces with respect to peak versus slide deceleration.

5) The Reduced level of sliding deceleration seen for NOABS Dry NEG surfaces as a lower value of SlideG/PeakG is not reflected in any other ABS or NOABS combination (Figure 66 & Figure 67).

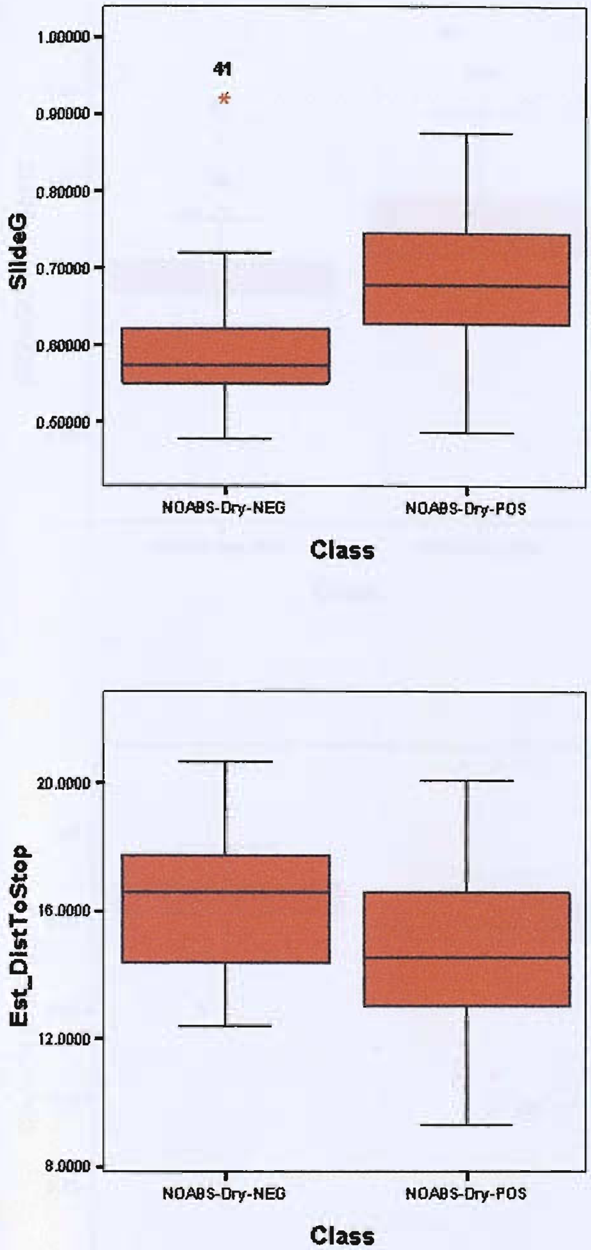


Figure 65 NOABS POS versus NOABS NEG box plots

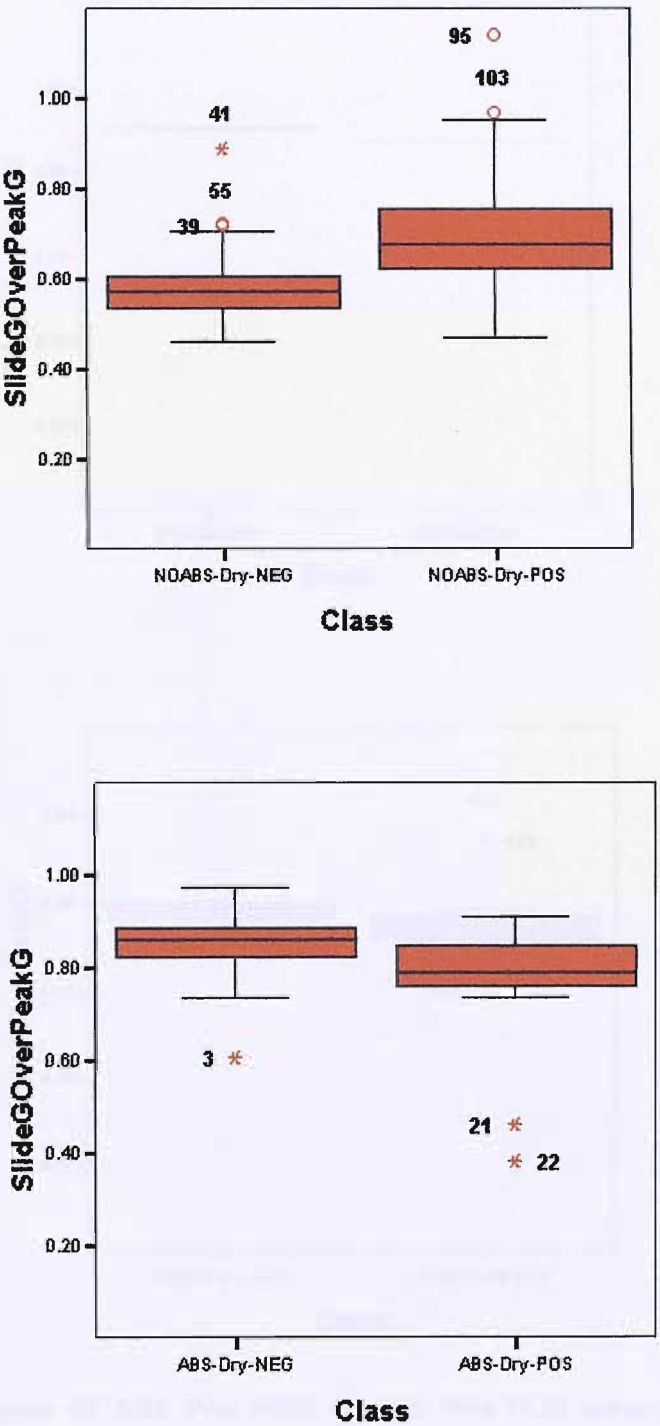


Figure 66 NOABS Dry NEG & NOABS Dry POS versus ABS Dry NEG & ABS Dry POS

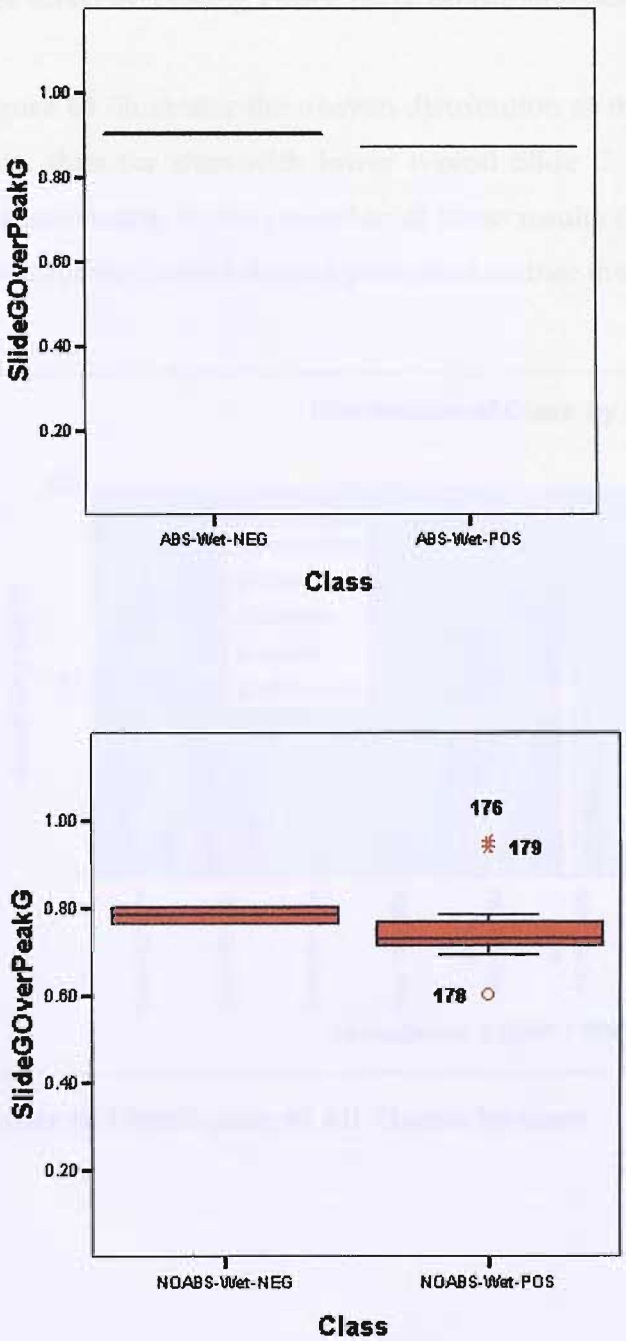


Figure 67 ABS Wet NEG & ABS Wet POS versus NOABS Wet NEG & NOABS Wet POS

The effect of Testing Police Force on the analysis

Figure 68 illustrates the uneven distribution of the classes between the forces submitting data, thus for sites with lower typical Slide G i.e. NOABS NEG Dry Tests the forces predominating in the provision of these results (Figure 69) will be reflect in the analysis however the limited dataset prevented further investigation of this.

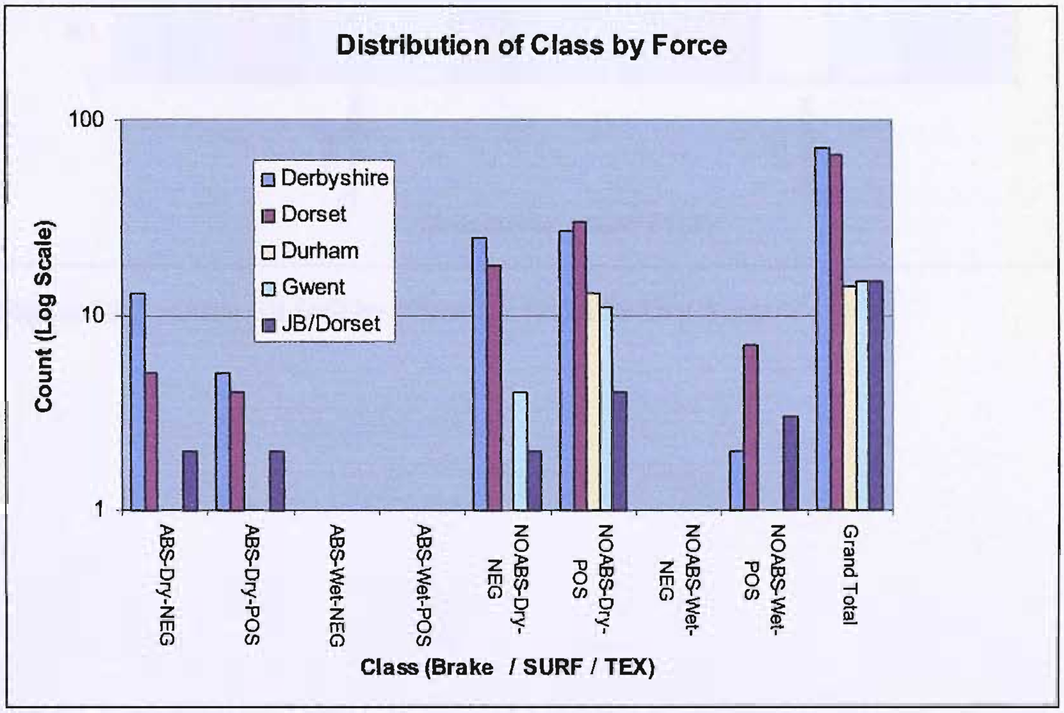


Figure 68 Distribution of All Classes by force

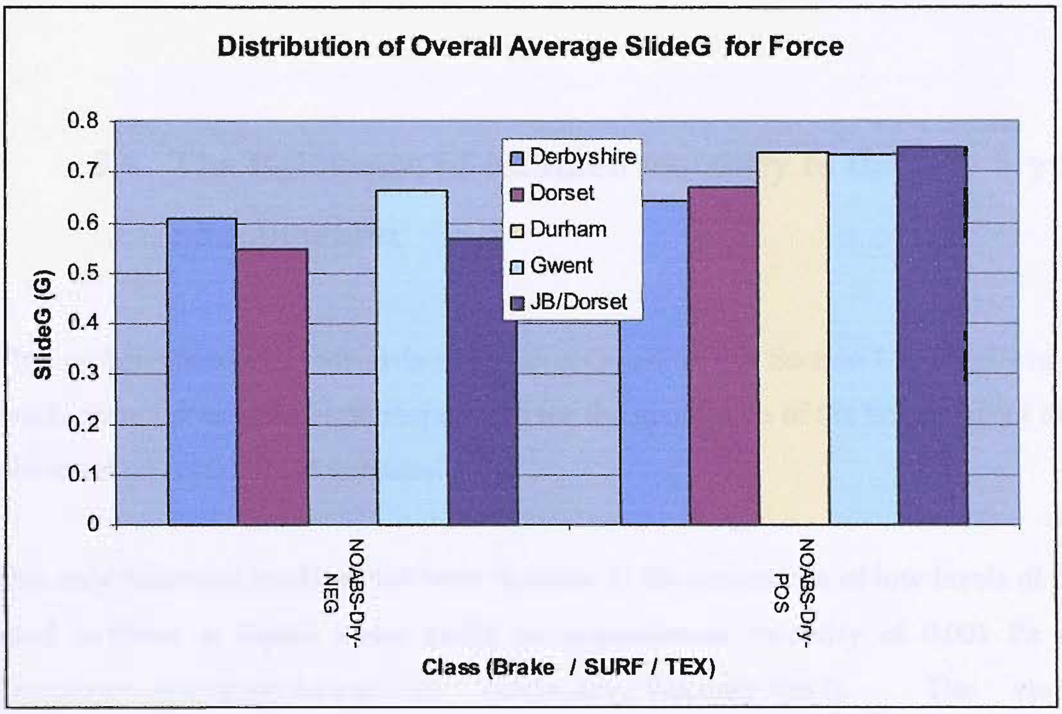
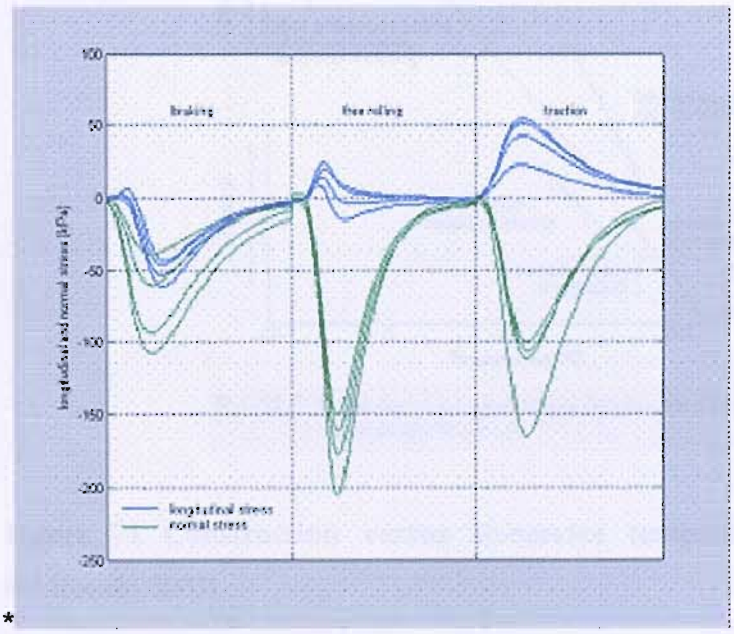


Figure 69 Average SlideG by Force for NOABS Dry Tests

3.4 The Relevance of bitumen viscosity to the low dry friction phenomenon

This section contributes towards addressing Question 4 in Section 1.4: What was the likely mechanism (or mechanisms) responsible for the generation of the low levels of dry friction observed on certain NTS surfaces?

The only reference medium we have to relate to the generation of low levels of friction on road surfaces is liquid water (with an approximate viscosity of 0.001 Pa s (source: http://www.spacegrant.hawaii.edu /class_acts/Viscosity.html). The viscosity of bituminous binders is typically 10^5-10^9 Pa S, (Read and Whiteoak, 2003).



*

Figure 70 Tyre/road contact pressures observed by Anghelache (Anghelache and Moisescu, 2006)

The figure reproduced from the Shell Bitumen Handbook (Figure 72) suggests 100 pen bitumen could possess a viscosity as low as that of engine oils at temperatures in excess of

135°c. The viscosity of SAE 10 - SAE 50 Motor Oil 0.2-0.5 Pa S, calculated using the conversion from http://www.liquidcontrol.com/etoolbox/viscosity.html : (1 Centipoise = 1 mPas (Millipascal Second).

Research carried out by TRL (Viner and Poole, 2003, Lambourn and Viner, 2006) identified that waste engine oil (likely to be within the SAE range 10-50) on the road surface could generate locked wheel co-coefficients of friction as low as 0.41 on an asphalt surface. Diesel fuel oil on concrete could produce co-coefficients of friction as low as 0.44 (see Table 12). These low levels of locked wheel co-coefficients of friction are typical of those observed elsewhere for the low dry friction phenomenon, both for those bituplaning events documented in the literature and those identified within the deceleration database.

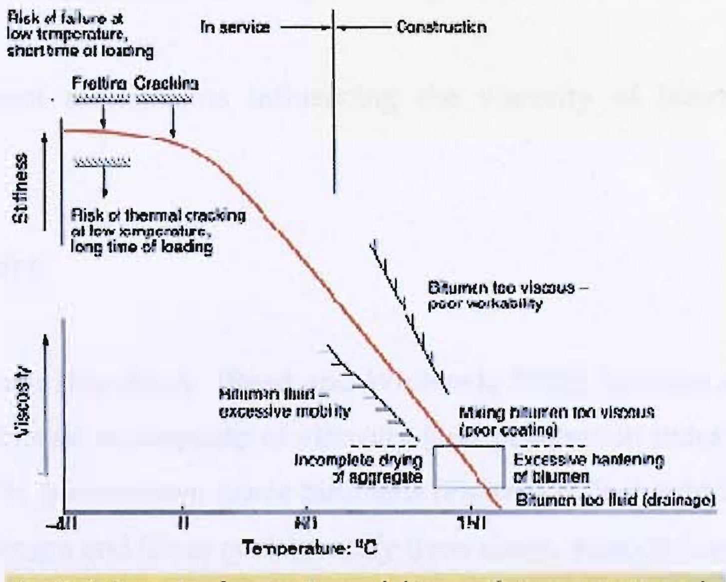


Fig. 10.1 Properties of penetration grade bitumens during construction and subsequently in service

Figure 71 Construction versus In-service temperatures for bitumens (Read and Whiteoak, 2003)

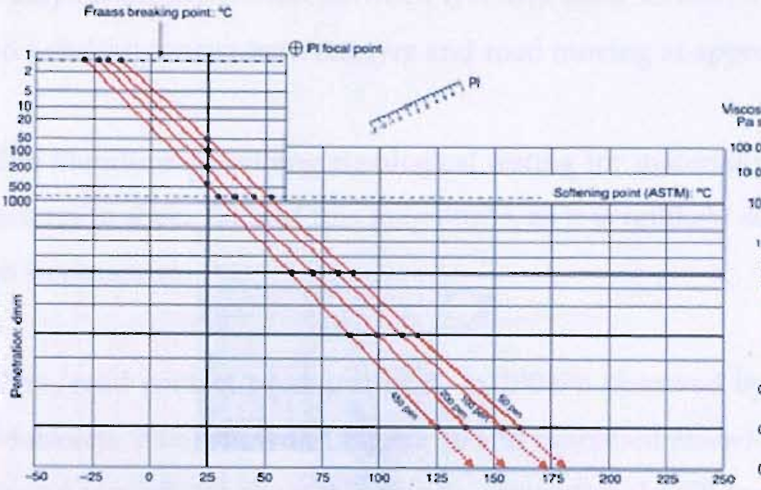


Figure 72 Bitumen viscosities with temperature (Read and Whiteoak, 2003)

The predominant mechanisms influencing the viscosity of bituminous binders are identified as:

1) Temperature.

The Shell Bitumen Handbook (Read and Whiteoak, 2003)) includes a number of figures illustrating the classic relationship of viscosity (and penetration index) to temperature for a number of PEN (penetration) grade bitumens (Figure 72). It should be observed that the addition of polymers and fibres could modify these classic relationships.

Figure 72 can be extrapolated towards the temperatures observed at the tyre/road interface during the IR imaging exercises at Madingley described elsewhere. Indeed an unmodified 100-pen binder would have its viscosity reduced to 0.1 Pa s (approximately equal to that of olive oil) was it to be able to stabilise at a temperature of 175°c.

2) Shear & Shear Thinning

Shearing of a bituminous material can potentially lead to a reduction in the effective viscosity of the bituminous film between tyre and road surfacing aggregate. When studying the interaction between tyre and road surface, a vehicle speed of 50kph equates to a sliding contact between tyre and road moving at approximately 13.4 m/sec.

The literature describing rheological testing for material performance does not appear to extend to shear rates of this magnitude, as it is unlikely such shear rates would ever exist in its structure.

Tyre/road contact pressures of 50 to 100kPa observed by Anghelache (Anghelache and Moisescu, 2006) shown in **Figure 70** and described elsewhere, equate to only 50% of those found to generate shear thinning in conventional DSR testing such as that carried out by Palade (Palade et al., 2000).

Surface condition	Asphalt surface		Concrete surface	
	Skid cars	PFT	Skid cars	PFT
Dry	0.78	N/A	0.85	N/A
Wet	0.64	0.68	0.64	0.52†
Waste engine oil	0.41	0.01	-	-
Engine oil & absorbent	0.55	0.30	-	-
Oil & absorbent swept off	0.57	0.58	-	-
Diesel oil	-	-	0.44	0.24
Diesel oil & absorbent	-	-	0.52	0.57
Diesel & absorbent swept off	-	-	0.65	0.82
Diesel and rain water	-	-	0.63	0.24
Wet clay	0.48	0.28	0.54	0.38
Wet clay swept off	0.66	0.54	0.59	0.36
Coarse sand	0.52	0.14	0.56	0.25

†Value for pre-wetted tests only. Value including self-wetted tests is 0.48.

Table 12 Observed locked wheel coefficients of friction for contaminated sections of Road (Lambourn and Viner, 2006)

3) Thin Layer Deformation

Without direct evidence of shear thinning or thermally reduced viscosity, it may be possible to envisage a known condition: that of the high shear described above to being a factor in the generation of low levels of dry friction when combined with a raised contact patch temperature.

The binder film on a typical UK NTS (an SMA) would be approximately 11μm thick (Richardson, 1999).

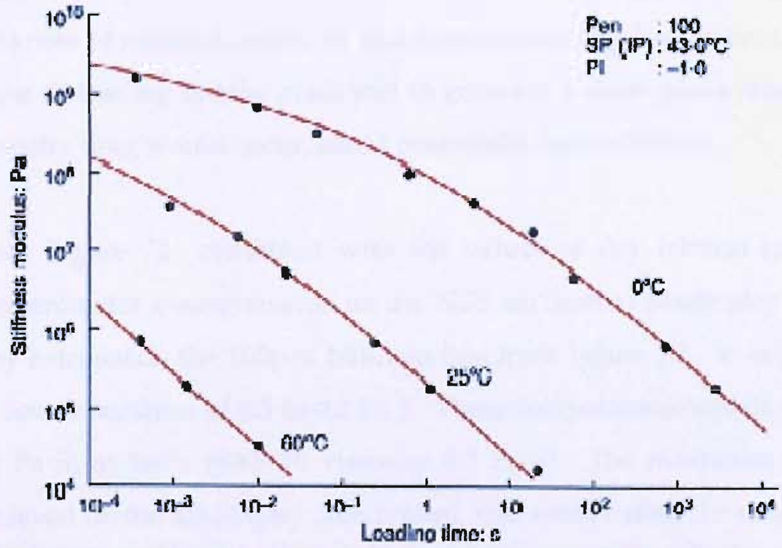


Fig. 7.16 The effect of temperature and loading time on the stiffness of a 100 pen bitumen

Figure 73 Temperature and loading time effects on bitumen stiffness (Read and Whiteoak, 2003)

Based on a vehicle speed of 13m/sec at the onset of braking at 50 kph the loading time across a contact patch estimated to be approximately 190mm wide and 150mm longitudinally (from the "hot footprint" of the road/tyre contact show in Figure 74) would be;

(150mm/13000mm) seconds = 0.0115 seconds (approximately 10^{-2} seconds)

From
Figure 73 , this would equate to a stiffness modulus of between 10^4 and 10^5 Pa at 60°c. If the temperatures observed at the tyre road interface are brought into the equation one might expect a greatly reduced stiffness modulus (i.e. deformation would occur). However, this assumes there would be time for the heating of the road surface by the tyre to have an effect. Additionally any influence of the added rubber polymer has not been considered.

With the temperature of the road surface seen to have reached a given value, the necessary thickness of material heated to that temperature required to enable deformation along the plane of loading to take place and to generate a shear plane along which apparently low viscosity drag would occur, could potentially be established.

From Figure 72 combined with the values of dry friction (μ) from the dry NOABS decelerometer measurements on the NTS surfaces at Madingley (approximately 0.5), one may extrapolate the 100pen bitumen line from Figure 72 to estimate the temperature to achieve viscosities of 0.5 to 0.2 Pa S. These temperatures equate to 140°c (SAE50 viscosity 0.5 Pa S) to 160°c (SAE 10 viscosity 0.2 Pa S). The maximum temperatures commonly achieved on the Madingley ABS braked tests were within the range 100°c to 140°c.

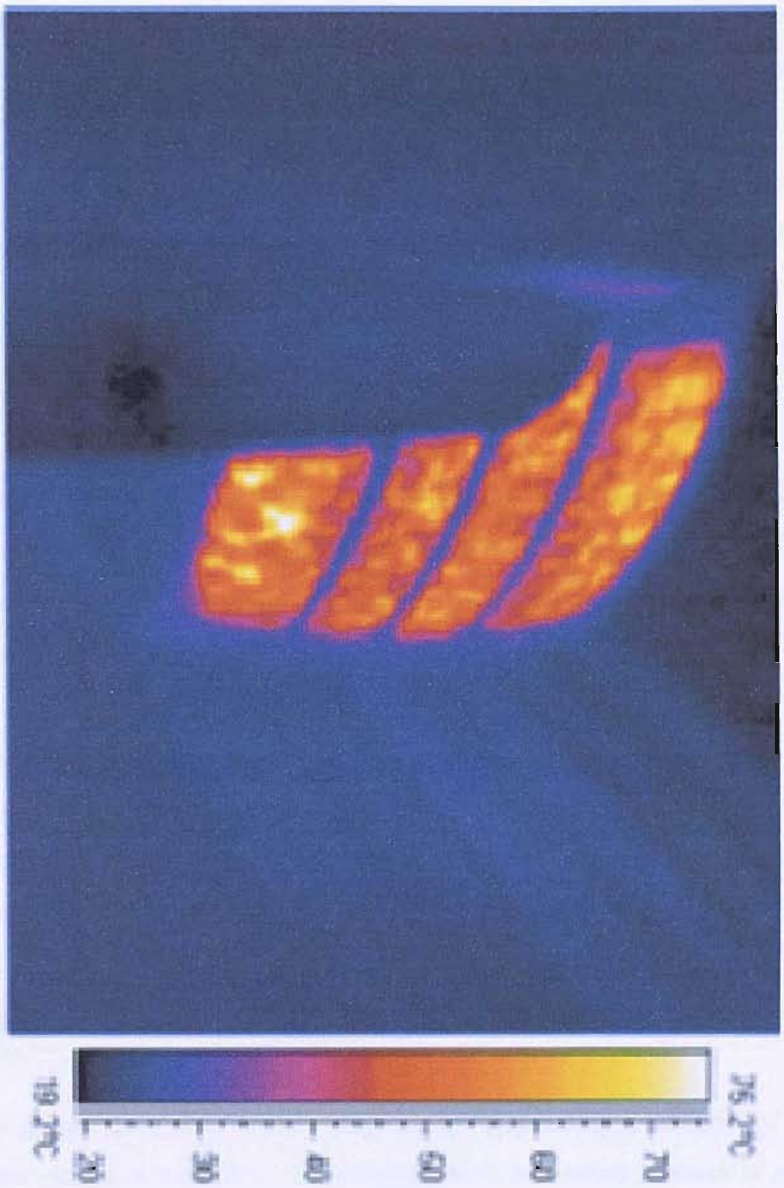


Figure 74 Post-skid Tyre Contact Patch visualised at Madingley using infrared camera (photograph by the author)

4) Bitumen Exudative Hardening (Oil exudation)

The following findings led the researcher to investigate other possible causes of the low skid resistance on the tyre/road interface on thick binder film thin surfaces:

- The presence of a glassy/hard phase (possibly a remnant after removal of light phases), as seen within a skid mark laid down during testing on a worn DBM at Dorset Police Headquarters on 27 July 2006
- a visible lubricated patch observed on the tyre after NTS tests at Madingley,
- a similar greasy patch following NOABS testing on an SMA (NTS) in Dorset

During a conversation with Martin Heslop (former Technical Director, Colas), other properties of bitumens were discussed:

Since bitumen is not a liquid but a colloid, the oil phase can easily exude under loading to lubricate the tyre/road contact patch. Friction/slip stress/deformation may thus result in the exudation of light oil lubricating fractions from the bitumen leaving a harder/glassy residue through exudative hardening (Read and Whiteoak, 2003).

Modern bitumens may contain more waxes and be less well engineered as colloidal systems, reference to any binders' performance in the exudation droplet test (EDT) may have potential in controlling this light fraction exudation should it be shown to be the cause of the low dry friction.

From Root & Moore (Root and Moore, 1992):

The exudation droplet test (EDT) was proposed by van Gooswilligen, de Bats and Harrison. It has been found that exudative hardening may contribute to premature fracture of pavements, which occurs more frequently with lean mixes. Exudative hardening is the loss of oily material that exudes from the binder into the mineral aggregate. Shell Method Series 2697 was the test procedure followed. Weighed quantities of asphalt are placed in drilled recesses of a marble plate of a specific Italian origin. The plates are heated to 60C for four days under a nitrogen blanket. During this period, oily rings develop which are measured with a microscope under ultraviolet light. For Asphaltic Concrete materials, a ring width of less than 2.0mm is an indicator of good performance.

If the low dry friction results from a poor colloidal engineering this test procedure may be used to establish if a bitumen may exude low viscosity elements.

3.5 Direct Observation of Bituplaning Events

The time-series decelerometer database provided the means to establish that NTS surfaces did behave significantly differently to PTS surfaces with respect to the influence on the deceleration of the vehicle in the dry.

To understand better the actual mechanisms responsible for the bituplaning phenomenon, direct study of the bituplaning events themselves was required.

Facilities can be found that enable the limited observation of the tyre/road contact patch during passage of the vehicle over a wet or dry surface. Such under track laboratory facilities exist (or existed) at MIRA (The Motor Industry Research Association) in Nuneaton, UK and at TRL Ltd (Transport Research Laboratory Ltd in Crowthorne, UK - however, this latter facility may have been decommissioned).

Unfortunately, as both the tyre and the road surface aggregate are opaque, and the interface between the macrotexture of the tyre and the road surface requires the presence of an opaque bituminous layer to generate the bituplane, it was impossible to provide a means of directly observing the contact patch line between tyre and road. The best possible observation point available was that to be had directly behind the tyre road contact line of the tyre.

The mounting of equipment to visualise this interface line was problematical in itself. Both suppliers of cameras used in the final study (camera valued at £37000 and £20000) expressed concern over the safety of their devices during emergency braking manoeuvres while in proximity to the road surface.

To allay the concerns of the camera providers, specialist photographic mounting equipment (manufactured by Manfroto and typically used for filming scenes from the outside of moving vehicles), was hired from Datron (UK). Securing lanyards and multiple layers of bubble wrap were used to offer protection to the camera equipment should the mounting detach from the bodywork of the test vehicle, a Mercedes Vito light commercial van (the only vehicle available to undertake testing on the allocated access days).

Bituplaning events were directly recorded along with "normal" braking events in this work via a number of means: decelerometers, non-contact temperature measurement sensors, infrared false colour video imaging of temperature high-speed video, wheel rotation and acceleration sensors.

The basic influence of anti-lock and standard braking systems and the physical characteristics of the individual components that form the physical media that interact at the tyre/road interface had been investigated via the literature search augmented by limited Dynamic Shear Rheometry (DSR) and very limited fluorescence microscopy.

Additional literature based studies were undertaken as required to investigate issues allied to the mechanism of the generation of low dry road friction that were raised following the individual experimental activities.

The individual research activities in this area untaken by The Researcher are described in the following sections. The collection and analysis of the deceleration database formed the initial part of this Work and has already been discussed.

3.5.1 Temperature Measurements of the tyre/road interface Braking Events: Devon and Cornwall Police (08 June 2004)

This section contributes towards addressing Question 4 in Section 1.4: What was the likely mechanism (or mechanisms) responsible for the generation of the low levels of dry friction observed on certain NTS surfaces?

Purpose of trial

With the assistance of Devon & Cornwall Police, FLIR systems and Datron, equipment was obtained on free loan to investigate the potential for measuring the temperatures generated during a locked wheel skids using technology already in use in automotive testing and development.

Equipment

Datron (UK) kindly provided equipment on free extended loan to the Researcher and Devon & Cornwall Constabulary Collision Investigation (Exeter). Representative photographs of the equipment setup are shown in **Figure 77**.

Two "2D" S-IR Type T1 A & B infrared sensors (one wide angle one narrow angle) were used to measure the road and tyre temperature as closely as could be achieved to the tyre road contact patch of the left front wheel. The need to limit the potential for damage to the sensor when the vehicle suspension was compressed during the initial braking dive limited the minimum separation distance between the tyre and the sensors.

The sensors were mounted on a bracket secured to the wing of the Vauxhall Astra Van using a modified chalk gun suction cup apparatus. The output of the two sensors was fed simultaneously into the data logger to match the data outputs from the WPT and GPS described below.

As the degree of suspension dive at any part of the braking manoeuvre could not be measured the detection area of the two sensors varied during the events making the measurements approximate.

The angular rotation of the front left hand wheel (converted into distance) was recorded using a Corrsys Datron WPT Incremental Wheel Pulse Transducer.

The distance travelled by the vehicle (accurate to 0.05% / 1cm resolution) was established using a Corrsys Datron MicroSAT non-contact GPS sensor and roof mounted aerial.

Tyre deformation during braking may have introduced a small error between angular rotation and real distance covered. By combining the output of these devices into a single data stream using a data logger provided by Datron the relative movement of the tyre and vehicle could be plotted to identify when wheel lockup occurred.

Unfortunately, it was not possible to procure an integrated measure of deceleration from the Skidman and wheel rotation from the WPT to establish the slip/friction relationship.

The small offset observed between tyre/road temperature changes and wheel rotation speed changes (which should occur almost simultaneously) results from the time taken for the "hot patches" to emerge/rotate from the tyre/road interface and be captured by the sensors in question.

Test Procedure

The vehicle was braked to a halt as per typical locked wheel or ABS brake tests carried out by the Police on an NTS. In this case, the vehicles were NOT braked to a halt when the NOABS tests were carried out to enable the temperature of the sliding contact patch to "roll out" and be viewed by the sensor.

Data processing

The data stream from the Datron Sensors required post processing by Datron to produce a suitable tabulated output to be used in the analysis.

Results NO ABS Braking

After a single NON ABS emergency stop (Figure 75), a temperature of approximately 70°c was measured on the road surface, (with an ambient temperature of only 30°c, a 40°c increase after one manoeuvre). A temperature of approximately 55°c was subsequently measured on the "rolled out" tyre contact patch, also with a pre-test temperature of approximately 30°c, a 25°c increase after one manoeuvre.

Closer examination of the plot from the sensors during the NOABS manoeuvre identifies several discrete mechanisms (GPS2 is the GPS determined speed, WhS1 is the rotating wheel speed, ROAD is the road temperature, TYRE is the tyre temperature):

1) Cooling of the tyre in the moving air stream prior to lockup following the previous braking event.

2) Heating of the tyre during lockup.

3) Heat transfer to the road surface during lockup (+35°c)

4) Evidence of heat transferred to the road surface from the rotating "hot patch" generated during the locked wheel braking to the road surface, as the vehicles moves forward following skid.

5) A general cooling of the tyre tread area with time (vehicle remained in motion throughout the test to enable the "hot patch" to be measured as it rotated with the tyre).

6) A measure of the rotation time of the tyre independent of the WPT as the hot patch rotates during "rollout" following the braking event is captured by the tyre sensor.

Results ABS Braking

After a single ABS emergency stop (Figure 76) momentary (rather than sustained) maximum temperatures of only 45-50°c were measured on the road surface during braking when the ABS system delivered high levels of slip to the test tyre. Closer examination of the plots from the sensors during this ABS manoeuvre identifies several discrete features (GPS2 is the GPS determined speed, WhS1 is the rotating wheel speed, ROAD is the road temperature, TYRE is the tyre temperature):

1) Cooling of the tyre in the moving air stream prior to braking following the previous braking event.

2) Heating of the tyre during braking.

+10-15°c on the contact patch during momentary periods of high slip.
A smaller peak temperature for the tyre during the braking.

Minimal heat transfer to the road surface during braking.

A measurement of the heat transferred from the rotating "hot patch" generated during the locked wheel braking.

A general cooling of the tyre tread area with time.

A measure of the rotation time of the tyre independent of the WPT as the hot patch rotates during "rollout" following the braking event.

This simple experiment has illustrated (via only two tests) the fundamental differences between ABS and NOABS braking events. It has also shown how these differences can reflect on the heat transfer between tyre and road .

ABS emergency braking , by attempting to prevent wheel lockup and maintain the effective functioning of the braking mechanism allows for the bulk of heat transfer to be between the braking system friction linings and the rotating brake components resulting in a gradual and progressive (rather than momentary and high magnitude) increase in the temperature of the tyre as a whole.

NOABS emergency braking resulting in wheel lockup immediately halts any transfer of heat between the braking components as wheel rotation ceases, the only remaining heat transfer for the same requirement to dissipate kinetic energy is between the tyre contact patch and the road.

Some heat transfer between the tyre wheel and the brake components and the air flowing past them will occur but this has not been taken into consideration as devices commonly installed to aid ventilation of, and radiation cooling of, brake components are likely to be effective during braking where wheel rotation is taking place.

Summary of Results

The data recorded successfully delivered simple graphical representations (Figure 75, Figure 76) of the approximate and relative temperatures generated for the road and tyre during both simulated ABS and NONABS emergency braking manoeuvres.

Unfortunately the data recorded from the emergency braking manoeuvres (on a dry negative textured surface) using infrared temperature sensors must be considered solely "of interest". The findings are inconclusive, as the measurements of tyre/road contact patch temperatures were made from either the cooling tyre patch rotated to the sensor sensing point or the cooling road patch a split second after the braking event. A similar lack of complete confidence in the actual area of temperature detection must be held.

- **Thus the equipment and technique used for this experiment was not used again in connection with any further investigation of tyre/road interface temperature generation.**

Conclusion

Though of low resolution, the non-contact measurement sensors enabled the general temperature trends of the ABS and NOABS braking events to be quantified, thus providing positive evidence of the potential success of the use of more sophisticated equipment.

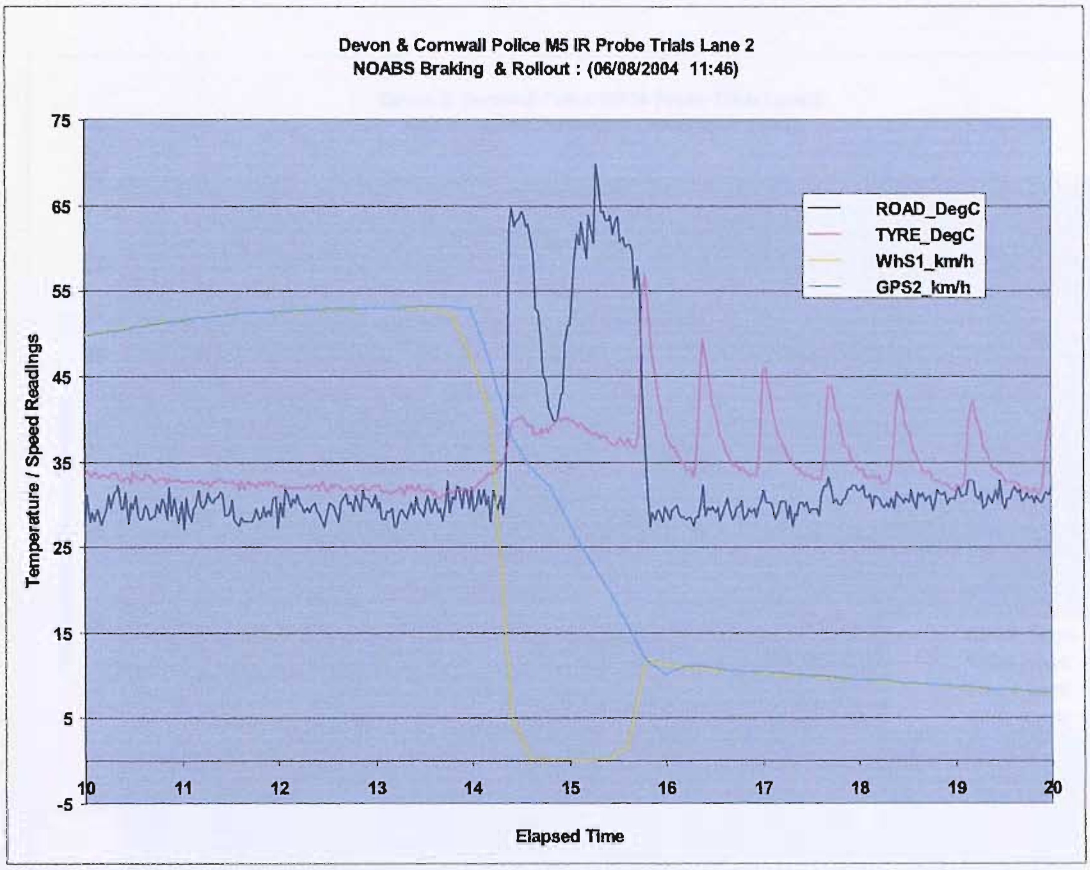


Figure 75: Sensor outputs during a locked wheel NOABS braking event on a negative textured surfacing

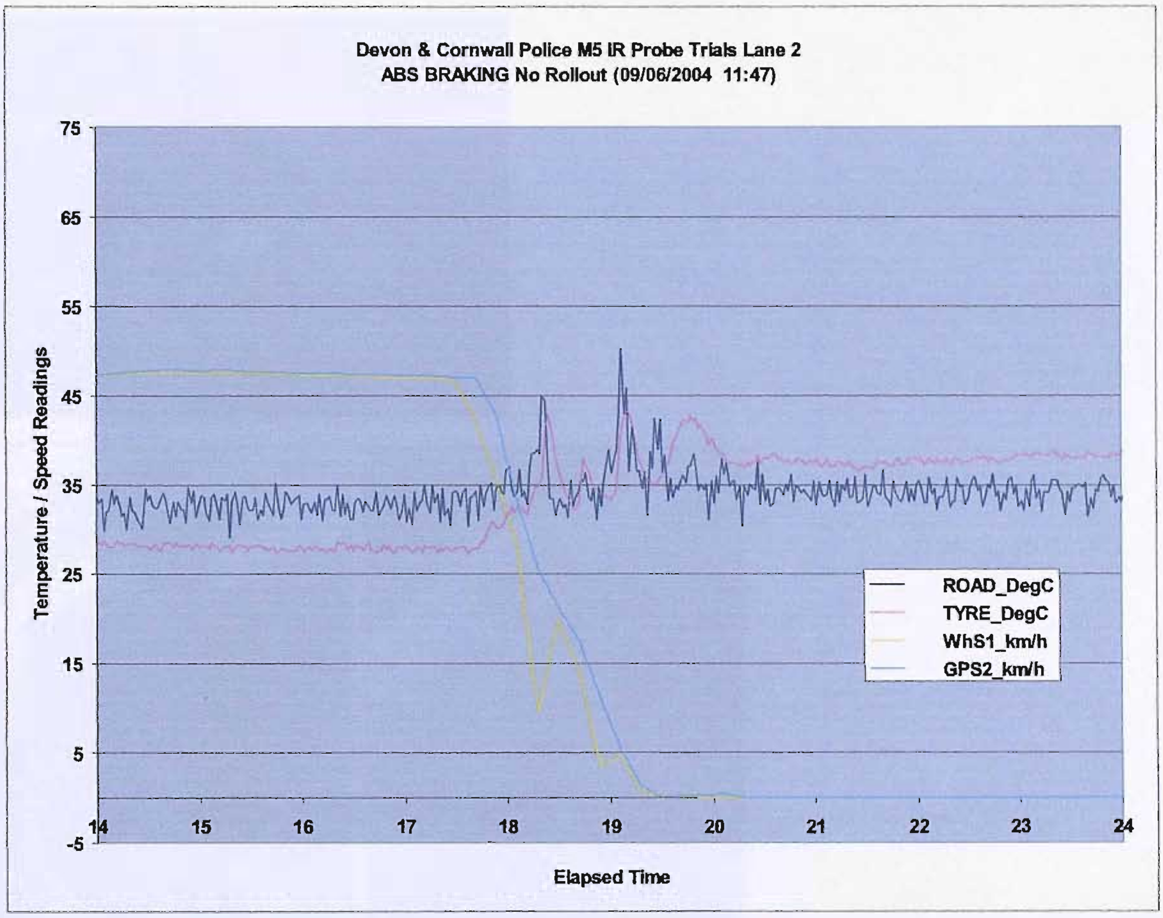


Figure 76: Sensor outputs during an ABS braked event (Bottom) on a negative textured surfacing The NOABS, lock-wheel test vehicle skidded to 10 kph and then rolled forwards (Yellow: wheel rotation speed, light blue: vehicle speed, purple: temperature sensor looking at back of tyre, blue: temperature sensor looking at road behind tyre)

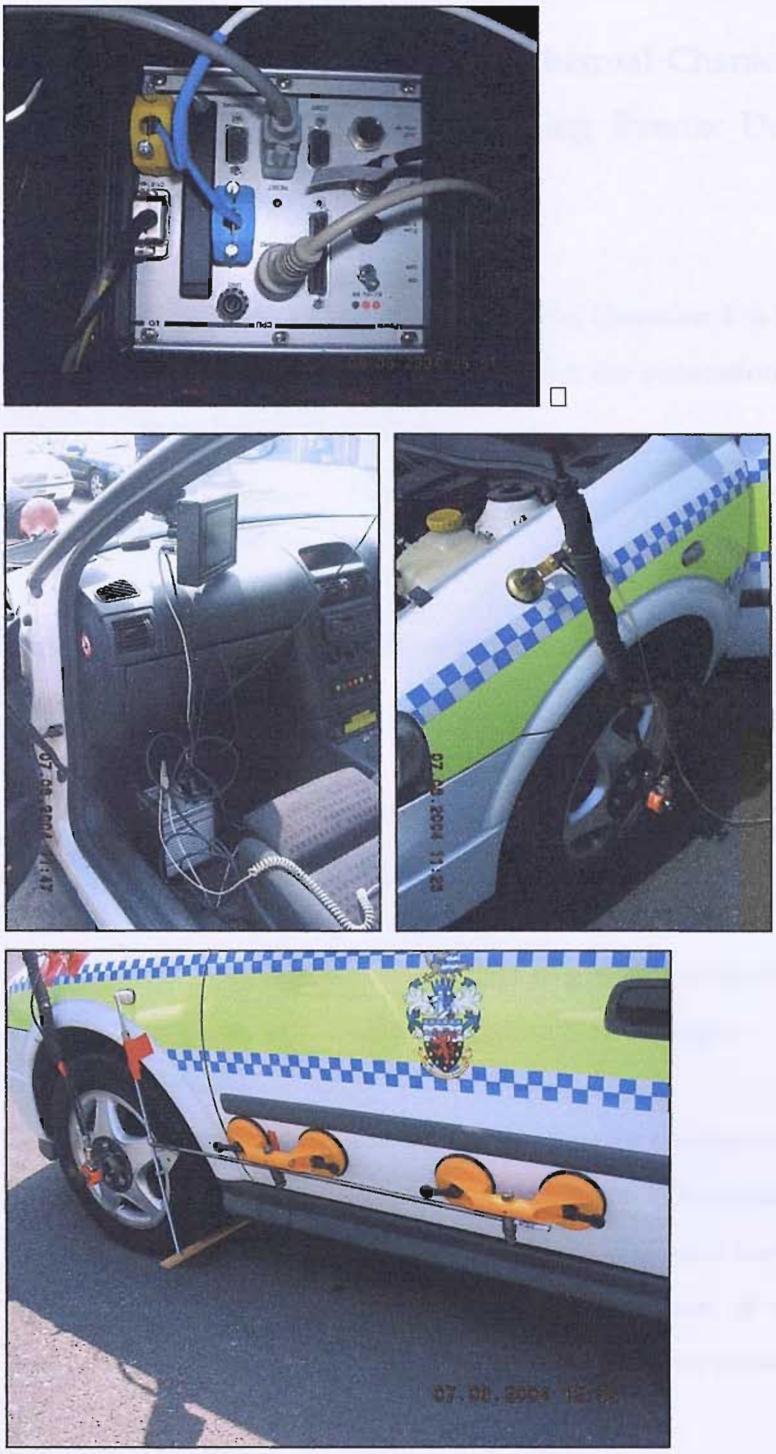


Figure 77: Infra red Sensor Trial Equipment (top left to bottom right) Data recorder, temperature sensor locations (left - tyre, right - road), data recorder and display, wheel speed detector, sensor array mounted using adapted chalk gun mounting (photos by the Researcher)

3.5.2 Visualisation of the Thermal Characteristics of the Tyre/Road Interface during Braking Events: Devon and Cornwall Police (27 October 2004)

This section contributes towards addressing Question 4 in Section 1.4: What was the likely mechanism (or mechanisms) responsible for the generation of the low levels of dry friction observed on certain NTS surfaces?

Purpose of the trial

The observations made on the temperature probe outputs from the earlier experiments suggested:

(i) a lower magnitude of heat transfer between tyre and road during ABS braking and conversely that:

(ii) NOABS braking would lead to a higher level of localised heat transfer between the tyre and road at the sliding contact patch

These observations were augmented by directly visualising ABS And NOABS emergency braking events using infrared video techniques. This would provide firmer evidence for the nature of the heat transfer between tyre and road surface during the braking events and provide supporting evidence of the generation of temperatures within the zones thought capable of softening/melting the bituminous binders.

Equipment

FLIR Systems kindly provided a ThermoCam P65 device and operator to record a number of wet skid tests carried out on the skidpan at the Devon County Council driver-training centre in Exeter.

The infra-red imaging of the brake tests were compared with the simultaneous recording of the deceleration events using two Skidman devices, a Vericom VC3000DAQ and two Kistler k-Beam accelerometers.

The K-Beam devices were secured to the Skidman devices using Duck Tape as a more suitable mounting was not available. The VC3000 was calibrated to automatically to convert the voltage outputs of the Kistler devices to a reading of G. The Kistler devices were connected to the VC3000 via a Vericom 6 Sensor Junction Box (Part number 117302, provided free of charge by Vericom).

The outputs of the four devices were to be compared to assess the relative sensitivity of the VC3000 and Skidman devices (with unknown accelerometer technical specification) compared with industrial accelerometers with well-documented specifications.

Unfortunately, there were no means available to introduce a synchronising mark between the Skidman and the other devices as the Skidman does not output a data stream nor can it function as a data logger for the other devices. A brake-pedal trip-switch would offer one method to trigger simultaneously the recording of both the Skidman and the VC3000 however; no brake pedal trigger was available for the Skidman on the day of the test.

Results: Thermal Imaging

Refer to Appendix 4 \Devon Wet ABS versus NOABS for infra video media of these activities.

When compared with dry road emergency braking visualisations undertaken at Winchester, the wet state of the road resulted in reduced heat as a result on the cooling influence of the surface water. However, the differences between the heat transfer mechanisms during ABS and NOABS emergency braking were successfully visualised though only as FLIR SEQ data files.

ABS braking generated "hot spots" on the road surface analogous with the "dashes" typically noted by collision investigators as indicative of the limited skid marks left by ABS vehicles. Though greatly reduced by the presence of water, the heat input from the sliding tyre/road contact generated a unique thermal signature in the video footage for both ABS and NOABS braking events. The brake discs and wheel castings were also seen to absorb more heat during ABS braking compare with a cooling following wheel lockup during NOABS tests. The video images captured from this trial suggest further use of this technology will be beneficial in improving the understanding of the thermal dynamics of the bituplaning event.

The results of this imaging trial were sufficiently successful to plan for arrange for more testing on a dry new road surface.

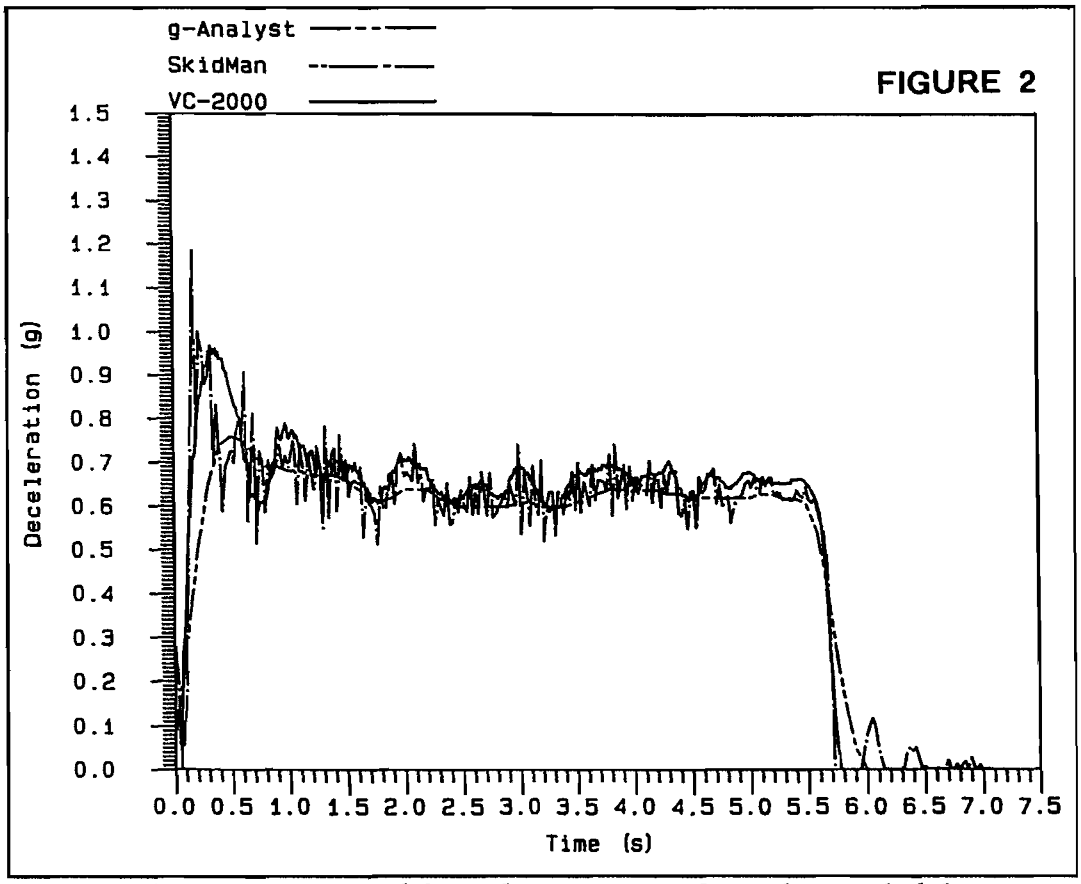
Results: Decelerometer Comparisons

Figure 79 illustrates some initial plotting of the parallel data streams for the decelerometer testing, the comparison appears similar in trend to that of Hague (Hague et al., 1995) shown in **Figure 78** for the VC2000, however the output of the Kistler industrial devices needs more study as their mounting may have been less than ideal.

The infrared images, on a wet road, were sensitive enough to highlight the steam generated during ABS tests. The dashes associated with the deployment of the ABS system (Figure 80) and the increase in temperature of the road surface of 20 c generated by a sliding tyre on a wet road where ABS was not used was also seen (Figure 81).

Conclusions

Though limited, the Vericom versus Skidman comparisons indicated a good general agreement between the two devices, such a relationship had already been suggested in the



literature. The images returned from the IR camera showed a good ability to resolve the subtle temperature differences on a wet road; this suggested that its use on a dry road would be successful. ABS and NOABS events could easily be discriminated.

Figure 78 Comparison of data streams from VC2000 DAQ, Skidman g-analyst Decelerometers (Hague et al., 1995)

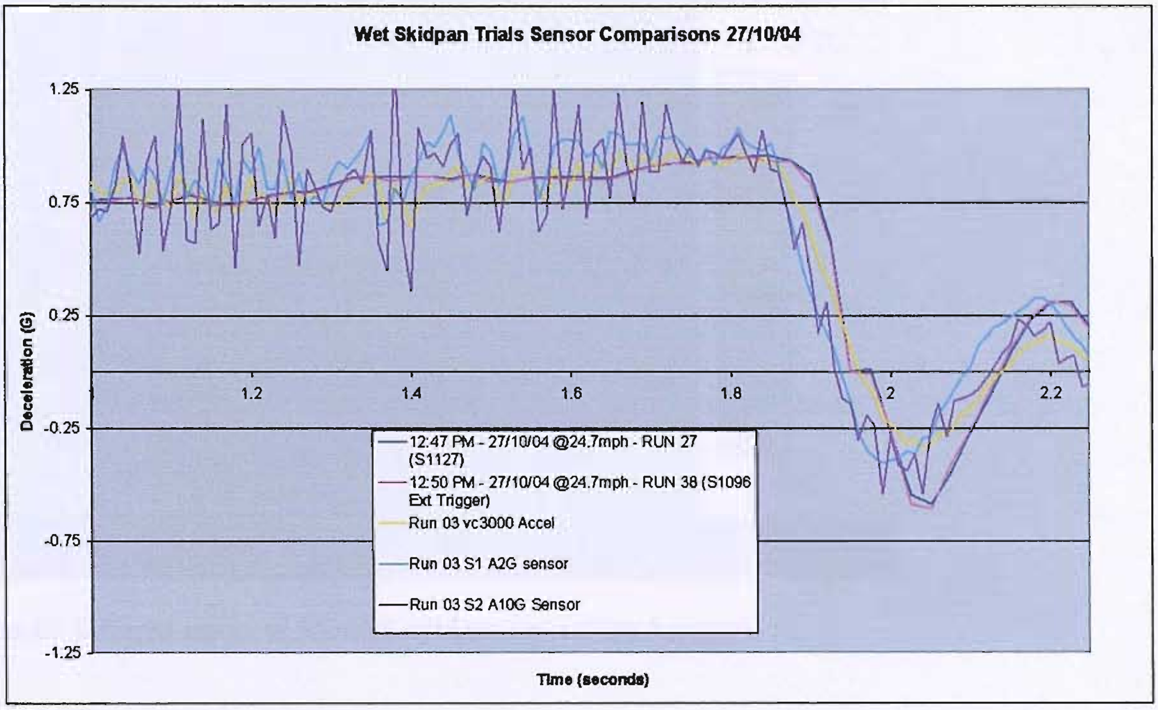


Figure 79 Initial Comparison of data streams from VC3000 DAQ (yellow), Skidman (blue and pink), and Kistler Decelerometers (turquoise and purple) for one location

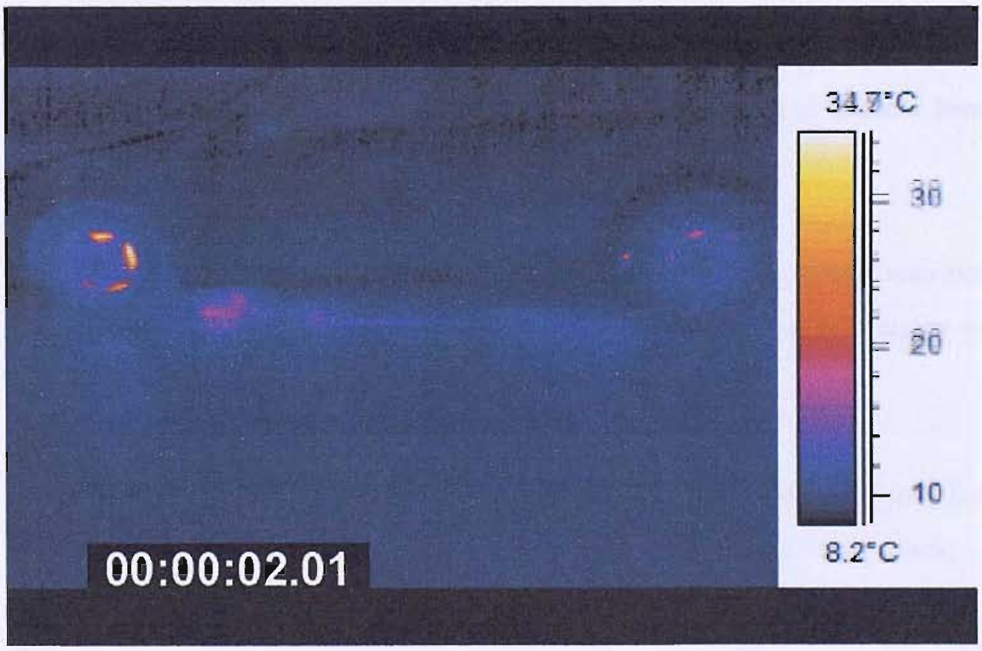


Figure 80 Infrared image of ABS skid test on wet road surface

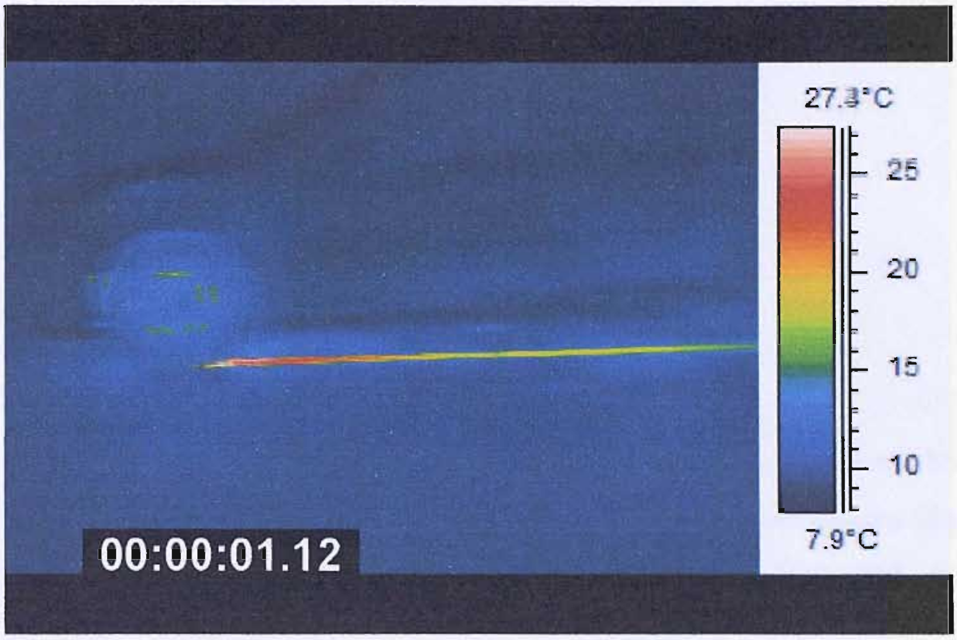


Figure 81 Infrared image of NOABS skid test on wet road surface

3.5.3 Pilot Field Measurement of Decelerations and Limited Video Visualisation Hampshire, 13 December 2004.

This section contributes towards addressing Question 4 in Section 1.4: What was the likely mechanism (or mechanisms) responsible for the generation of the low levels of dry friction observed on certain NTS surfaces?

Prior to the full scale application of the imaging techniques, a trial was run on a two week old untrafficked PTS (hot rolled asphalt) the Bar End household waste recycling centre in Winchester.

A FLIR P65 camera was mounted on a tripod and a skidding Ford Galaxy was filmed from a fixed location in addition to Skidman measurements being made.

Refer to Appendix 4 \Thesis DVD\HANTS DRY ABS versus NOABS for infra video media of these activities

Results

On the dry HRA, it was possible to identify the difference between ABS and NOABS skid tests via both the Skidman Plots (Figure 82) and the infrared images (Figure 83). The ABS images showed the momentary reductions in friction illustrated in Figure 82 as hot patches. Unfortunately, the SEQ files carrying the momentary temperature grids (analysed s part of the later Madingley tests) were not saved and the automatic temperature display in the video recording had not been activated.

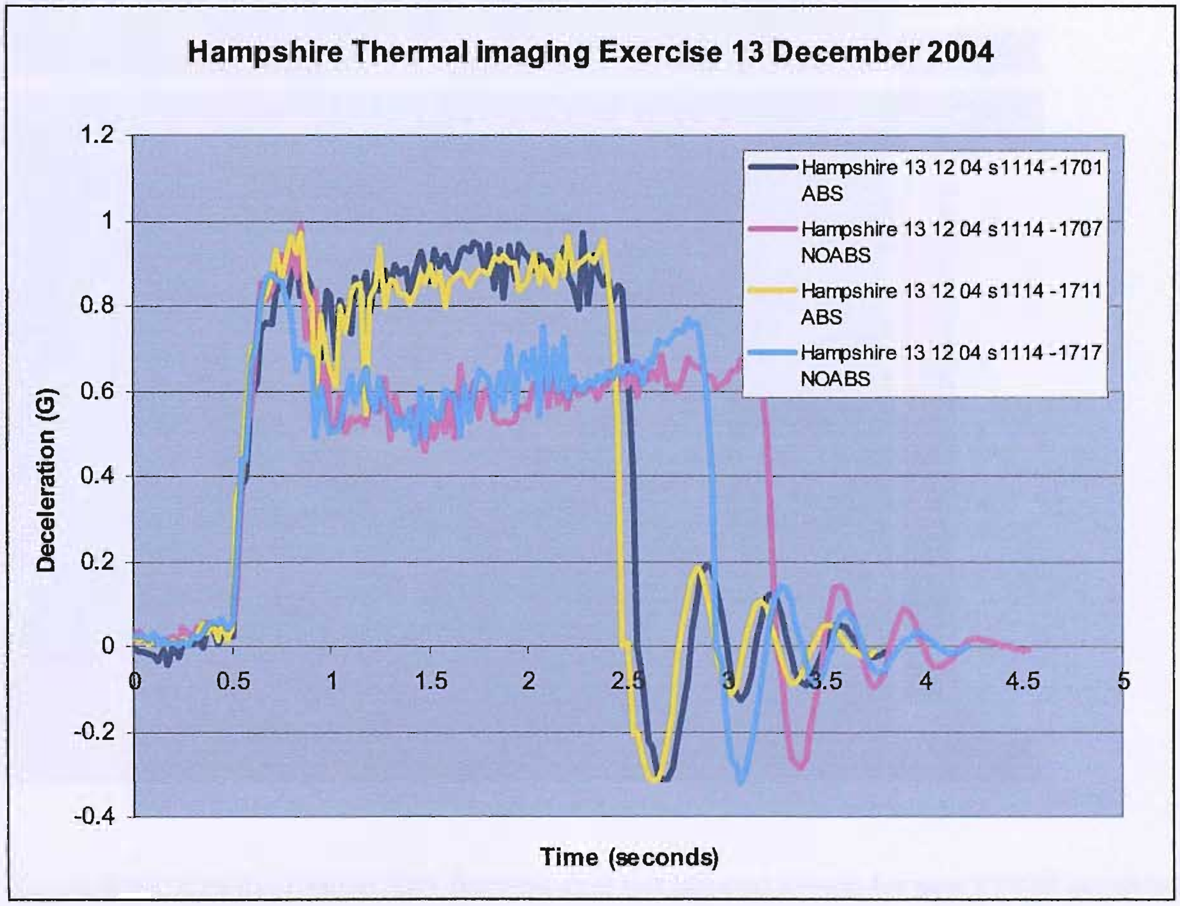


Figure 82 ABS versus NOABS skid test results for new PTS (Hampshire)

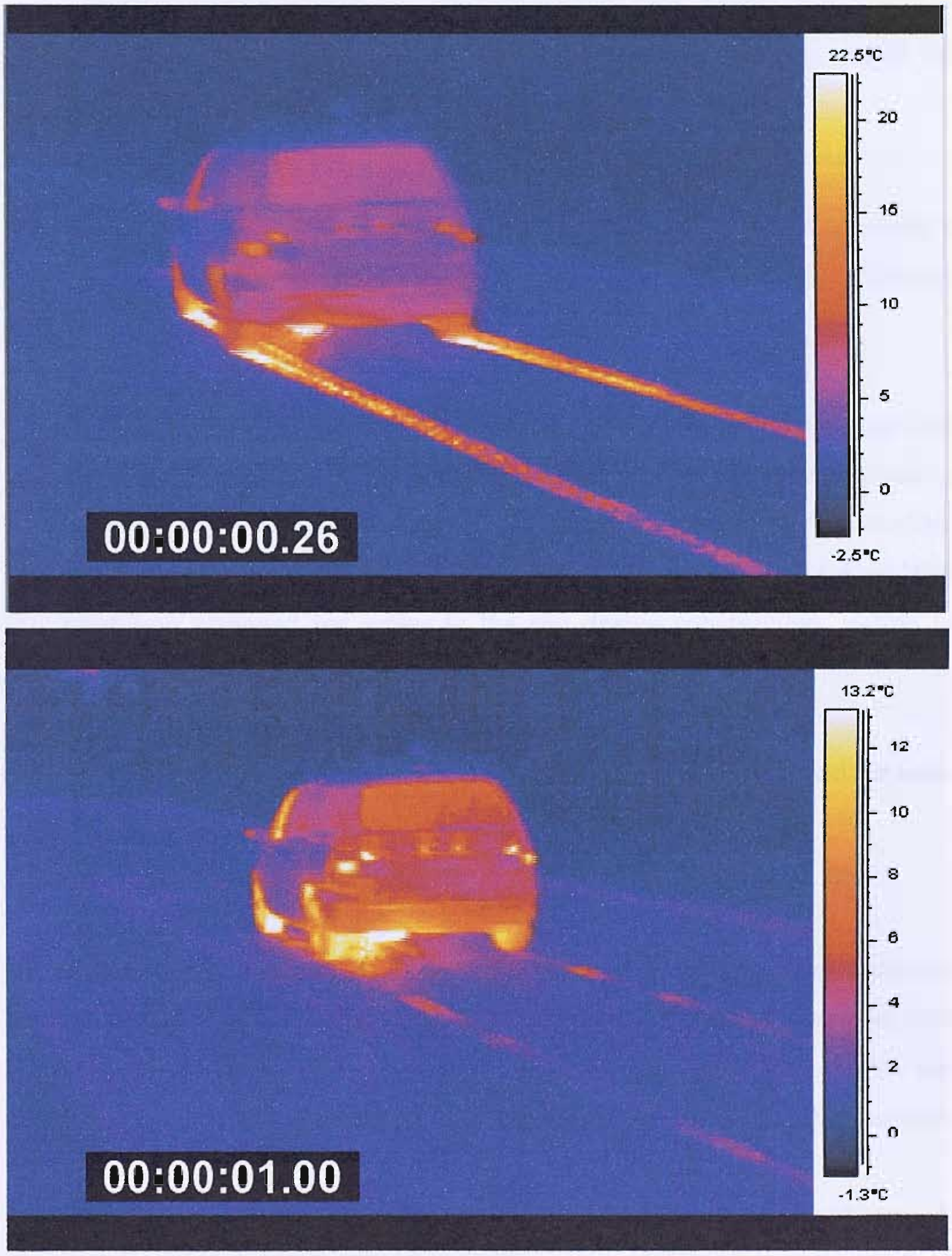


Figure 83 NOABS (top) versus ABS (bottom) skid test infrared images for new PTS (Hampshire)

The results of this exercise strongly suggested the use of similar vehicle mounted technology would be successful.

3.5.4 Measurement of Decelerations and Video Visualisation of the Tyre/Road Interface during Braking Events: A428 Madingley (June 2006)

This section partially addresses Question 4 in Section 1.4: What was the likely mechanism (or mechanisms) responsible for the generation of the low levels of dry friction observed on certain NTS surfaces?

Following receipt of sponsorship monies from the Highways Agency in response to a presentation made by the Author in New Zealand (Bullas, 2005) a study was undertaken on a stretch of the A428 near Madingley (Figure 84) undergoing reconstruction / overlay. The Highways Agency in communication with Carillion-URS and Atkins Highways and Transportation arranged for access to the site during construction, testing in live dual carriageway would have otherwise been impossible.

Refer to Appendix 4 \MADINGLEY SKID TESTS for video of the skid car testing

Deceleration recordings at Madingley

The exercise undertaken at Madingley was primarily undertaken to capture high-speed and infrared images of simulated emergency braking manoeuvres on both NTS and PTS. It would have been most ill advised not to record deceleration data for the same braking events as the equipment to do this was already in the possession of the Researcher.

Notwithstanding a number of false trigger events resulting in loss of some deceleration data for one or the two devices run simultaneously, the majority of the braking events at Madingley were successfully recorded (on Vericom and Skidman) as deceleration time series (the data corresponding to the format collected for the assembly of the deceleration database used for the statistical exercise) .

The deceleration sequences from the Vericom and SkidMan could be used in association with the thermal and high-speed imaging in an attempt to link friction generation to thermal behaviour.

Figure 86 illustrates that the general trends illustrated in the Madingley deceleration time-series data correspond to those of the events recorded in the deceleration database already discussed and already described in the literature

What should be observed for Madingley is:

1) The NTS surfacing tested was approximately 24 hours old and the PTS surface (a HRA) showed evidence of some failures (it was being replaced by the NTS tested).

2) The NOABS tests show momentary minima equivalent to the sliding NOABS deceleration or lower. The NTS sites showed noticeable "dashes" of bitumen along the ABS skidding line which had the decelerometer and high speed video streams been synchronised may well have corresponded with visible tyre slip.

3) No smoke was observed during the passage of the NOABS skid test vehicles on the NTS surfaces (unlike during the skid tests on the PTS). The right wheel track of the vehicle in Figure 85 illustrates what was typically seen at Madingley during NOABS Tests on the PTS: the PTS side generated significant tyre smoke whereas the NTS left side generated no smoke.

Figure 84 Site location Madingley A428 (Highways Agency, not published)

Infrared Imaging

Refer to Appendix 4 \MADINGLEY - RESEARCHER SCREEN CAPTURES for screen captures of the infrared camera output.

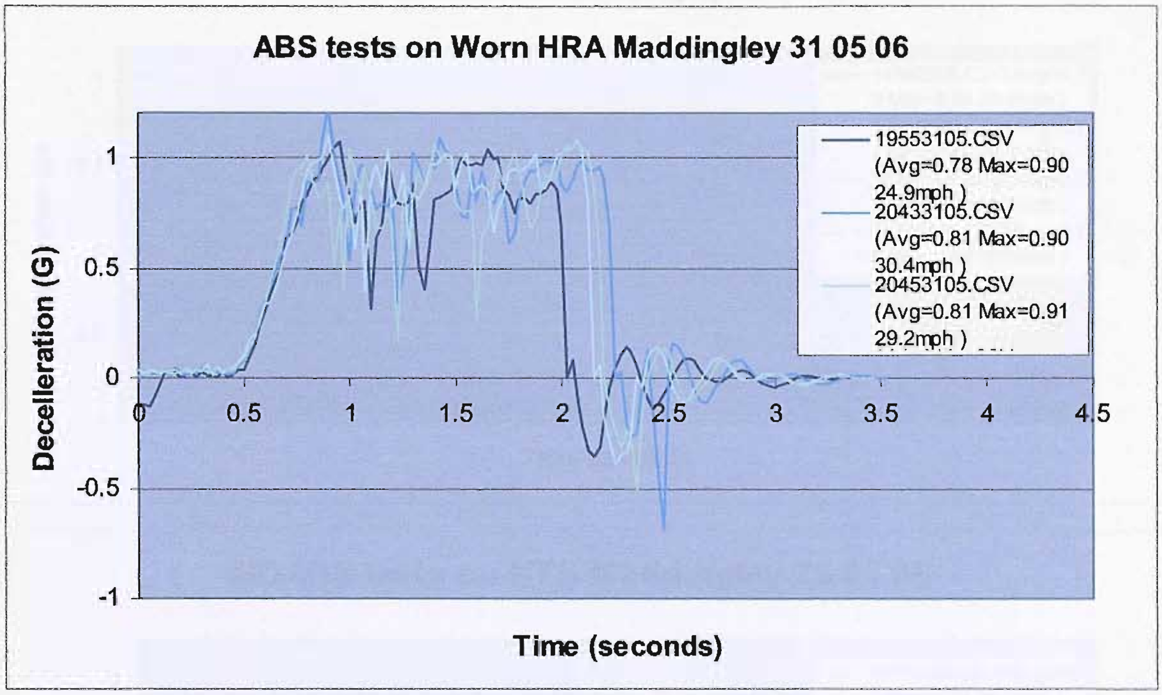
The compact size of the FLIR P65 Infrared camera used at Madingley enabled it to be mounted relatively closely to the rear contact line between the front tyre of the Mercedes Vito test vehicle and the road surface.

The FLIR camera captures at a rate of 60 frames per second a combined data output comprising a simple AVI false colour video image with computer generated temperature/colour scale between the maxima and minima for the frame (this composite image was output via firewire to an inexpensive DV camera) along with a SEQ format data stream file enabling complex frame-by-frame or over-time measurement of the thermal environment in the visual field of the device.

The Researcher Software (kindly loaned by FLIR) was capable of generating numerical output as CSV (Comma Separated Variable) files of temperatures as well as post-test video output. The software generates false colour images from the point temperatures within the SEQ files and graphical outputs related to the specified lines or polygons programmed onto the image.

Figure 85 Skid test on split surface (PTS on right NTS on left)

The capabilities of the Researcher software were fully exploited beyond the one-month free trial of the software by installing it sequentially on a number of PCs, the £3000 purchase cost of a working copy of the Researcher software could not be funded and analysis using the Researcher functionality could only be completed via this route.



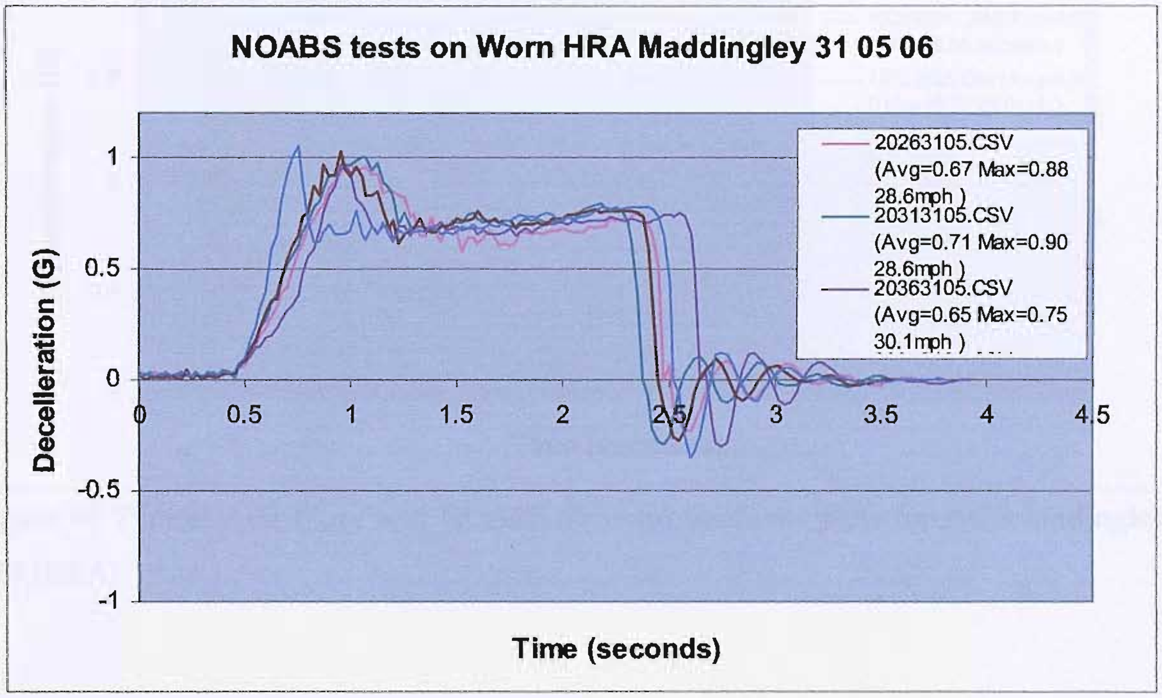


Figure 86 Typical ABS (Top) and NOABS (Bottom) Skidman plots for A428 Madingley NTS

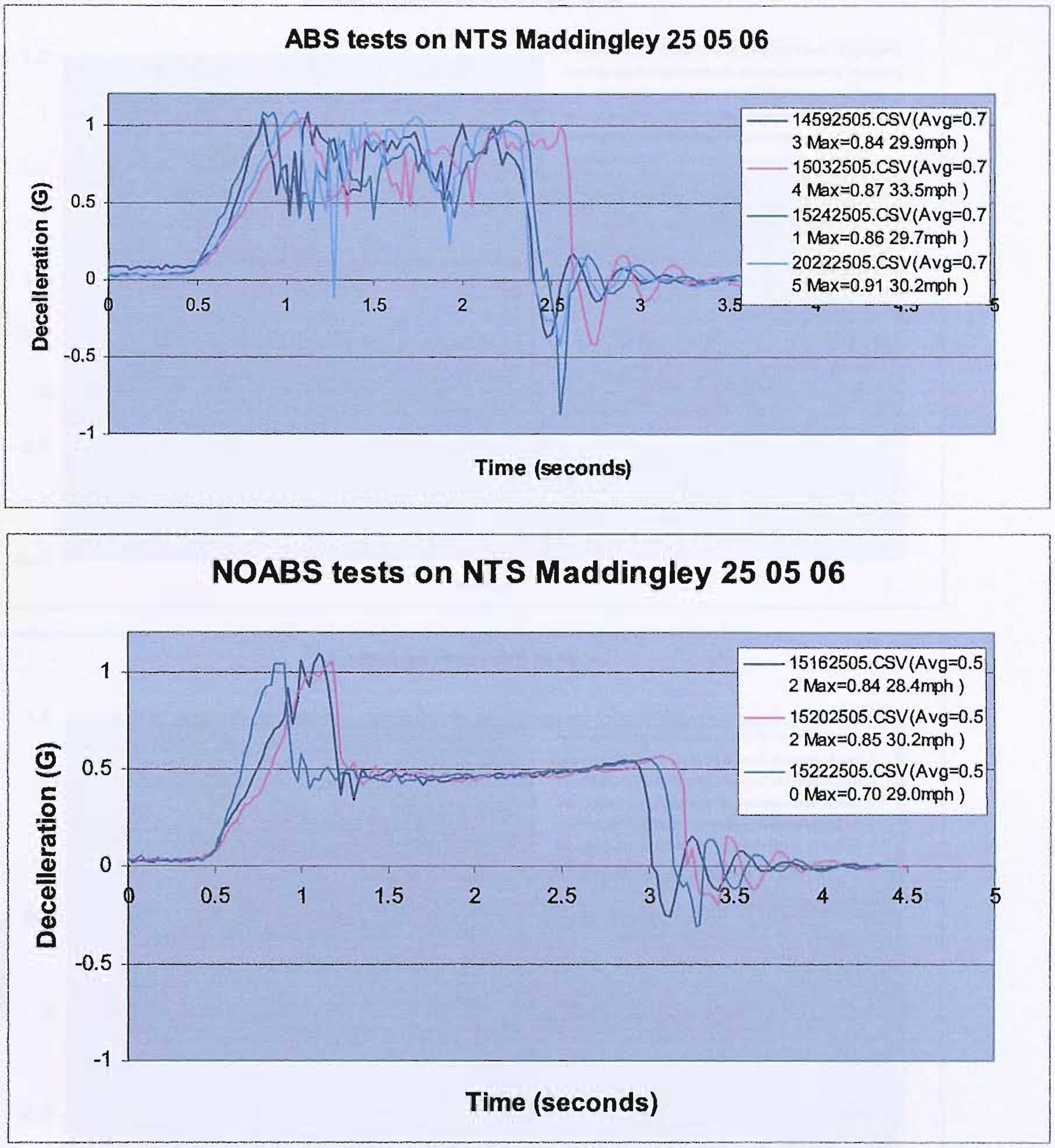


Figure 87 Typical ABS (Top) and NOABS (Bottom) Skidman plots for A428 Madingley PTS (HRA)

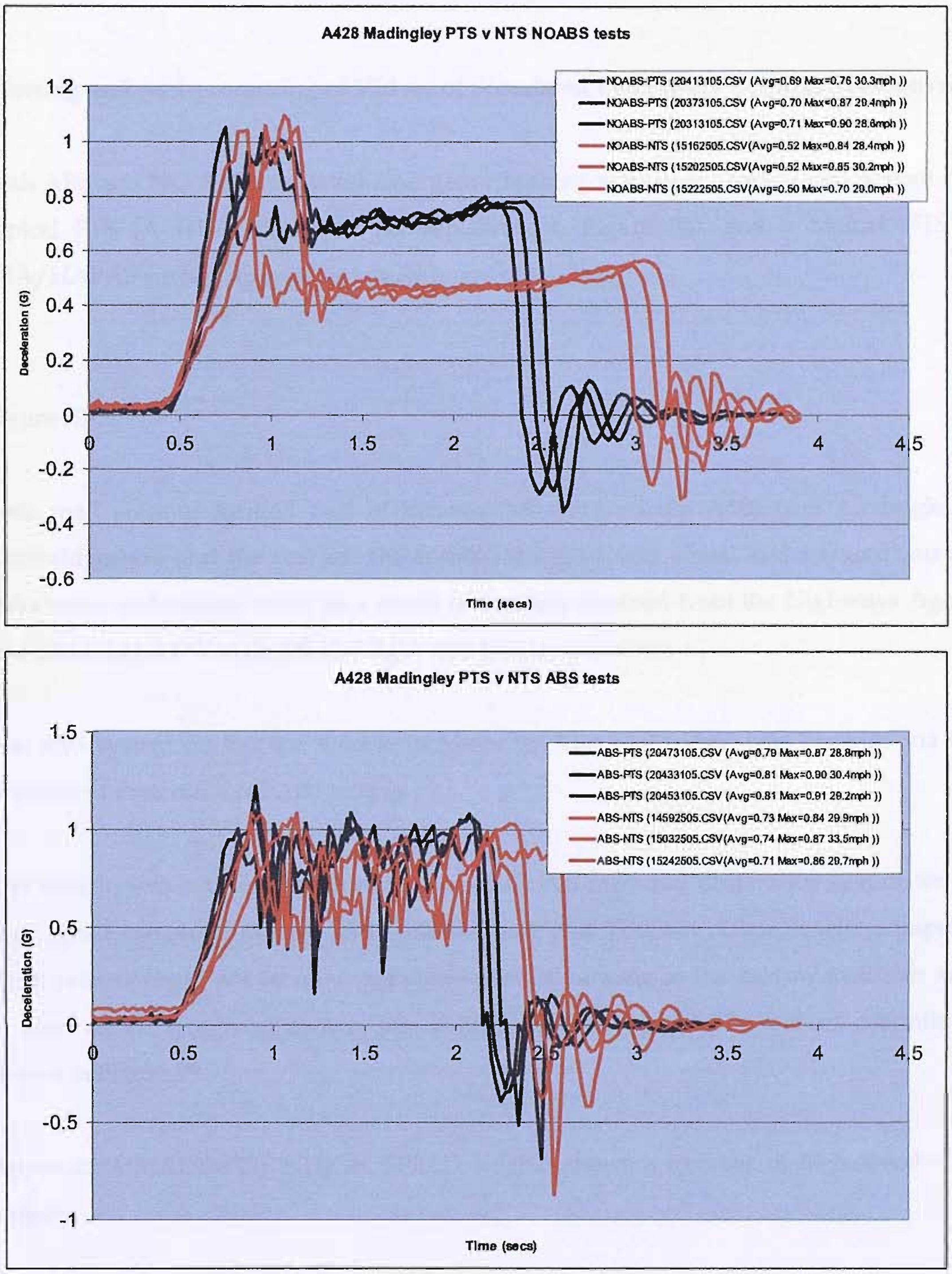


Figure 88 NTS NOABS (red) v PTS NOABS decelerometer plots (top) and NTS ABS v PTS ABS decelerometer plots (bottom) for Madingley

Viewing and post-processing of Videos of Simulated Emergency Braking Manoeuvres

Both ABS and NO ABS simulated emergency braking manoeuvres were undertaken on a typical PTS (A HRA scheduled for replacement, Figure 92), and a typical NTS (A BBA/HAPAS surface approximately 24 hours old,

Figure 93).

Both road sections formed part of the reconstruction of the A428 near Madingley in Cambridgeshire and the cost of the combined high-speed visual and infrared imaging tasks were undertaken solely as a result of funding received from the Highways Agency and administered though Atkins Highways & Transportation.

The ABS system on the test vehicle (a Mercedes Vito Light Van) was disabled via fuse removal to undertake NOABS testing.

The vehicle was equipped with either the FLIR P65 infra red camera (60 fps) or the M3 high speed camera (1000 fps) and both Skidman and Vericom decelerometer equipment (both camera could not be mounted simultaneously owing to the narrow available angle of view of the tyre/road contact line behind the front tyre). The camera mounting is shown in Figure 89.

Appendix 4 MADINGLEY HIGH SPEED VIDEO shows a number of high-speed video outputs.

The key phases of the simulated emergency braking manoeuvres identified in the classification of the deceleration events for the purpose of statistical analysis could easily be discerned in the AVI sequences. This could be achieved via a combination of temperature changes related to the transition between the states (using Infrared video) or visible changes in the rotation speed of the tyre (using high-speed video and infrared video at a far lower frame rate).

Onset of braking, wheel lock, the sliding phase (NOABS) or the pulsing of the ABS system (as peak is reached and brake effort is released before lock occurs during ABS braking) can all be seen in changes in the thermal distribution between tyre and road. The final "bounce" when the braking vehicle has become stationary can be discerned by the up-and-down movement of the suspension system.

General Video Post-Processing Techniques

The images generated by both the FLIR Infrared device (60 fps) and the M2 high speed camera (1000 fps) were in the form of large AVI videos, these videos were post processed using Redlake MiDAS Player v 2.1.4 R (provided free of charge by Lake Images Ltd) to extract video sequences confined to individual braking manoeuvres.

Additional processing of the raw video images was necessary to study the tyre/road interactions during the individual sequences and to compare sequences with common elements.

Multi-view Software

One or more AVI videos could be opened simultaneously and synchronised at the point of , say, wheel lock or ABS peak to enable side-by-side comparisons of the behaviour of the road surfaces under examination, for example ABS and NOABS sequences for the same surface could be viewed simultaneously.

Redlake MiDAS Player v 2.1.4 R also offered the facility to zoom selectively into an area of each video and review this selective image synchronised with the full-frame image it is cropped from. This zooming enabled the temperature/colour scale between the maxima and minima to be added to the synchronised videos as an additional window or each AVI running within Redlake MiDAS.

Extracting Composite Videos and Stills

Synchronised video sequences generated within Redlake MiDAS were captured as new AVIs using the screen capture functionality of TechSmith Camtasia. Individual still images illustrating particular events within the synchronised AVIs were captured as bitmaps (BMP) using the MS-DOS print screen keyboard functionality ("screen dumps"). These were combined with the "paste as new image" function and cropping function within MicroGraphics Picture Publisher 7a.

Sony Vegas 6.0 (www.sonymediasoftware.com/ products/vegasfamily.asp) was used to add frame counters to the video footage lacking such elapsed time markings (Figure 90), the annotated video files were split into individual frames using Redlake MiDAS and transformed into multi-image sheets using the contact sheet functionality of IrfanView (www.irfanview.com free software, Figure 91).

Figure 89 FLIR P65 Camera on Mercedes Vito Van using Manfrotto mountings

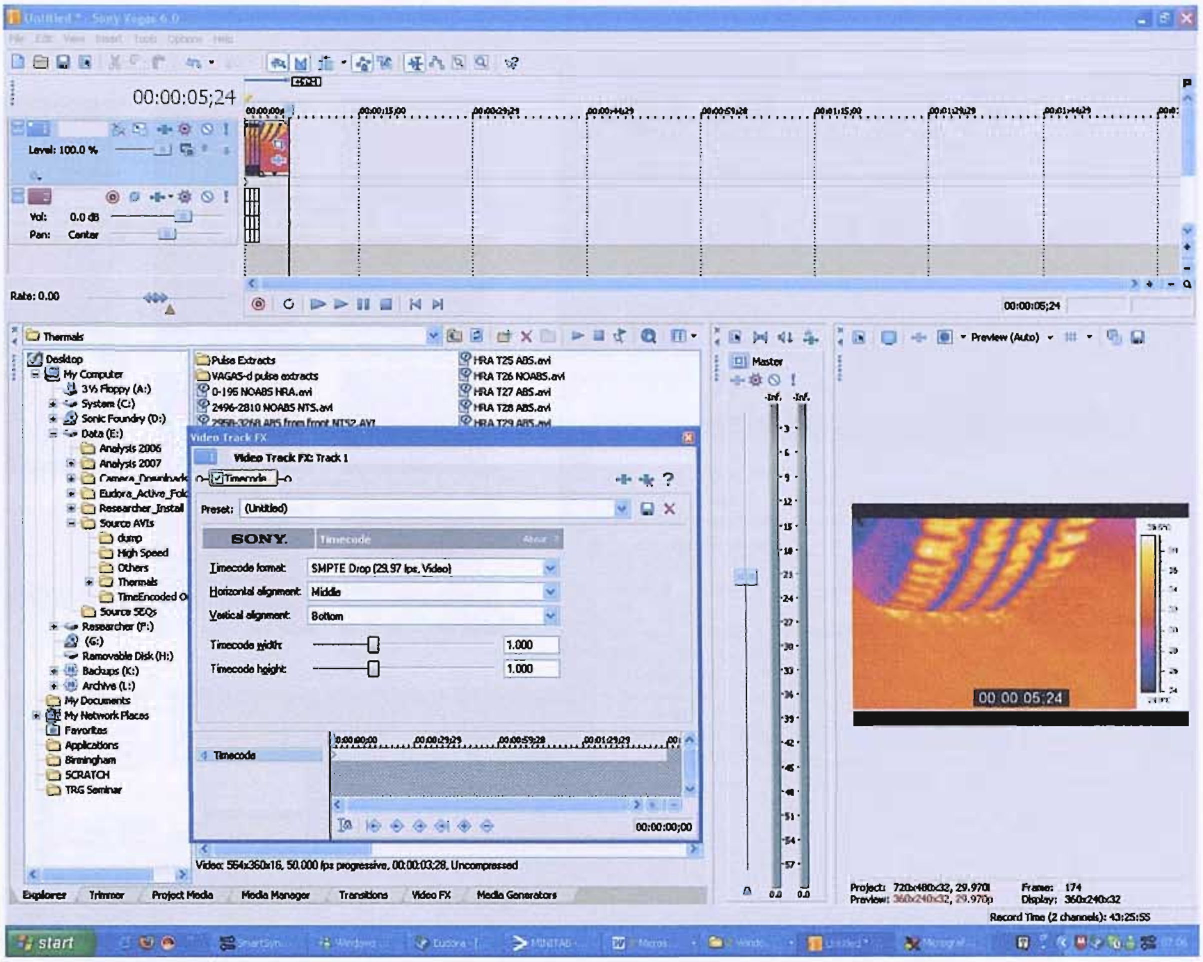


Figure 90 Frame Encoding using Sony Vegas

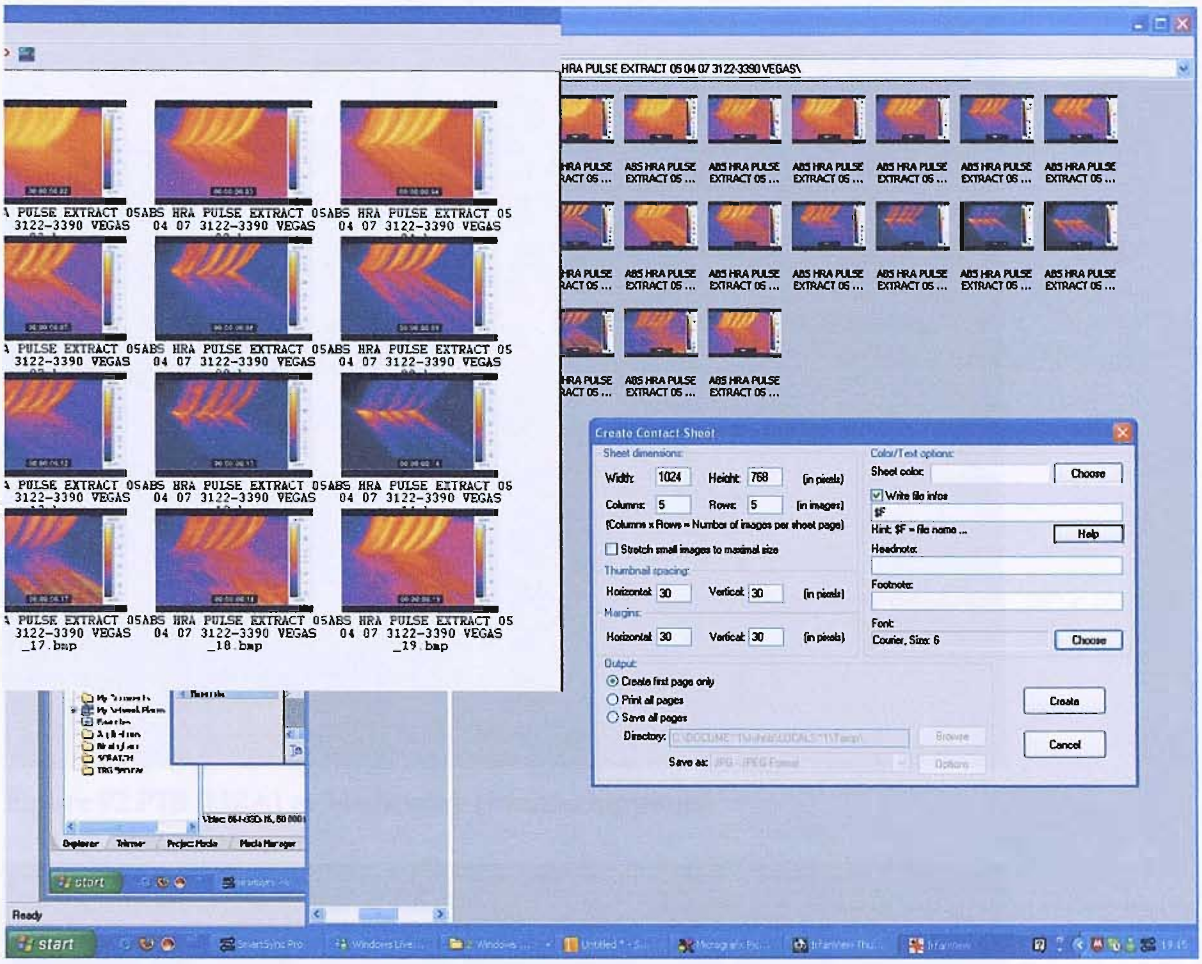


Figure 91 Irfanview graphics manipulation package

Figure 92 PTS (HRA) at Madingley (28mm chippings)

Figure 93 NTS (14mm Bardon MasterPave) at Madingley

Key findings the combined infrared imaging / high-speed imaging / deceleration time series analysis at Madingley

The use of high-speed imaging has secured high-resolution images of both ABS and NOABS braking manoeuvres. In the case of the NOABS braking manoeuvres on the NTS surface, a "bituplaning" (low dry friction) event has been captured for the first time.

Discrete events in the deceleration history of any given skid test may now be linked to visible changes in the high speed video recordings, (in the case of the onset of skidding in NOABS tests). These high speed videos may also show periods of thermal changes at the tyre road interface with visible smoke and/or deceleration (in the case of pulses in the ABS braking cycle or the onset of slip during NO ABS testing).

Deceleration data alone cannot deliver the additional information gained regarding the transitions observed in peak temperatures between tyre and road during the ABS peaks and NOABS peak-slide transition as the decelerometer measures the deceleration of the vehicle in response to tyre/road interactions, and cannot discriminate whether the tyre or the road dominates.

DVD / CD media of Madingley video content

As it is impossible to comprehensively describe or illustrate the events captured in the video recordings, a number of typical Madingley video events are provided in Appendix 4 for examination. These video files may be played using any compatible media player however a licence-free install of Redlake MiDAS Player v 2.1.4 R can also be provided to enable a frame by frame review of this content.

The thermal cycle between peak and non-peak during simulated emergency braking.

The thermal cycle during simulated emergency braking has been quantified by the use of the Researcher software.

The differences in the temperature trends seen between the ABS and NOABS braking sequences when viewed as temperature plots mirror the deceleration pattern of peak-sustained slide in the case of NOABS tests and maintained near-peak in the case of ABS.

The thermal cycle between road and tyre during simulated emergency braking.

Changes in the thermal transfer between tyre and road surface at the point of onset of sliding (in the case of NOABS testing) or at peak friction prior to ABS release (in the case of ABS tests) have been captured.

Deceleration behaviour during simulated emergency braking.

2) ABS Tests on NTS

As tests were undertaken on the NTS surfaces using both ABS and NOABS braking, it was possible to identify if any deceleration limits experienced in the ABS tests were related to the sliding level of deceleration experienced in the NO ABS tests.

Examination of juxtaposed ABS and NOABS plots for the NTS surface confirms that the limiting minimum deceleration measured in ABS tests was approximately that encountered during the sliding phase of the NOABS tests suggesting the same limiting mechanisms are at work.

Short duration sliding was also observed during the ABS brake tests on the PTS limiting the available time for any cumulative thermal effects to have an influence as a mechanism for the observed bituplaning.

3) NOABS tests on PTS

High speed video of the NOABS tests on the NTS surface confirmed structural damage to the surface and its generally poor state of maintenance resulted in the generation of debris from the action of the sliding locked tyre, It was therefore likely that the deceleration

Examination of juxtaposed ABS and NOABS deceleration plots for the PTS surface confirms that the limiting minimum deceleration measured in ABS tests was well below that encountered during the sliding phase of the NOABS tests. These frictional minima may correspond to sliding on surface detritus or sudden loosening of the particles forming the tyre/road contact patch rather than a thermodynamic cause.

Figure 88 illustrates that BOTH the ABS and NOABS stopping times are greater for the NEW NTS surface despite the poor condition of the PTS (HRA). The ABS tests show more momentary frictional minima for the NTS surface and the sliding NOABS friction measured for the NTS is approximately 60% of that of the PTS.

Though the PTS surface was in poor condition (

Figure 92), it appears the binder film of the NTS (

Figure 93) generated multiple low friction events detected and corrected by the ABS to give a lower average level of ABS deceleration than the failing HRA.

Peak temperatures experienced simulated emergency braking.

Use of the Researcher software to capture the maximum temperature measured along a line just behind and parallel to the contact line between the trialling edge of the tyre and the road surface revealed a noticeable difference in the temperatures achieved between tests on the PTS and NTS surfaces.

The graphs shown in Figure 95 and Figure 96 confirm the general findings of Zipkes (Zipkes, 1944). The presence of a layer of bitumen between tyre and road surface aggregate (as in the NTS surface) appears to limit the ultimate maximum temperature that can be generated between the two, without the bituminous separating layer the limiting factor is the tyre rubber (the case of the PTS (HRA)) .

For ease of interpretation, Figure 94 illustrates a comparison between the temperatures generated at the tyre/road interface during NOABS braking on both the NTS and PTS at Madingley, it can easily observed that the temperature rise is faster and the ultimate temperature greater for the PTS (HRA) surface.

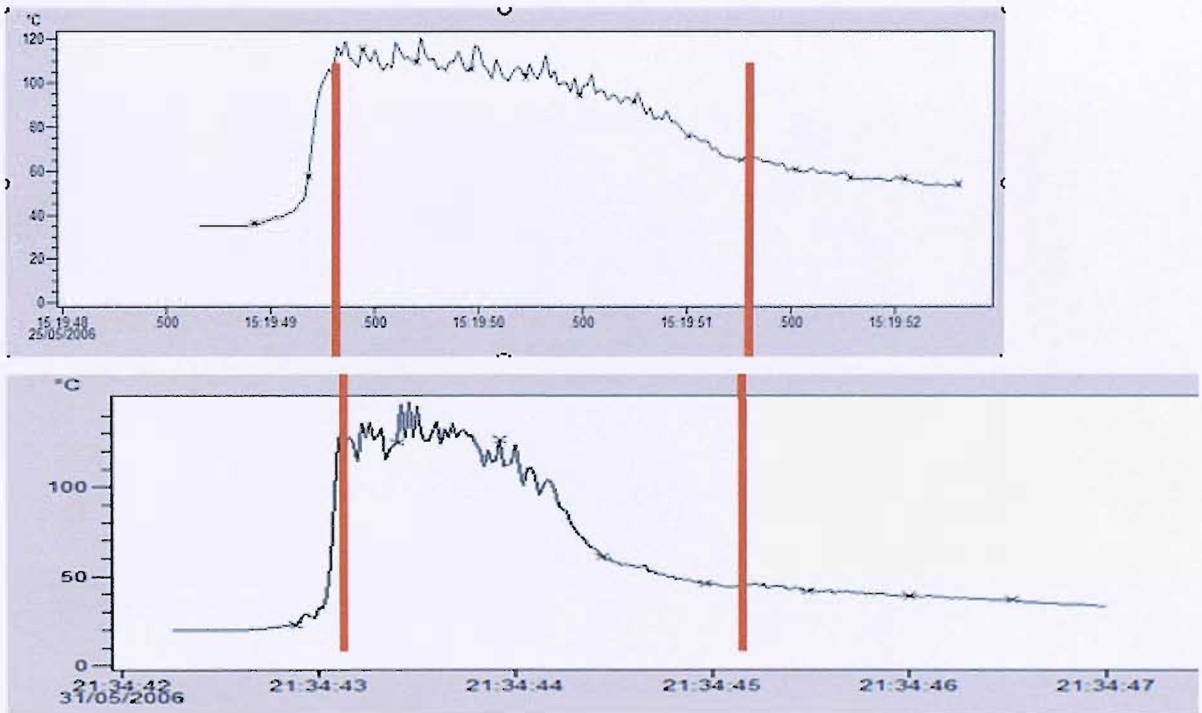


Figure 94 Tyre/Road Maximum Temperature Data extracted using FLIR Researcher: NTS top, PTS bottom

Visualisation of the Grip/Slip Transition for the ABS and NOABS Events

This section partially addresses Question 4 in Section 1.4: What was the likely mechanism (or mechanisms) responsible for the generation of the low levels of dry friction observed on certain NTS surfaces?

Though of little direct value in terms of delivering numerical outputs, the examination of the frame sequences extracted from the RAW AVI format DV videos using Redlake MiDAS Player v 2.1.4 R , frame referenced using Sony Vegas 6.0 and combined into multi image sheets using IrfanView.

Figure 97, Figure 98, Figure 99, Figure 100, Figure 101 and Figure 102 show sequences captured of the ABS braking cycles where the level of grip generated was approaching peak and slip was detected. Figure 103 and

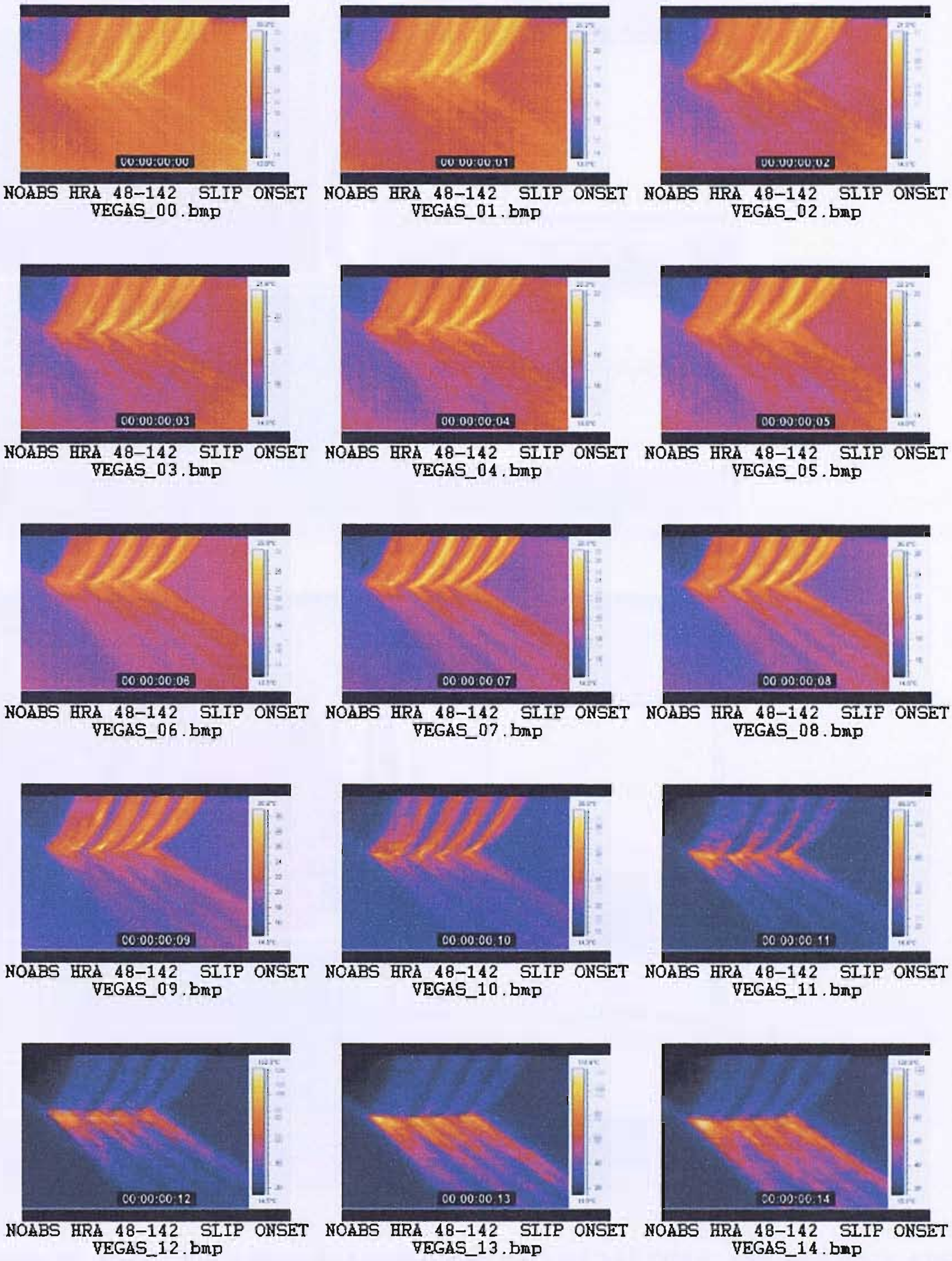
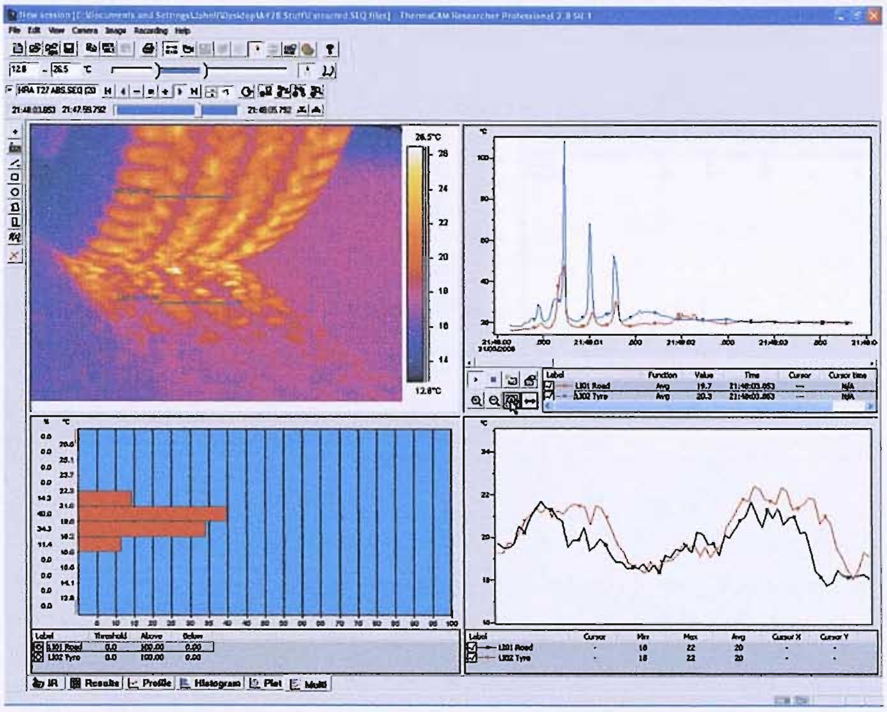


Figure 104 illustrate the onset and continuation of wheel lockup in two typical NOABS tests undertaken at Madingley. The appearance of the frames up to lockup is very similar to those for the ABS sequences confirming the dynamics are similar however, actual lockup is not supposed to occur in the case of ABS.

One related item of note are the visible periods of locked wheel braking during the NTS ABS sequences, these represents the regular ,multiple, near minima deceleration events seen in the ABS NTS SkidMan deceleration plots.

These sequences enable the dynamic nature of the tyre/road interface to be better understood, even if only at a basic level.

They are shown in Appendix 4: \MADINGLEY- MINI DV ABS PULSE and NOABS LOCK ONSET VIDEOS.



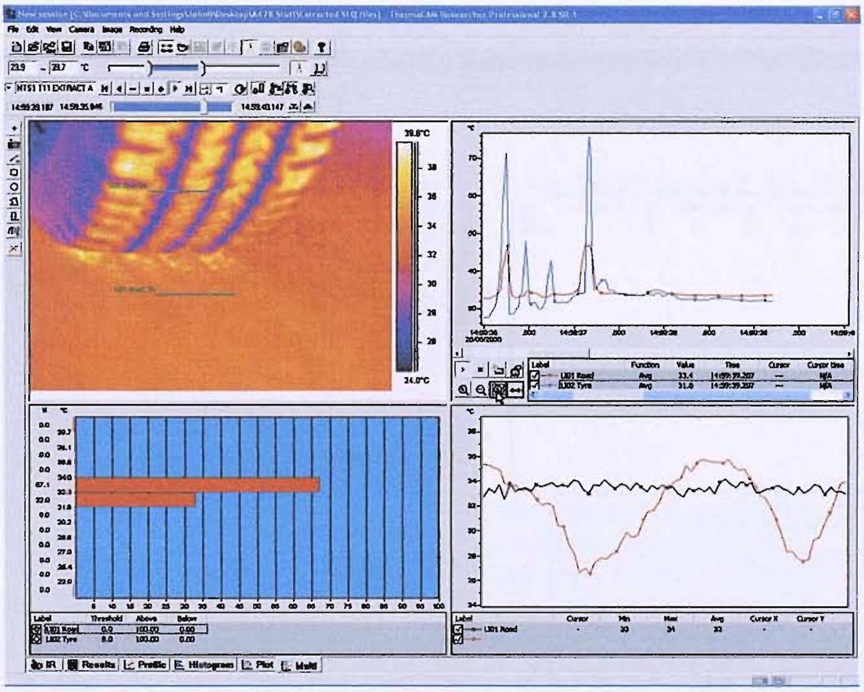


Figure 95 Researcher Software derived ABS thermal MAXIMA ABS PTS (top) ABS NTS (bottom)

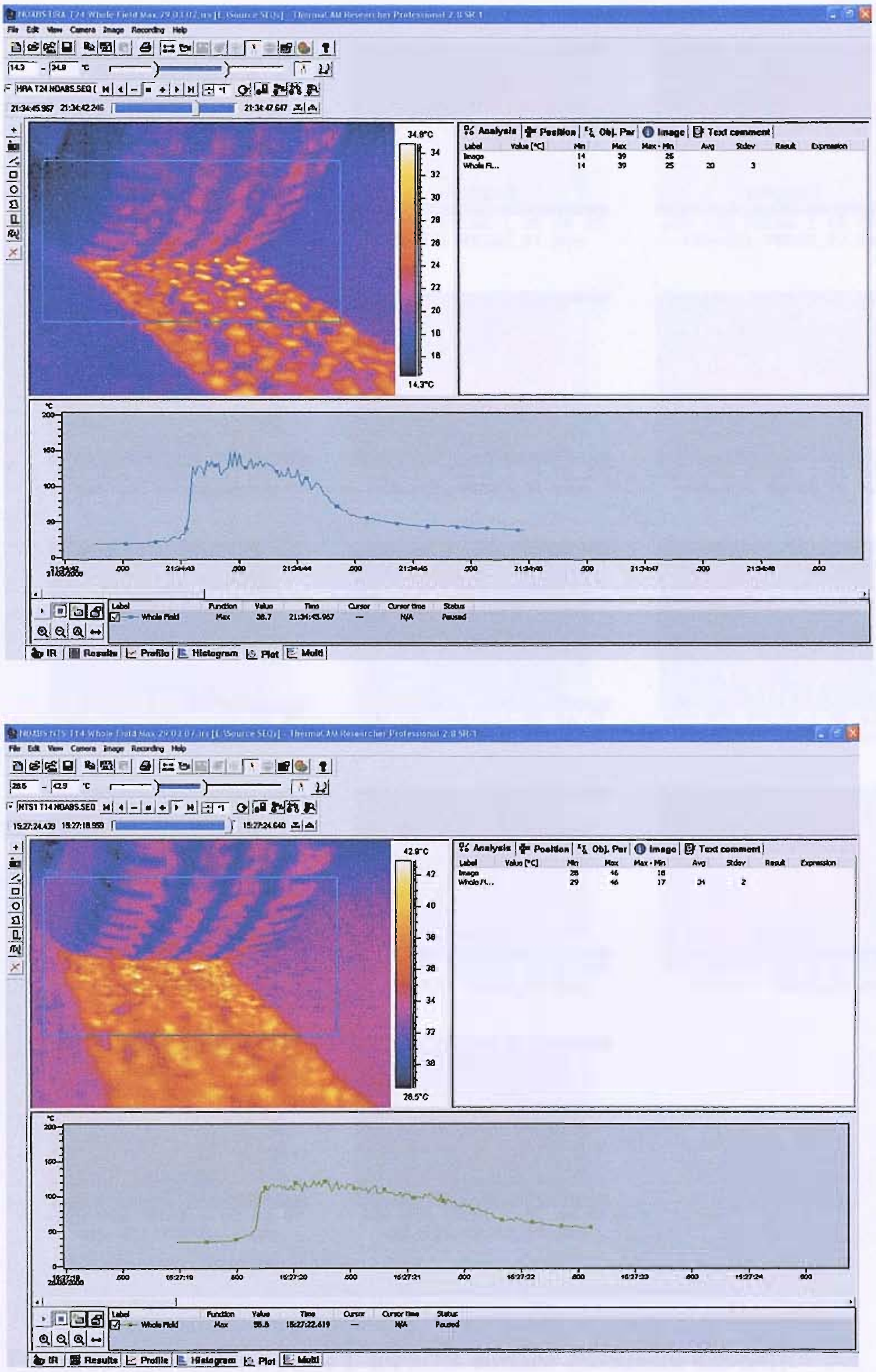


Figure 96 Researcher Software derived NOABS thermal MAXIMA NOABS PTS (top) NOABS NTS (bottom)

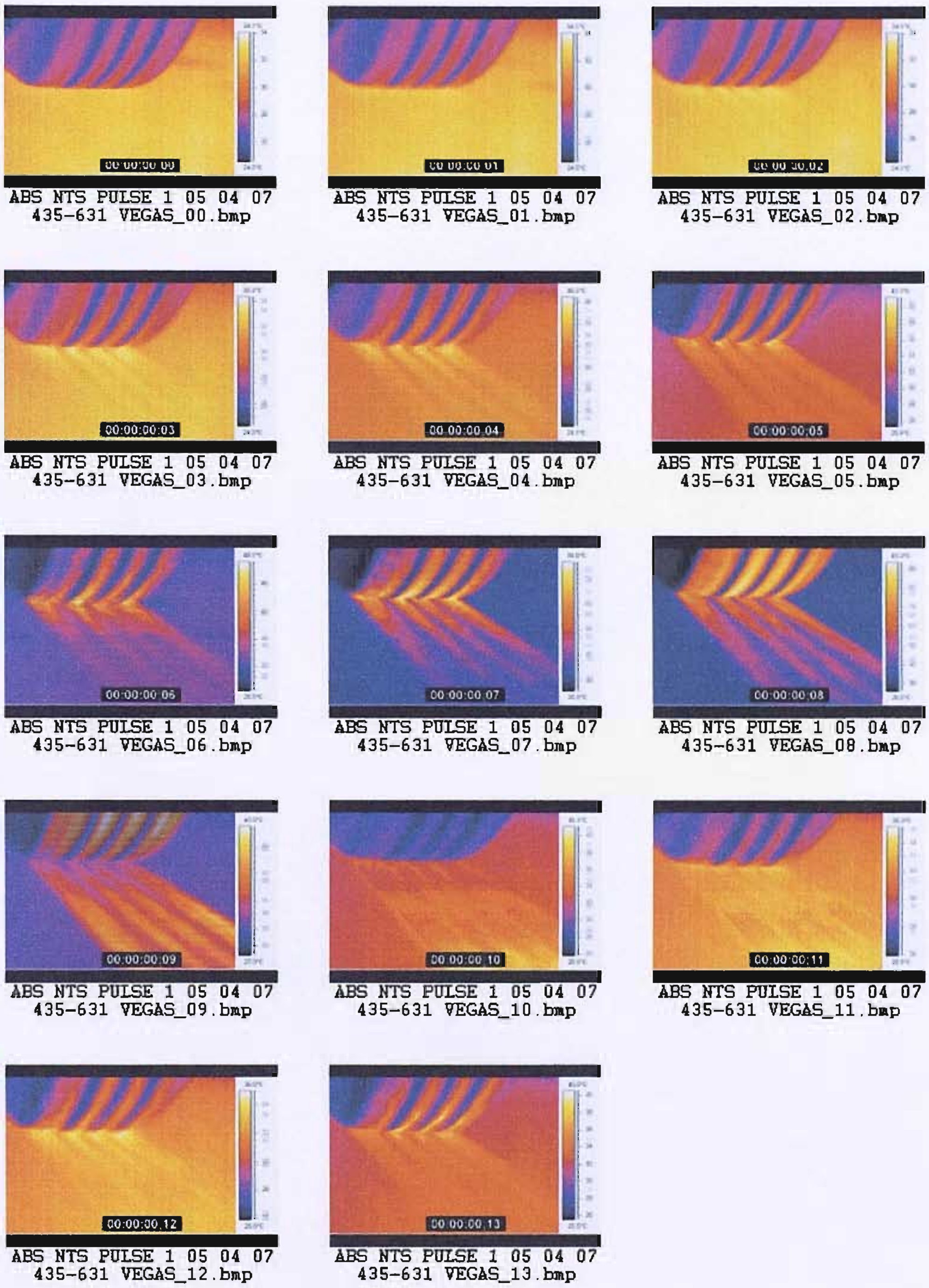


Figure 97 ABS braking pulse 1 for NTS surface (Sequence 435-631)

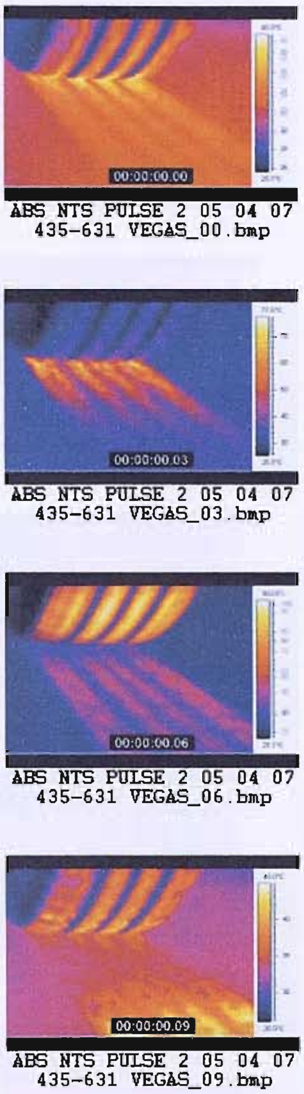


Figure 98 ABS braking pulse 2 for NTS surface (Sequence 435-631)

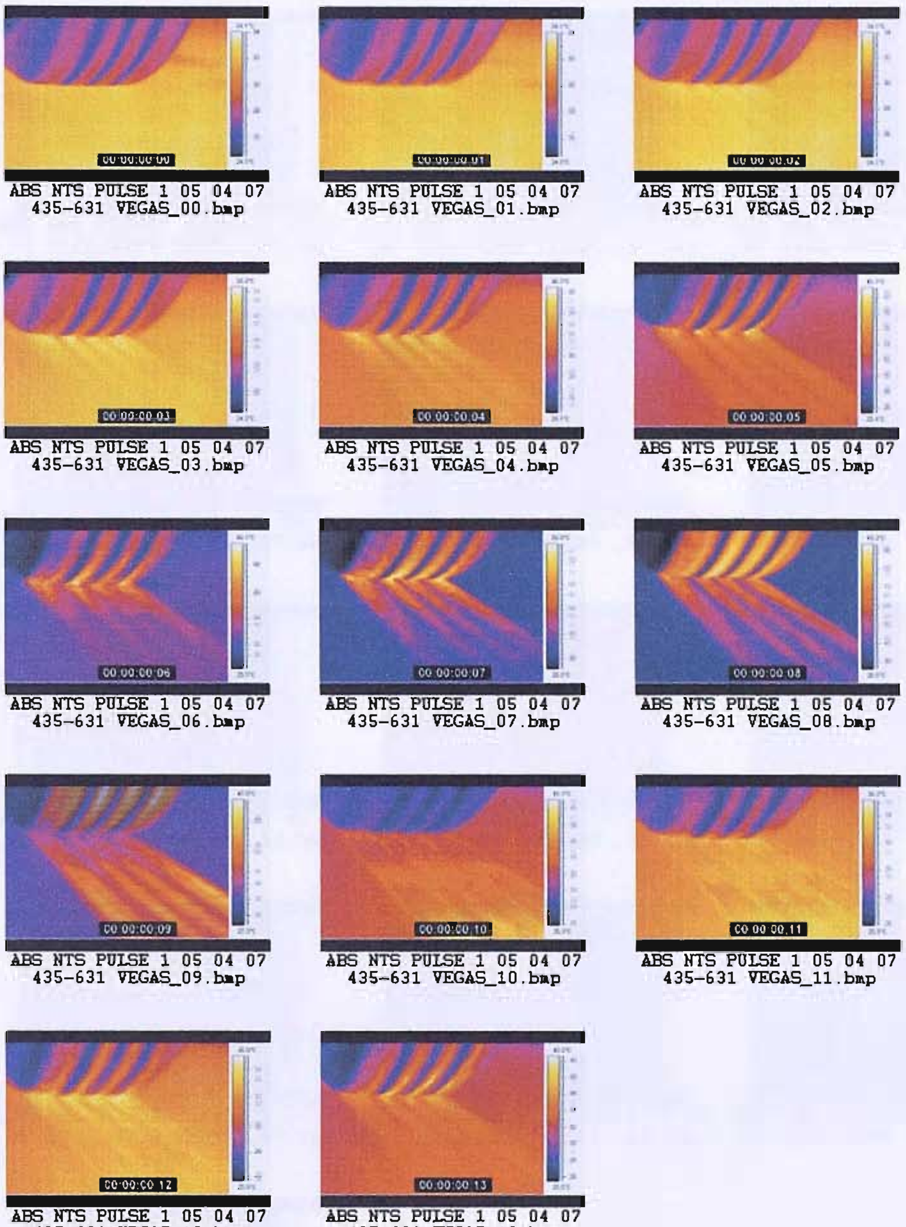


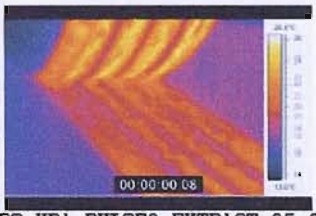
Figure 99 ABS braking pulse 1 for PTS (HRA) surface (sequence 435-631)

ABS HRA PULSE2 EXTRACT 05 04 07 3122-3390 VEGAS _04.bmp

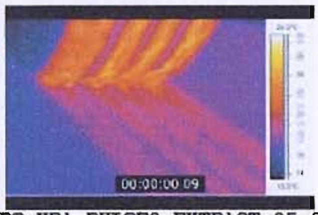
ABS HRA PULSE2 EXTRACT 05 04 07 3122-3390 VEGAS _05.bmp

ABS HRA PULSE2 EXTRACT 05 04 07 3122-3390 VEGAS _06.bmp

ABS HRA PULSE2 EXTRACT 05 04 07 3122-3390 VEGAS _07.bmp



ABS HRA PULSE2 EXTRACT 05 04 07 3122-3390 VEGAS _08.bmp

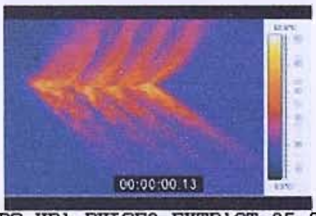


ABS HRA PULSE2 EXTRACT 05 04 07 3122-3390 VEGAS _09.bmp

ABS HRA PULSE2 EXTRACT 05 04 07 3122-3390 VEGAS _10.bmp

ABS HRA PULSE2 EXTRACT 05 04 07 3122-3390 VEGAS _11.bmp

ABS HRA PULSE2 EXTRACT 05 04 07 3122-3390 VEGAS _12.bmp



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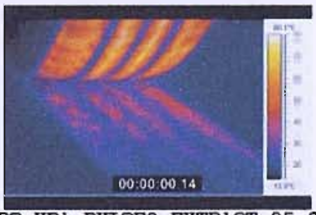

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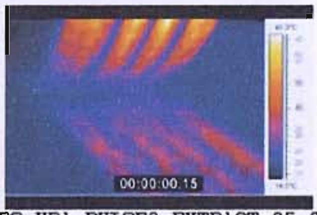
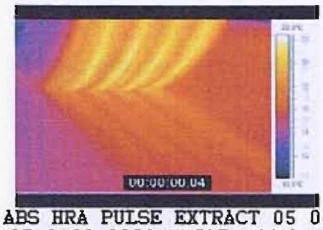


ABS HRA PULSE2 EXTRACT 05 04 07 3122-3390 VEGAS _15.bmp

ABS HRA PULSE2 EXTRACT 05 04 07 3122-3390 VEGAS _16.bmp

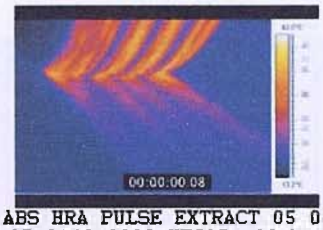
Figure 100 ABS Braking Pulse 2 on PTS (sequence 3122-3390)


ABS HRA PULSE EXTRACT 05 04 07 3122-3390 VEGAS _04.bmp


ABS HRA PULSE EXTRACT 05 04 07 3122-3390 VEGAS _05.bmp


ABS HRA PULSE EXTRACT 05 04 07 3122-3390 VEGAS _06.bmp

ABS HRA PULSE EXTRACT 05 04 07 3122-3390 VEGAS _07.bmp



ABS HRA PULSE EXTRACT 05 04 07 3122-3390 VEGAS _08.bmp

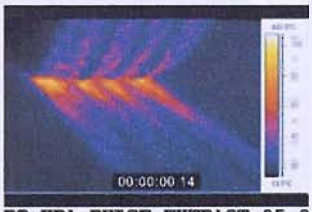
ABS HRA PULSE EXTRACT 05 04 07 3122-3390 VEGAS _09.bmp

ABS HRA PULSE EXTRACT 05 04 07 3122-3390 VEGAS _10.bmp

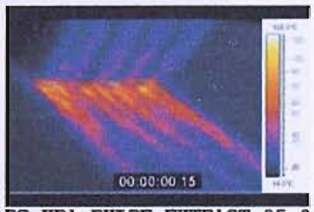
ABS HRA PULSE EXTRACT 05 04 07 3122-3390 VEGAS _11.bmp

ABS HRA PULSE EXTRACT 05 04 07 3122-3390 VEGAS _12.bmp

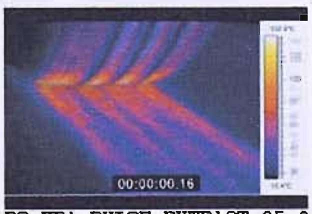
ABS HRA PULSE EXTRACT 05 04 07 3122-3390 VEGAS _13.bmp



ABS HRA PULSE EXTRACT 05 04 07 3122-3390 VEGAS _14.bmp



ABS HRA PULSE EXTRACT 05 04 07 3122-3390 VEGAS _15.bmp



ABS HRA PULSE EXTRACT 05 04 07 3122-3390 VEGAS _16.bmp

ABS HRA PULSE EXTRACT 05 04 07 3122-3390 VEGAS _17.bmp

Figure 101 ABS Braking on PTS Pulse 1 (sequence 3122-3390)

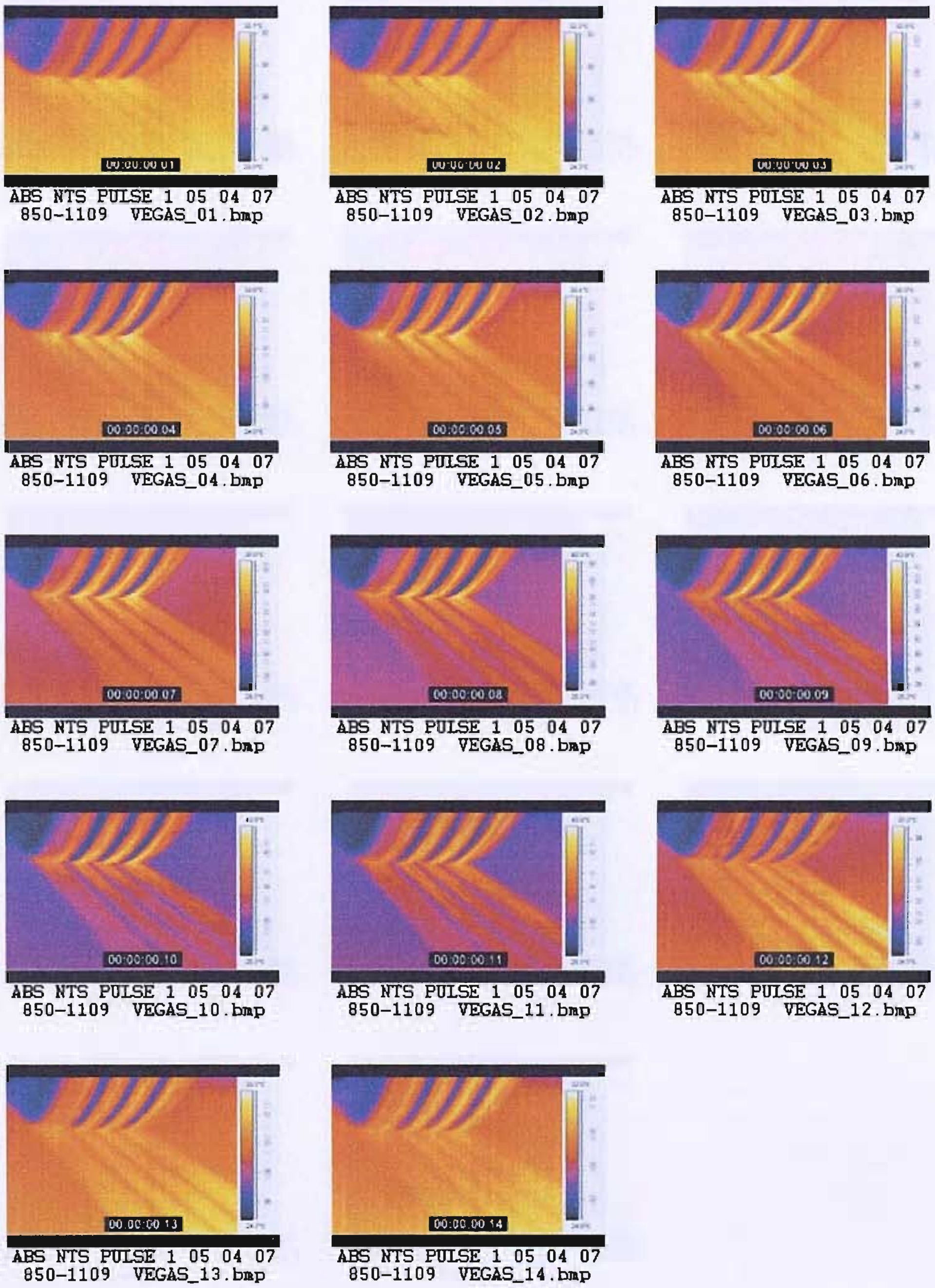


Figure 102 ABS braking pulse 1 for NTS surface (sequence 850-1109)

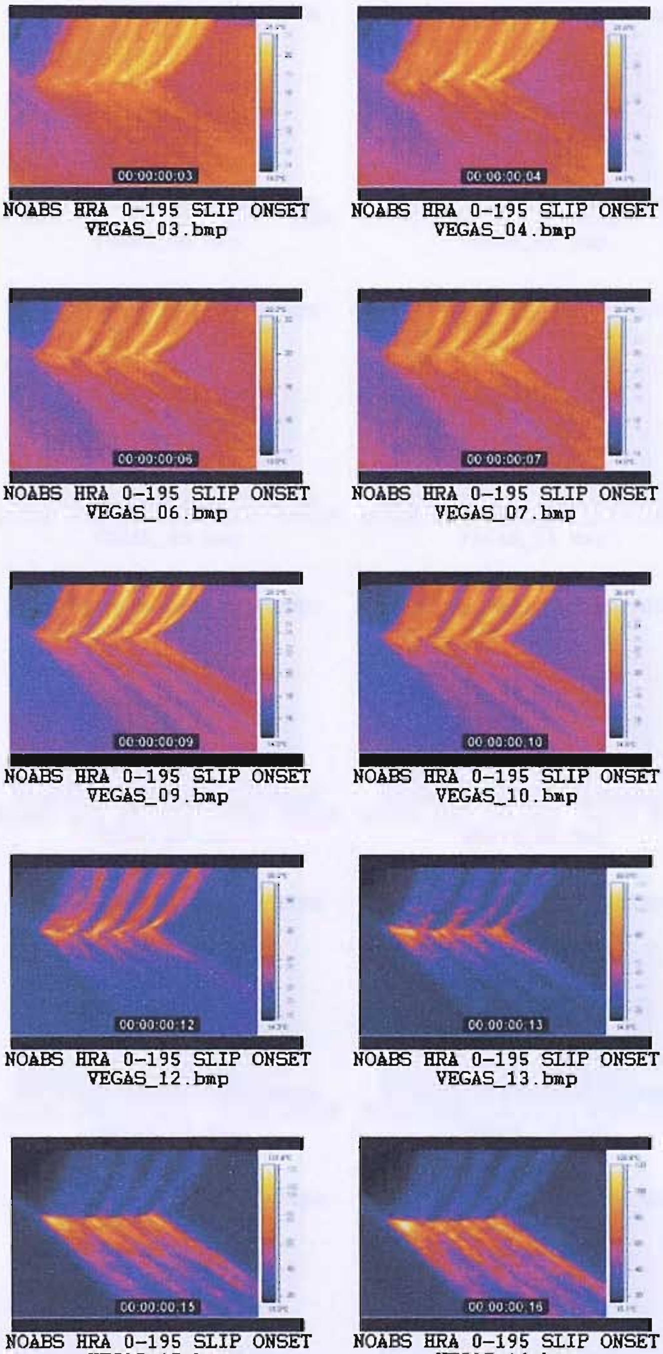


Figure 103 NOABS braking lockup for PTS surface (sequence 0-195)

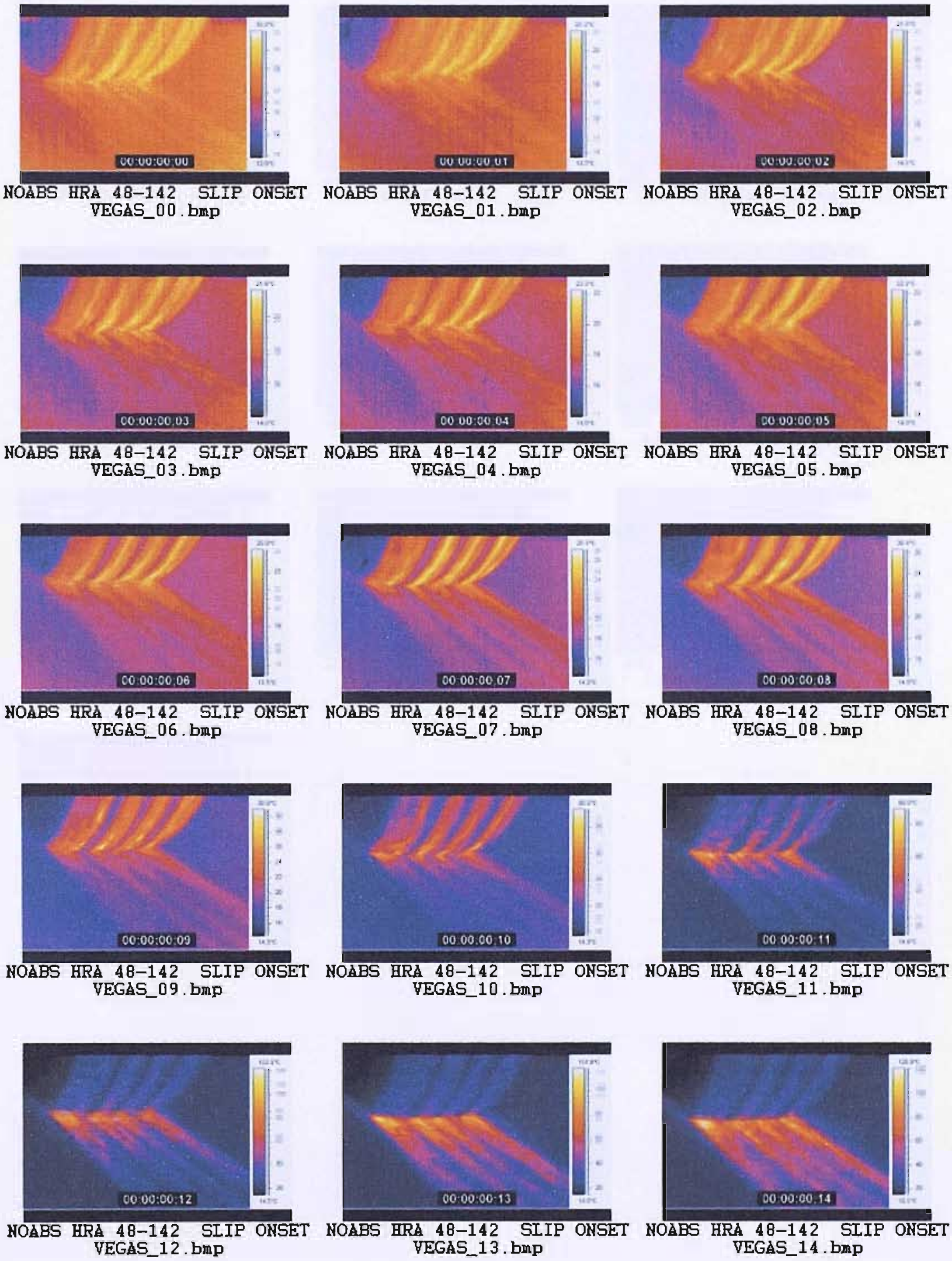


Figure 104 NOABS braking lockup for PTS surface (sequence 48-142)

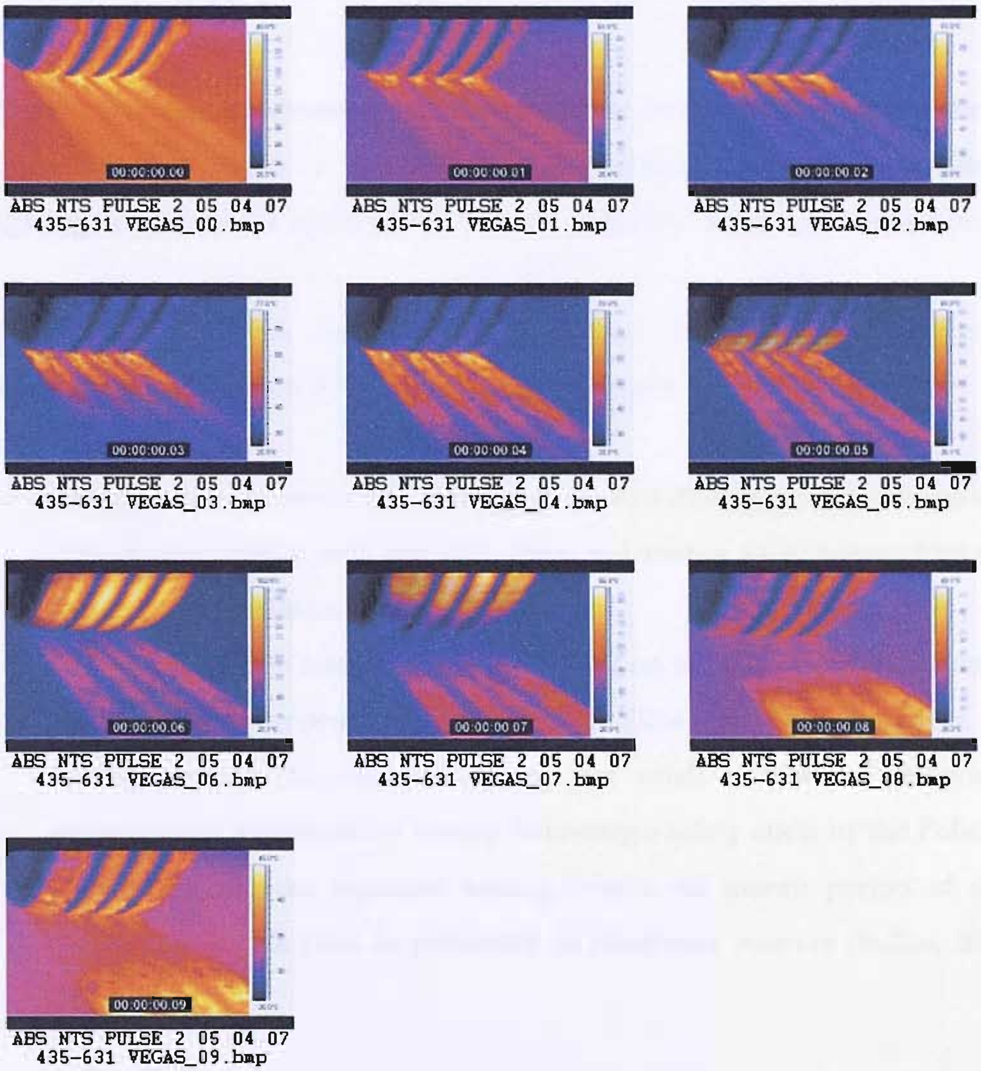


Figure 105 ABS braking pulse 2 for NTS surface (sequence 435-631)

3.5.5 Dry Friction over Time: Site Monitoring

This section addresses Question 5 in Section 1.4: Over what period of time following surfacing did low levels of dry friction still manifest themselves and what were the mitigating circumstances leading to the hiatus in the low friction phenomenon with time?

A number of separate exercises were carried out using dry friction Skidman measurements undertaken by the police or consultants:

- Dorset: testing over time of a number of NTS (SMA) sections of known age. The testing programme was severely restricted owing to ongoing obligations of the Dorset Police collision investigators.
- Derbyshire: single testing day (Figure 112) on section of different and known age (the "snapshot approach" used by TRL (Roe and Lagarde-Forest, 2005)). The testing programme was limited by the small number of proposed sections subsequently approved for testing following a safety audit by the Police.
- Hanson aggregates: repeated testing over a six month period of a number of surfaces on a link road in proximity to Heathrow Airport (Bullas, 2006a) (Figure 111).

Summary of results

All of the testing highlighted changes over time in the dry frictional properties of the sections tested. Derbyshire data is summarised herein (Table 14). In Derbyshire sections over 4 years old were still showing lower than typical levels of dry friction (
Figure 107) with an increase in dry friction both in response to traffic levels and surfacing age. Plotted with respect to traffic flow it appeared that ABS performance decreases with cumulative traffic (Figure 108) however, more confidence was shown in the use of surfacing age as the comparator. As both ABS and NOABS tests were undertake on the same section on the same day, a measure of the ABS to NOABS sliding friction could be made. Table 14 and Figure 106 illustrate the difference between the ABS and NOABS

sliding average friction and it can be easily seen that the difference between ABS And NOABS performance for NTS is greater than or HRA.

In Dorset all sections tested were delivering approximately typical levels of dry friction within 24 months (Figure 109) however, the sections tested were typically suburban dual carriageways rather than the rural sites tested in Derbyshire.

The test sections in London studied for Hanson showed a progressive increase in dry friction over the period of the tests, after six months the dry friction for the sections was approaching the "typical" levels of dry friction expected (Table 13). ABS tests showed the characteristic ABS dashes and low-G momentary events (Figure 110).

Material	Section	Average m/s2
Control DBM "old", well trafficked		7.12
14mm MT Tuffpave	S1 L1	6.55
14mm Tuffpave	S1 L1	6.22
14mm Durafalt LS Fines	S2	6.67
14mm Durafalt HS Fines	S3	6.1

Table 13 Hanson material performance after six months trafficking (Bullas, 2006a)

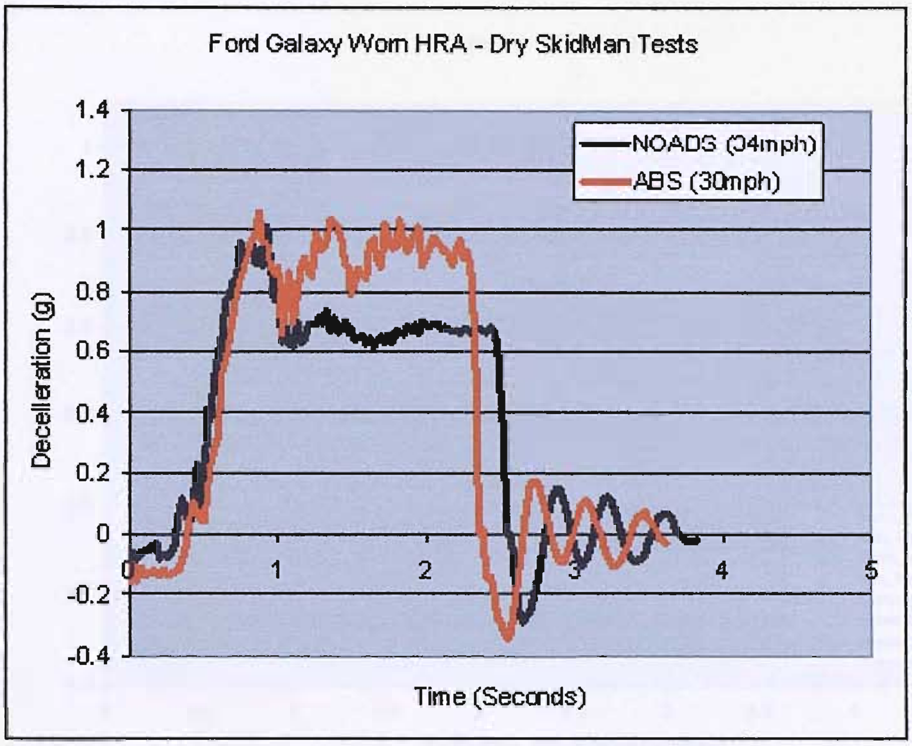
The time required for new NTS to reach a threshold level of acceptable friction of is commonly thought to be approximately six months (Highways Agency, 2003b),, the time observed for the London sites, TRL observed a 15 month period for a road in Derbyshire (Roe and Lagarde-Forest, 2005) and three months for the M3.

Insufficient data existed in each of the studies to represent statistically designed experiments thus no proven relationships can be established, however the common trends observed do mirror those seen elsewhere.

Skidman test number	ABS or NO ABS	ROAD	SURFACE	Section	Notes	Mean_G	Peak_G
13	NOABS	A515	SMA	H-J	1 deg uphill	0.633	0.823
16	NOABS	A515	SMA	F-G	4 deg uphill	0.858	0.949
18	NOABS	A515	SMA	K-L	2.5 deg uphill	0.662	0.82
20	NOABS	A610	SMA	6	n/a	0.565	0.745
22	NOABS	A610	SMA	5	n/a	0.602	0.797
24	NOABS	A610	SMA	1	n/a	0.661	0.813
26	NOABS	A610	SMA	8	Recent Resurface	0.537	0.751
28	NOABS	A615	14mm Masterphalt	F-E	uphill	0.564	0.786
30	NOABS	A615	14mm Masterphalt	E-D	n/a	0.637	0.802
32	NOABS	A615	14mm Masterphalt	D-C	n/a	0.597	0.727
34	NOABS	A615	14mm Masterphalt	B-A	1.5 deg uphill	0.636	0.814
36	NOABS	A632	PSV>65 Masterphalt	3	exposed	0.628	0.847
38	NOABS	A632	PSV>60 Masterphalt	1	2 deg uphill	0.61	0.812
40	NOABS	A632	HRA	HRA Control	fatted & low tex	0.69	0.861

Measurement	Surface	ABS/NOAE
MEAN INT ABS	PSV>60 Masterphalt	70.0%
MEAN INT ABS	PSV>65 Masterphalt	72.5%
MEAN INT ABS	14mm Masterphalt	73.6%
MEAN INT ABS	SMA	78.4%
MEAN INT ABS	HRA	80.8%
PEAK INT NOABS	PSV>60 Masterphalt	81.9%
PEAK INT NOABS	14mm Masterphalt	85.8%
PEAK INT NOABS	SMA	87.0%
PEAK INT NOABS	PSV>65 Masterphalt	88.6%
PEAK INT NOABS	HRA	91.5%

Table 14 Summary data and ABS/NOABS ratios for Derbyshire



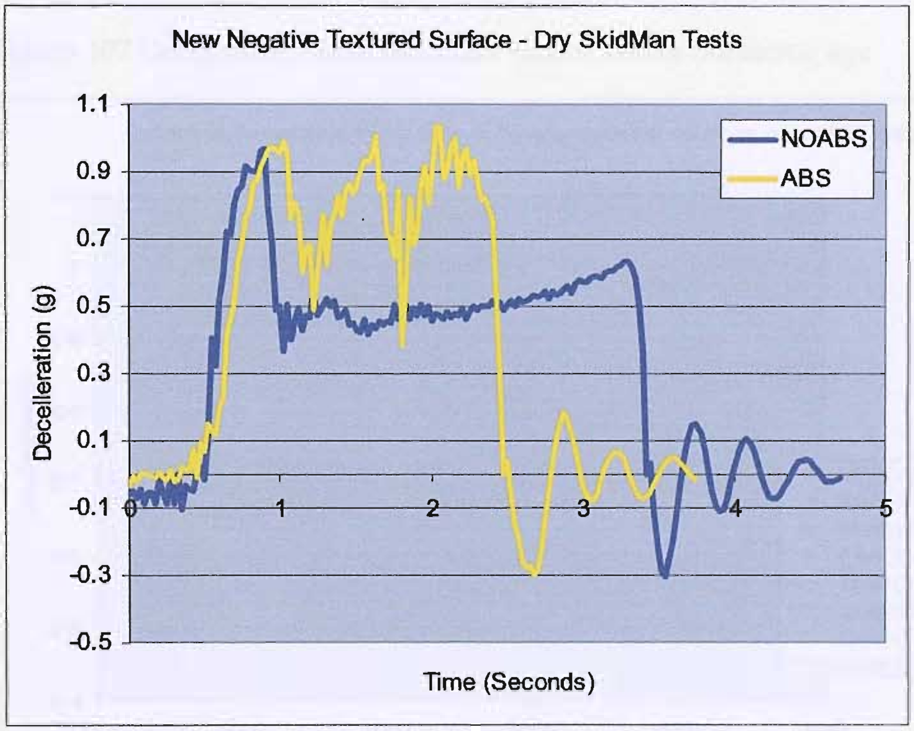


Figure 106 ABS / NOABS comparisons NTS (bottom) & PTS (top)

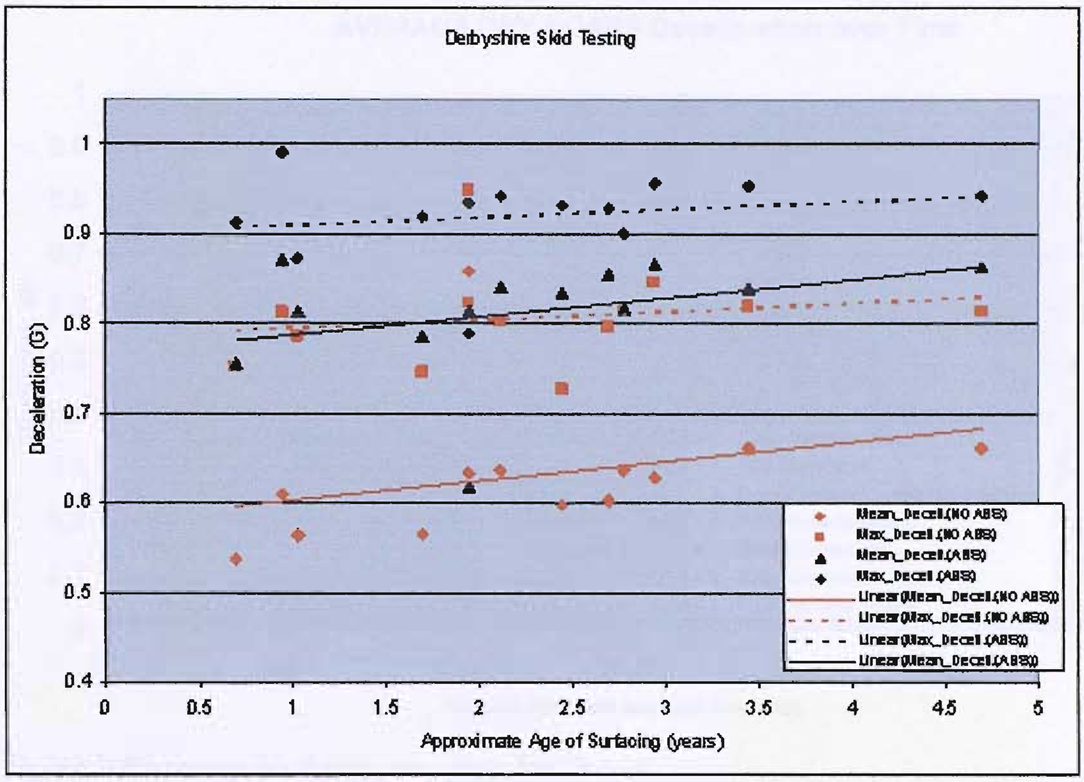


Figure 107 Derbyshire: Mean Skidman values versus Surfacing age

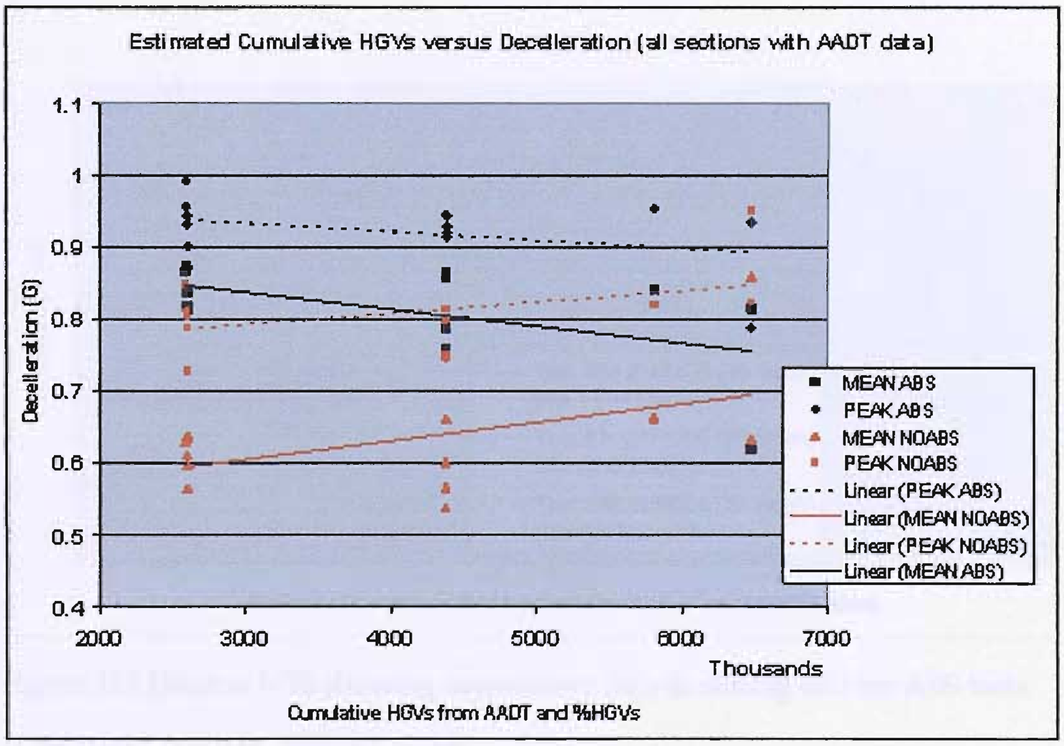


Figure 108 Derbyshire: Mean Skidman values versus Cumulative Traffic

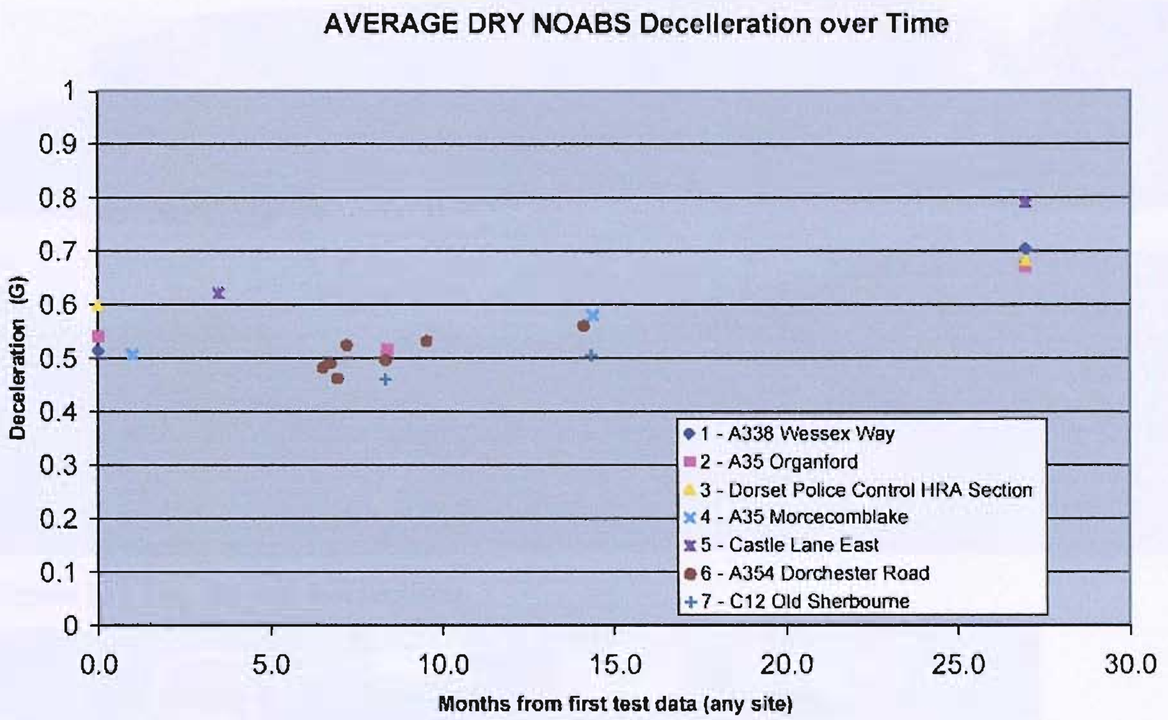


Figure 109Average Skidman over time for Dorset

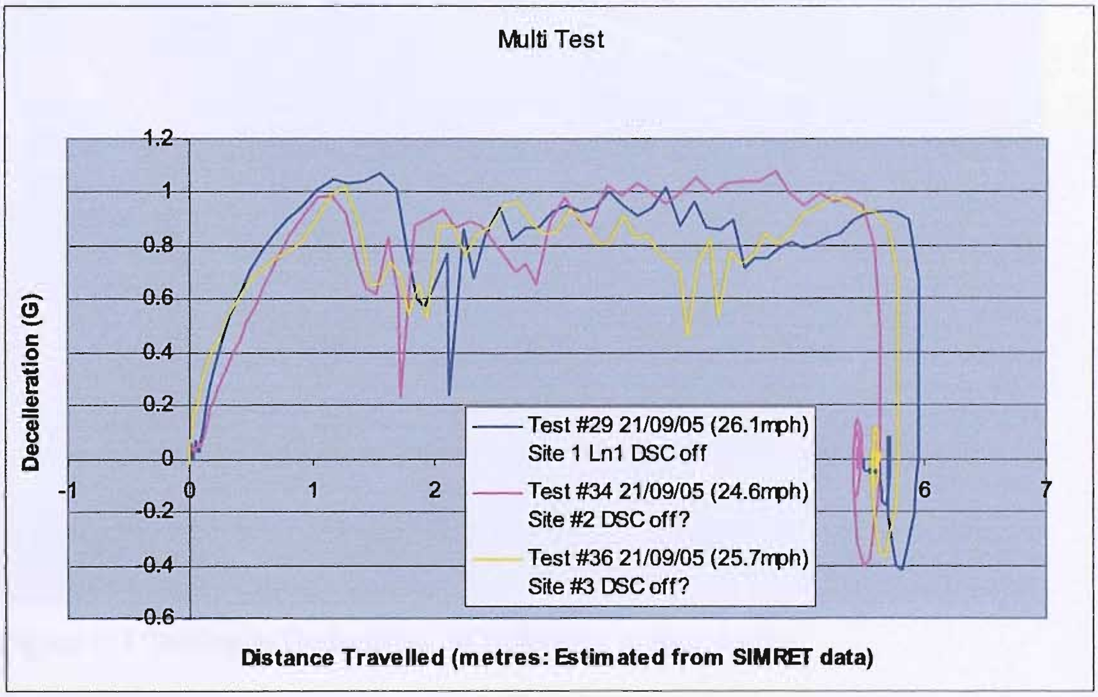


Figure 110 Hanson NTS showing momentary dips to sliding MU for ABS tests.

Figure 111 The Hanson test sections

Figure 112 Testing in Derbyshire, NOABS skid marks visible

3.5.6 Grip/Slip Characteristics of binder rich surfaces: Smeatharpe

This section partially addresses Question 4 in Section 1.4: What was the likely mechanism (or mechanisms) responsible for the generation of the low levels of dry friction observed on certain NTS surfaces?

The characteristics of the grip/slip curve for a braking tyre appear to be assumed to correspond to one of a very limited number of possible alternatives based on whether the surface being traversed was wet dry or icy. The observations made regarding the unique characteristic of NTS during dry locked wheel braking suggested that the grip/slip curve for such materials might depart from the choice of existing curves already discussed.
Devon County Council were undertaking resurfacing work on the main C road near in Smeatharpe, Devon.

The laying of the SMA was proceeded by the laying of a bond coat, Gripclean made by Colas (Anon, 2006) , this coating is designed to optimise the bond between layers and is a spray applied medium free from the coarse fraction present in a laid SMA. Thus, it provided an opportunity to test the grip/slip capabilities of a fine bitumen layer.

Datron (UK) kindly loan the Researcher a WRT (wheel rotation sensor) (Figure 114) an accelerometer and a sensitive MicroSAT GPS movement logger (Figure 113) to enable the measurement of the movement of a tyre on a vehicle relative to the movement of the road surface and relative to deceleration. Datron also provided a data logger to record a simultaneous data stream from all three devices (Figure 115).

Unfortunately, the equipment was only available to the Researcher for two days at it was usually committed to commercial testing so this particular testing was limited to Smeatharpe as a pilot scale investigation.

Figure 113 The Datron MicroSAT GPS Unit (Datron UK)

Figure 114 The Datron Corrsys WRT wheel rotation sensor in position

Figure 115 The data logger, GPS and antennae and accelerometer

The data stream from standard skid tests on the Gripclean was plotted to produce the equivalent of the grip/ slip plots already seen from the literature.

Summary of results

The deceleration plots appeared similar to measurements made on the North Circular Road (BBA/HAPAS NTS) and in Derbyshire on an SMA. ABS tests could not be undertaken at Smeatharpe, as the test vehicle was not equipped with ABS. The slip/grip curves obtained for the Gripclean showed a noticeable difference to those already described in the literature Figure 116, Figure 117 with peak grip being developed at very low slip % then reducing to that intermediate from snow or wet asphalt.

The use of proven technology from Datron for the testing does not conclusively confirm the findings of the limited testing on the Gripclean. Similar tests need to be undertaken on more NTS materials in order to support the observations at Smeatharpe.

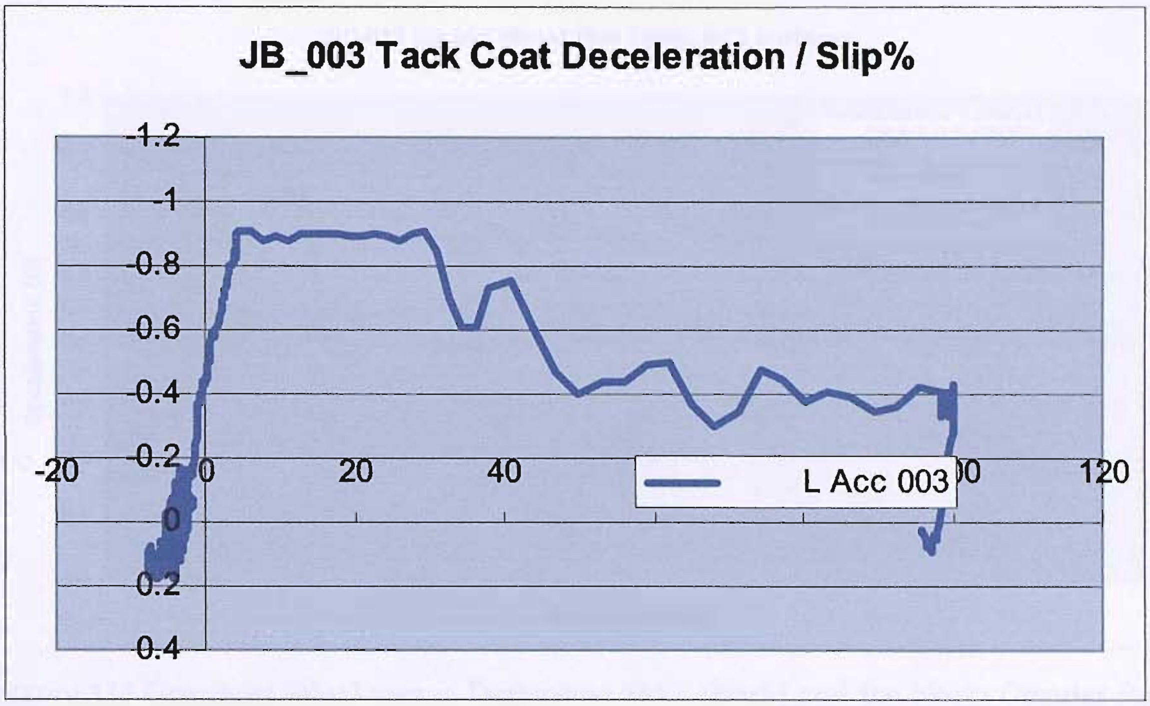


Figure 116 Grip versus Slip percentage for DRY Gripclean

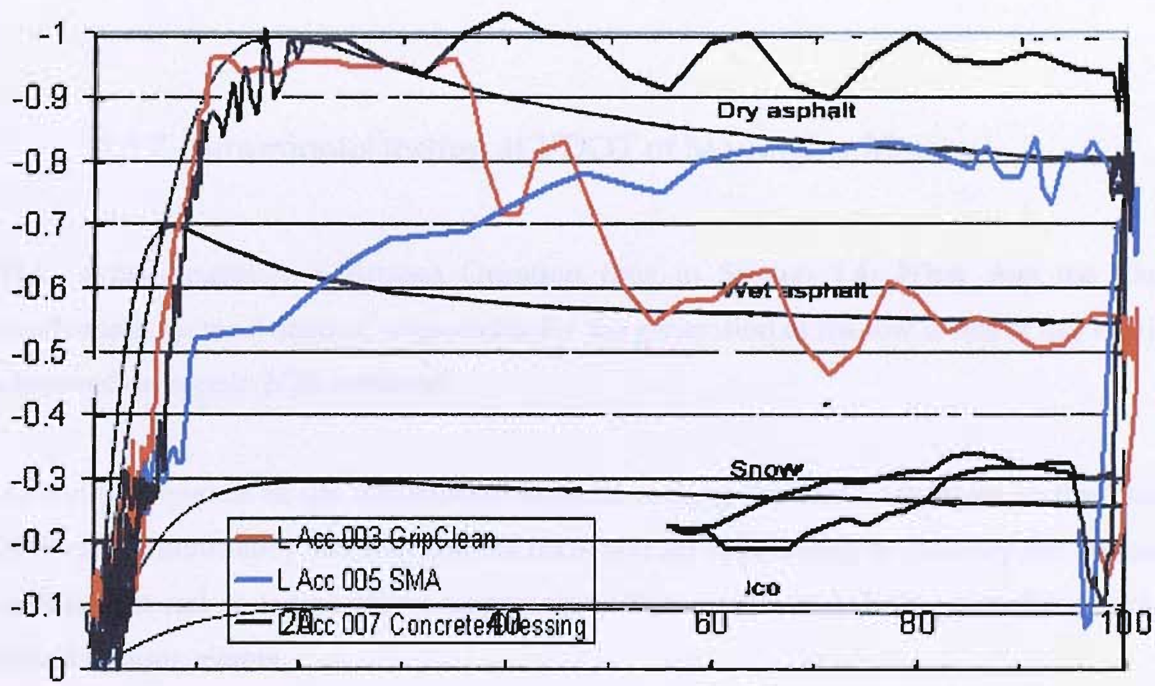


Figure 117 Grip versus Slip percentage for DRY Gripclean (red), SMA (blue), and Concrete (black) versus typical grip slip curves

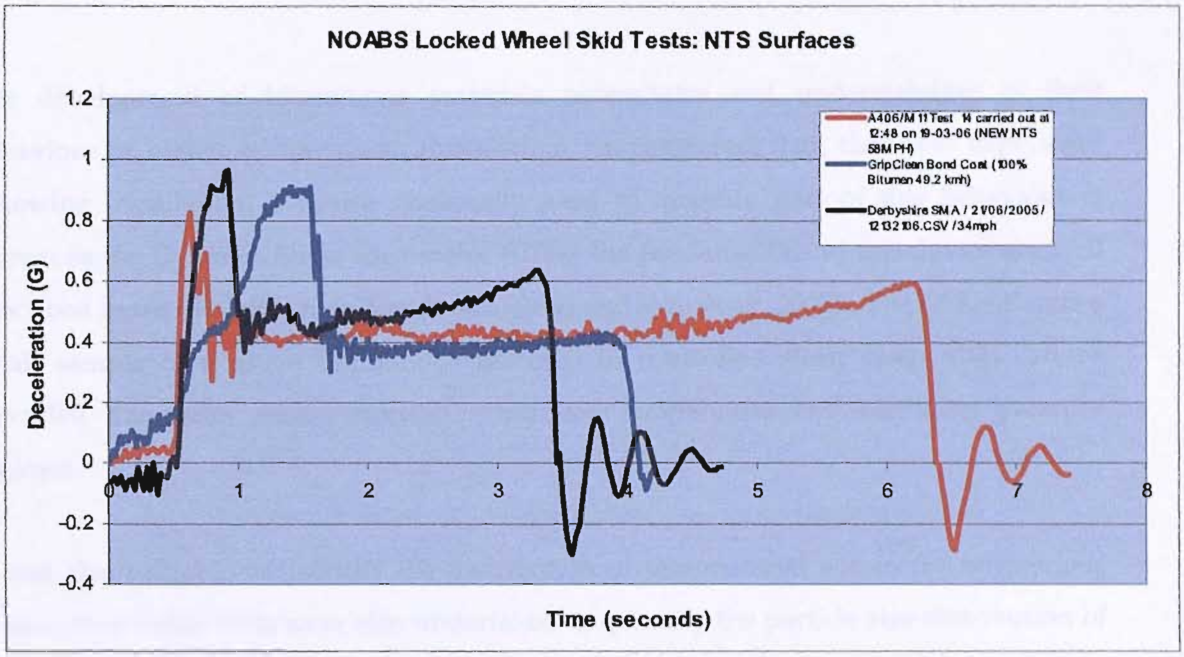


Figure 118 Gripclean (blue) versus Derbyshire SMA (black) and the North Circular Road NTS

3.5.7 Bituminous testing at VDOT of Madingley Material

This section partially addresses Question four in Section 1.4: What was the likely mechanism (or mechanisms) responsible for the generation of the low levels of dry friction observed on certain NTS surfaces?

As the provenance of the bituminous material coating the stone aggregate in the 14mm NTS on the Madingley site was known, there was an opportunity to quantify the viscosity of this material at temperatures approaching those measured during simulated locked wheel braking events.

The cost of commercial testing was beyond the budget of this research project and an approach was made to a contact at the Virginia Department of Transportation (VDOT) to procure free testing on the material in question.

The development of bituminous materials necessitates and understanding of their behaviour at higher temperatures (installation temperatures) than they will experience following installation, a device commonly used to quantify part of this behaviour is known as the Dynamic Shear Rheometer (DRS), the fundamentals of this device are well described in the Shell Bitumen Handbook (Read and Whiteoak, 2003) . The DSR submits a small sample of a given bituminous material to controlled shear over what can be extended timescales under precisely controlled temperature and confining pressure regimes.

It was also valuable to quantify the distribution of fine material within the bituminous mastic, thus reflux tests were also undertaken to quantify the particle size distribution of this nominally 14mm surfacing material.

The DSR testing thus carried out by Stacey Diefenderfer, Research Scientist, Virginia Transportation Research Council, Charlottesville, VA on a sample of Olexobit 100 documented the behaviour of the bituminous product used on the Madingley (A428 sections) along with a particle size distribution on a sample of recovered surfacing from the edge of the surfacing.

The VDOT analysis of the particle size distributions (PSDs) (Table 16 and Table 17) highlighted the potential for the significant particulate mass within the body of the mastic coating the coarse aggregate chippings to contribute to the rheological behaviour of the bituminous mass. The potential for the percentage of stone fines in the mastic to contribute towards the thermal transfer ability of the mastic has been studied in the Netherlands (Jutte and Siskens, 1997). Both VDOT PSDs (Figure 120) suggested that approximately 25% of the stone content of the mixture was below 2.36mm in size and would be active in the material behaviour of the bituminous mastic around the 14mm fraction forming the road surface.

Limited testing was performed on Olexobit 100 binder supplied by BP Bitumen. Testing consisted of strain sweep measurements performed on a TA AR2000 rheometer using parallel-plate geometry to determine the limiting strain within the linear visco-elastic response range. At temperatures of 40°C and below, 8mm diameter parallel plate geometry was used for testing with 2mm thick specimens; at temperatures 50°C and higher, 1mm thick specimens were tested with 25mm diameter parallel plate geometry. The data measured included complex shear modulus, complex shear viscosity, and phase angle.

Due to unforeseen constraints at VDOT, frequency sweep testing at specific strains was not conducted; however, data was extracted for analysis at specific frequencies and strains within the LVE (linear visco-elastic) region of the strain sweep testing, (The LVE limit was defined by VDOT as the point where the complex modulus (G*) decreased to 95% of its original value (Anderson et al., 1994)).

A plot of the measured complex viscosity for Olexobit 100 using 2.5% applied strain is shown in Figure 119 . If it is assumed that typical fluids that flow freely (without applied force) have typical viscosities of less than 10 Pa·s, and that fluids of a "spreadable" consistency typically have viscosities in the range of 10 – 400 Pa·s, as indicated in Table 15, it can be seen that Olexobit 100 is well within this range at most test frequencies at temperatures of 60°C and higher.

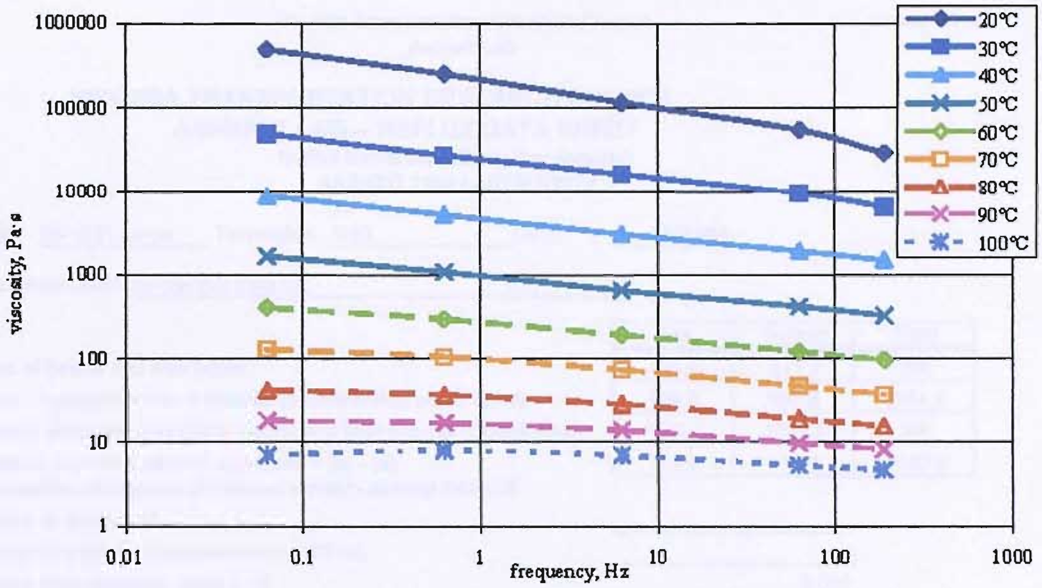


Figure 119 Complex shear viscosity for Olexobit 100 at 2.5% applied strain.

Fluid	**Viscosity**
Milk	1.2 cP / 0.012 Pa·s
Melted Butter	18 cP / 0.18 Pa·s @ 140°F
Corn Oil	30 cP / 0.3 Pa·s
Cough Syrup	190 cP / 1.9 Pa·s
Auto Lube Oil SAE 40	200 cP **/ 2.0 Pa·s @ 100°F**
Yogurt	1,100 cP / 11 Pa·s
Honey	1,500 cP / 15 Pa·s @ 100°F
Mayonnaise	5,000 - 10,000 cP / 50 - 100 Pa·s
Tomato Paste	7,000 cP / 70 Pa·s
Corn Syrup	15,000 cP / 150 Pa·s
Toothpaste	20,000 cP / 200 Pa·s
Hot Fudge	36,000 cP / 360 Pa·s

Table 15 Approximate viscosities of common materials.(APV Products, 2006) Car oil has been emboldened

Virginia Transportation Research Council
Asphalt Lab

Revised 8-14-00

VIRGINIA TRANSPORTATION RESEARCH COUNCIL
ASPHALT LAB -- REFLUX DATA SHEET
Reflux Extraction (Oven Dry Sample)
AASHTO T164 / ASTM D2172

VTRC # 06-1051 Large Technician: THD Date: 08/21/06

Sample Description: TA Sample from UK

	Top	Bottom	Total
(a) mass of basket and filter paper	418.4	411.2	NA
W1 mass of sample before extraction (basket & filter paper tared)	798.0	966.6	1764.6
(b) mass of extracted aggregate, basket and filter dried to contant mass	1180.3	1330.2	NA
W3 mass of extracted mineral aggregate = (b) - (a)	761.9	919.0	1680.9

Determination of amount of mineral matter - ashing method

V1 volume of extract, ml	
(c) volume of aliquot, ml (approximately 100 ml)	
V2 volume after removing aliquot, ml	0.000
(d) mass of ignition dish (nearest 0.001 g)	
(e) mass of ignition dish and ash residue - after ignition (nearest 0.001 g)	
(f) mass of ash residue = (e) - (d)	0.000
Amount of sat. amonium carbonate solution added, ml = 5 * (f) [1ml = 1.1 g]	0.000
(h) mass of ignition dish and digested ash (nearest 0.001 g)	
G mass of ash in aliquot = (h) - (d)	0.000
W4 mass of mineral matter = G[V1 / V1 - V2]	0.000
Asphalt Content, % = [(W1) - (W3 + W4)]/W1 * 100	4.743

Mechanical Analysis of Extracted Aggregate - AASHTO T30

Sieve Size	Mass Retained	% Retained	% Passing
25.0 mm, +1"		0.0	100
19.0 mm, +3/4"		0.0	100
12.5 mm, +1/2"	256.3	15.3	85
9.5 mm, +3/8"	569	33.9	51
4.75 mm, +4	289.3	17.2	34
2.36 mm, +8	173.1	10.3	23
1.18 mm, +16	122.4	7.3	16
0.600 mm, +30	67.8	4.0	12
0.300 mm, +50	44.8	2.7	9
0.150 mm, +100	39.6	2.4	7
0.075 mm, +200	31.1	1.9	5.1
Pan	5.8	0.3	NA

Total dry mass of aggregate before washing, g	1678.4
Total dry mass of aggregate after washing, g	1599.7
Total mass of aggregate after sieving, g	1599.2

530 Edgemont Rd., Charlottesville, VA 22903
Voice: (804) 293-1919 Fax: (804)293-1900

06/05/200707:28
VDOT 06-1051 Large Reflux.xls

Table 16 VDOT Large Reflux results sheet

VIRGINIA TRANSPORTATION RESEARCH COUNCIL
ASPHALT LAB – REFLUX DATA SHEET

VTRC # :	06-1051 Small	Agg. Type:		Sample Date:	
Producer:	Sample from UK	Sample # :		Date Tested:	21/08/2006
Plant:		Project # :	T/A	Technician:	
Time Sieved					

Weight of Basket and Filter paper :	816.0
Weight of sample Before Extraction :	1036.3
Total dry weight of aggregate Before Washing :	985.6
Total dry weight of aggregate After Washing :	938.4
Total dry weight of aggregate After Sieving :	939.1
Weight of Binder in sample :	50.7
Percent of Binder in sample :	4.89

U.S. Stand Sieve No.	Weight Retained	Percent Retained	Percent Passing	Sieve (mm	% passing
25.0 mm, 1 in.		0.0	100.0	25	100.0
19.0 mm, 3/4 in.		0.0	100.0	19	100.0
12.5 mm, 1/2 in.	149.2	15.1	84.9	12.5	84.9
9.5 mm, 3/8 in.	348.0	35.3	49.6	9.5	49.6
4.75 mm, No. 4	167.8	17.0	32.5	4.75	32.5
2.36 mm, No. 8	97.2	9.9	22.7	2.36	22.7
1.18 mm, No. 16	67.4	6.8	15.8	1.18	15.8
600 microns, No. 30	39.3	4.0	11.8	0.6	11.8
300 microns, No. 50	25.5	2.6	9.3	0.3	9.3
150 microns, No. 100	21.1	2.1	7.1	0.15	7.1
75 microns, No. 200	19.1	1.9	5.2	0.075	5.2
Pan	4.5	5.2	NA	0	0.0

Note:

Table 17 VDOT Small Reflux results sheet

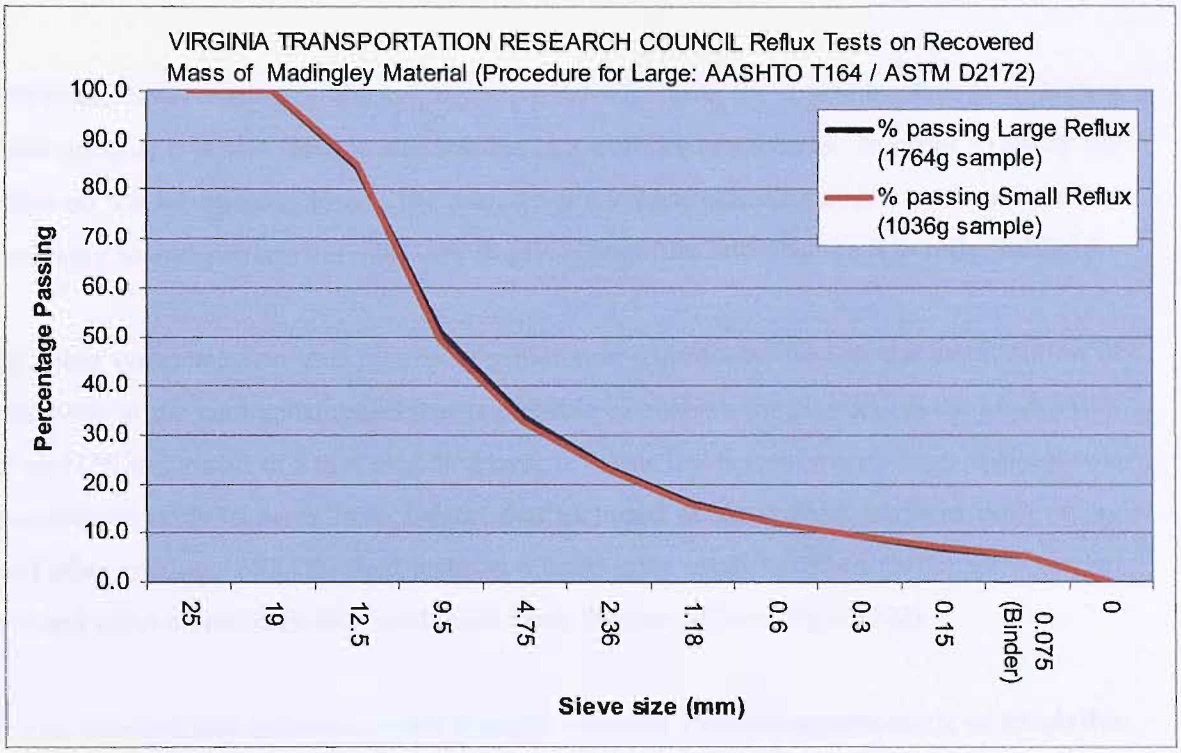


Figure 120 VDOT PSD for the recovered Madingley bituminous materials

The findings of the reflux testing confirm the presence of a significant (approx 20% sub 2mm) granular content in a medium commonly viewed as being almost entirely bituminous. The presence of the granular content will have a measurable effect on the rheological response of the mastic to the passage of a vehicle tyre over it, however how different mastic with a smaller granular content would perform, would need more work, indeed Jutte et al (Jutte and Siskens, 1997) considered the thermal effect of the fines content in the mastic.

3.5.8 Fluorescent Microscopy at University of Southampton Oceanographic Unit

This section partially addresses Question four in Section 1.4: What was the likely mechanism (or mechanisms) responsible for the generation of the low levels of dry friction observed on certain NTS surfaces?

The bituminous coating on the aggregate particles forming the coarse fraction of an NTS is itself opaque; it is also flexible and soluble in a number of solvents. In order to study the effect on this bituminous film of the passage of a vehicle skidding over a road surface, it is necessary to encapsulate the relatively fragile binder film and observe it in reflected light.

By using encapsulation and microscopy methods commonly used in the examination of bitumens in the geological realm it was possible to observe the changes in the binder film of an NTS as a result of a tyre skidding over it. Thus fluorescent microscopy analysis was undertaken on NTS cores from Devon that included skidded SMA surfaces both before and after gritting. NOABS Skid tests on a 6mm latex modified SMA (NTS) were carried out and cores taken from the visible skid mark (Figure 121 and Figure 122).

It was thought this microscopy work might visualise changes symptomatic of exudative hardening. The literature (Soenen et al., 2006) suggested fluorescent microscopy may provide a simple means of studying the surface change in the bitumens in the SMA thick films by thin section analysis of the road surface making contact with the tyre during skidding again un-skidded surface. The process proposed to be undertaken (Figure 123) by the University of Southampton's National Oceanographic Centre (NOC) is commonly in use in the investigation of changes in bitumens in response to metamorphic processes.

Detailed analysis of the bitumens in the samples prepared by NOC could not be undertaken owing to financial constraints.

- simple comparison of the composite photomicrographs of the un-skidded (Figure 124) and skidded (Figure 125) material did illustrate the effect of the passage of a sliding tyre on the surface of a generic Stone Mastic Asphalt (SMA) (by evidence of a thinned mastic layer on the test sample taken from the skid).

Some problems were unfortunately encountered during sample preparation from dissolution of the bitumen in the preparation solutions used; this in itself may have prevented the diagnostic visualisation of any layered bitumen changes resulting from the action of the skidding tyre.

- Future work in this area with alternative preparation solvents may be of value in establishing morphological changes in the bitumen on the road surface chippings.

Figure 121 Skidded Surface, Coring Rig, and Core Sample

Figure 122 Marked skid orientation and Cored NTS

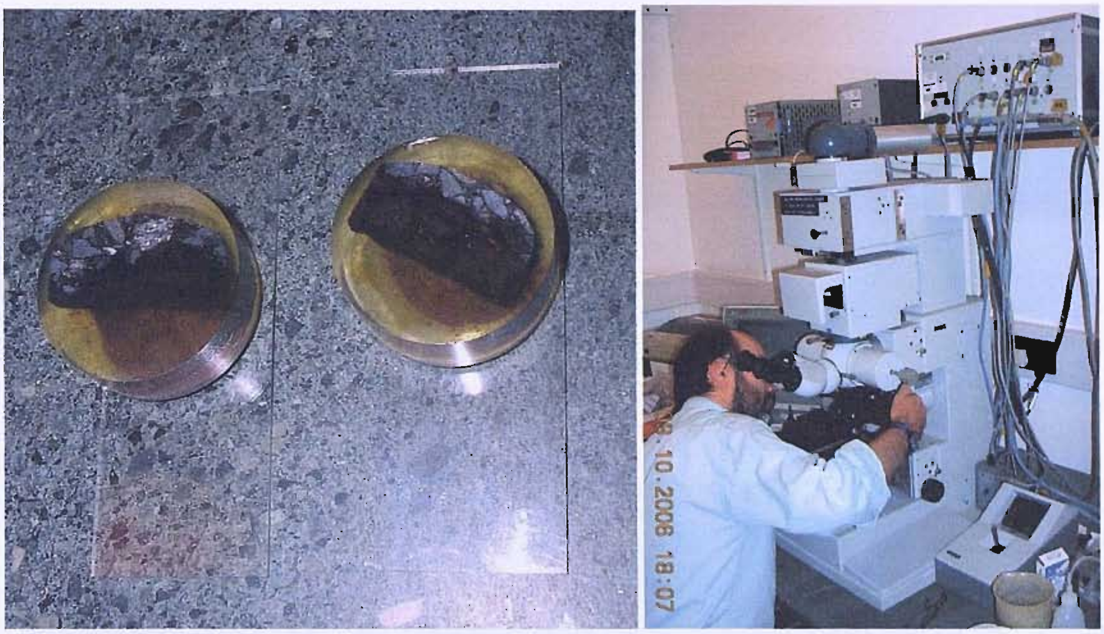
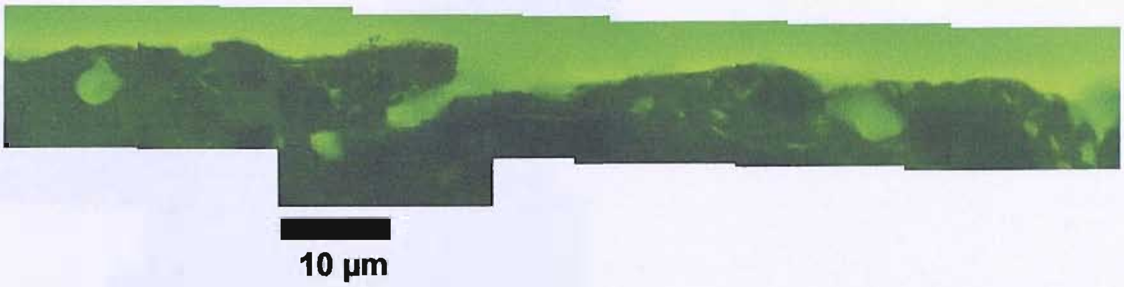


Figure 123 Impregnated 6mm SMA samples (left) and Fluorescence Microscope Equipment

Non-skidded 6mm latex SMA



Non-skidded 6mm latex SMA (Detail)

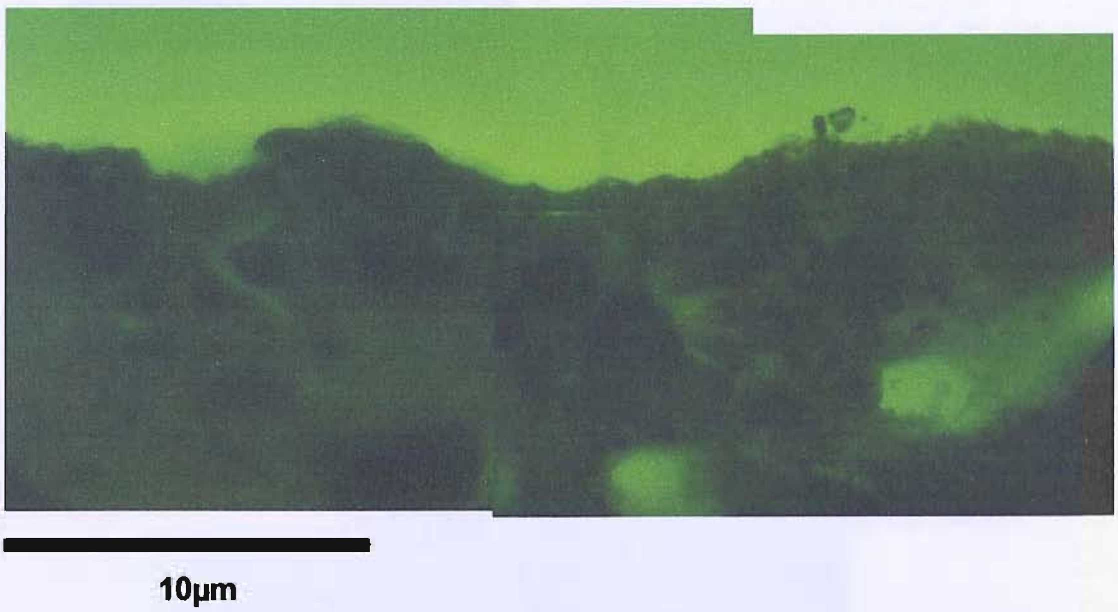


Figure 124 Non-Skidded 6mm SMA under fluorescence

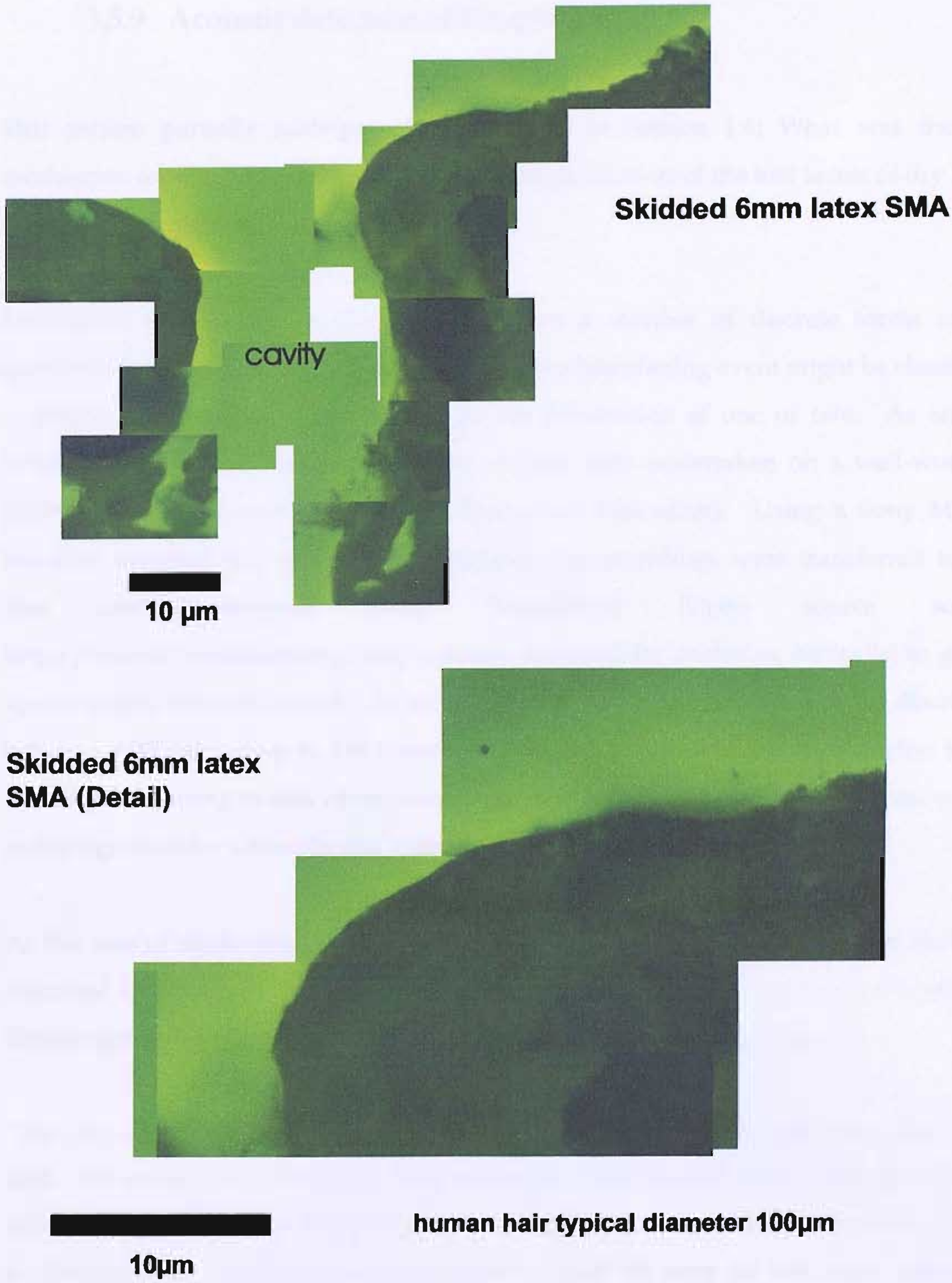


Figure 125 Skidded 6mm SMA under fluorescence

3.5.9 Acoustic detection of Bituplaning

This section partially addresses Question four in Section 1.4: What was the likely mechanism (or mechanisms) responsible for the generation of the low levels of dry friction observed on certain NTS surfaces?

Rasmussen (Rasmussen et al., 2007) describes a number of discrete forms of noise generated by tyres. It was postulated in this that a bituplaning event might be classified by a unique combination of tyre sounds or the domination of one or two. As an initial scoping exercise, recordings were made of skid tests undertaken on a well-worn NTS (SMA) and a well-worn PTS (Dense Bituminous Macadam). Using a Sony MZ-R700 MiniDisc recorder and powered microphone, the recordings were transferred to WAV files and processed using SoundRuler (Open source software: http://soundruler.sourceforge.net/ initially designed for analysing birdcalls) to generate spectrograms for each sound. As can be seen from Figure 128 it is easy to discriminate between ABS (recording to t=8.5 seconds) and NOABS braking, however what was not investigated (owing to lack of resources) was if it would be possible to generate a unique audio signature for a bituplaning event.

As this area of work was outside of the experience of the researcher, Dr. Patrik Andersson, Assistant Professor, Division of Applied Acoustics, Chalmers University of Technology, Göteborg SWEDEN kindly offer to comment on the SoundRuler outputs:

"The only sound that can be related to the tyre/road contact is the stick-slip noise when breaking (sic). The rather broad banded tyre/road noise with a peak around 1 kHz (radiation global tyre vibrations + radiation from the contact patch) are masked by the wind and engine noise and cannot be distinguished. The fundamental frequency is about the same for both cases: several peaks between 1000 Hz – 1050 Hz while the ABS is working, and a more stationary case when the wheels are looked (locked) for a longer time giving a clear peak at 1Hz that is drifting slightly."

These comments are supported in the literature (Sandberg, 2003).

With improved microphone shielding from wind noise and a higher audio sampling rate, this method of analysis may deliver results that are more positive. The differences seen between the NOABS NTS and NOABS PTS with respect to their thermal and deceleration signatures were valuable. The author has proposed to undertake this work in the near future.

Figure 126 Sony MiniDisc and microphone

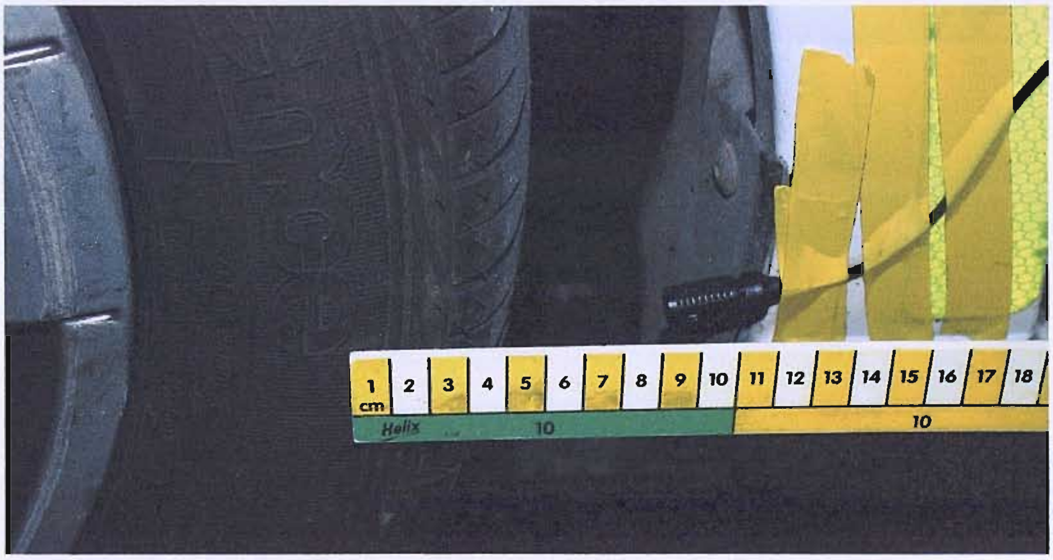


Figure 127 Microphone placement behind front tyre

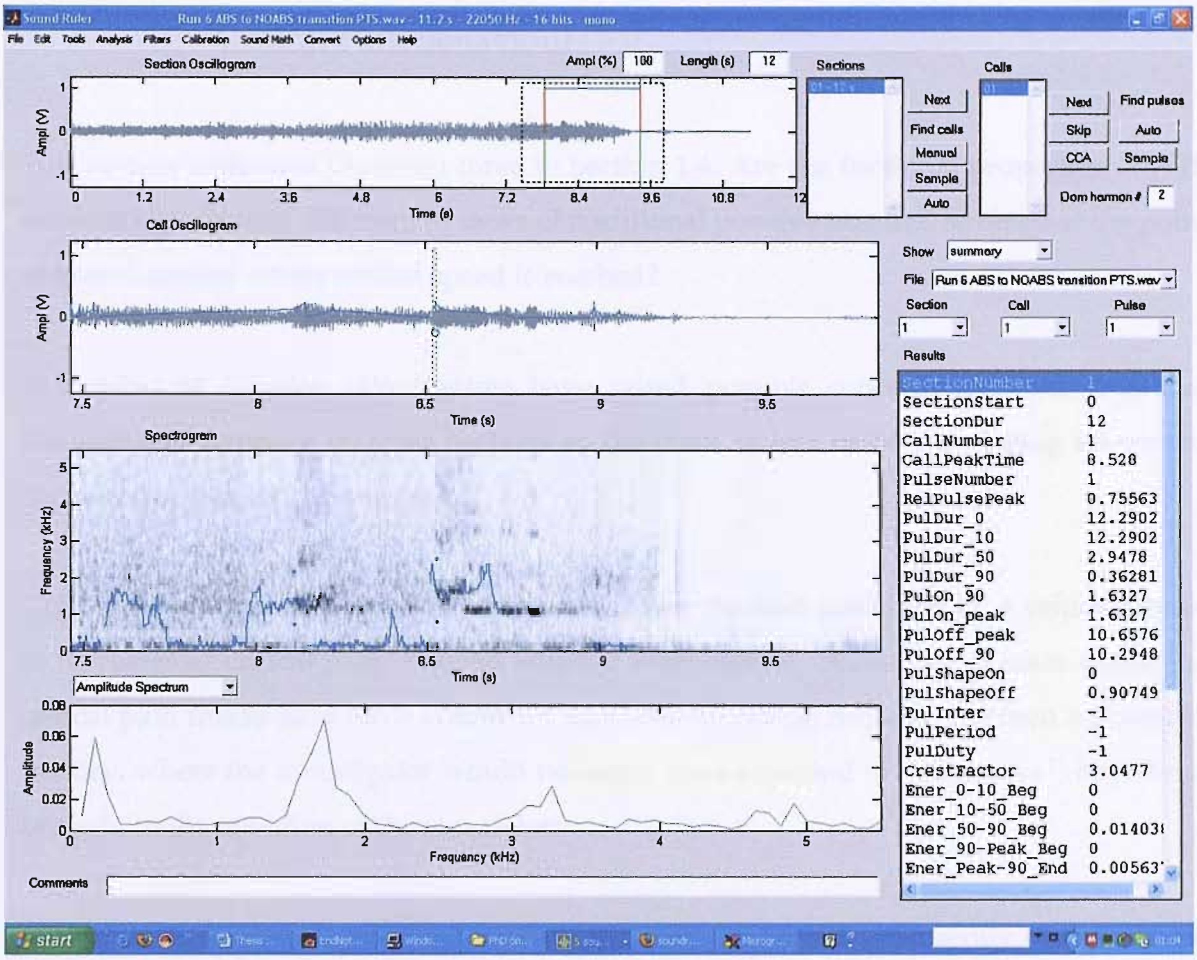


Figure 128 SoundRuler in use (ABS to NOABS transition)

The software author, Marcos Gridi-Papp (mgpapp@ucla.edu) kindly provided a guide to the interpretation of Figure 128:

"The blue markers (lines, dots) are graphical indications of the results of measurements that the program does. They allow the user to check graphically if the sounds are being measured correctly. On the oscillogram, the line connects the nine points that delineate the amplitude envelope of the sound. On the spectrogram, the blue lines show how the program tracks the dominant frequency along the call (it should stay on the same harmonic)".

3.5.10 Investigation of the Influence of Negative Textured Surfaces on Critical Path Behaviour

This section addresses Question three in Section 1.4: Are the frictional properties of NTS surfaces significantly different to those of traditional positive textured surfaces at the point of loss of control where critical speed is reached?

A number of collision investigators have raised possible concerns over the frictional behaviour of negative textured surfaces at the point of loss of control during attempted cornering or evasion manoeuvres.

Collision investigators place a lot of importance on the skid marks left by a vehicles' tyres as it crosses a "critical path" beyond which it loses control. A number of cases where the critical path marks have been absent for incidents involving negative textured surfaces in the dry, where the investigator would normally have expected to "see marks", have been brought to the attention of the researcher.

Comprehensive investigation of this "critical path" behaviour is presently outside of the scope of this project both logistically and financially. However, this does not mean it cannot be investigated in depth in the future. Such an investigation would require complex instrumentation, a duplicated expanse of different road surfaces and tightly controlled driving.

To date the only information relating to loss of control under experimental conditions on negative textured surfaces that has been collected is data from the trials carried out with Metropolitan Police Service where the VC3000DAQ device was used which records acceleration in both the forward and lateral directions.

Greatrix (Greatrix, 2002) Smith (Smith, 1991) and Brach (Brach, 2005) provide useful texts in describing the Critical Speed Formula (CSF), the importance of critical speed marks, the effect of braking on critical speed (hard braking can greatly reduce it) and the required tyre marks to make them indicative of critical speed.

TRL Metropolitan Police Testing

The unique marks left by the tyres of a vehicle at the point of loss of control (at critical speed) while going around a bend have been shown to follow a radius of curvature directly related to the Mu value of the road surface the turning manoeuvre was attempted on.

Critical speed runs are undertaken where it is necessary to establish a likely speed, along a curved path, that a given vehicle is likely to lose control.

A recent incident (Figure 130) on a relatively new NTS road had yielded very different values of MU between ABS And NOABS tests (Figure 129) and the concern regarding critical speed calculations where this difference existed related to the case to be brought against the driver of an ABS equipped vehicle involved in the fatal collision that took place.

Collision investigators from the Metropolitan Police Service undertook a number of straight-line skid tests on the central area of the TRL test track to establish values for the ABS and NOABS Mu values for the HRA and SMA surfaces, which had also been laid as radial sections enabling critical speed runs to be under taken.

The tests were carried out in a police vehicle and when loss of control was imminent, the trained police driver took evasive action to recover control.

The purpose of the testing was to establish if a surface delivering very different MU values between ABS and NOABS tests would result in different critical speeds dependant on whether ABS or NOABS was used in the critical speed runs.

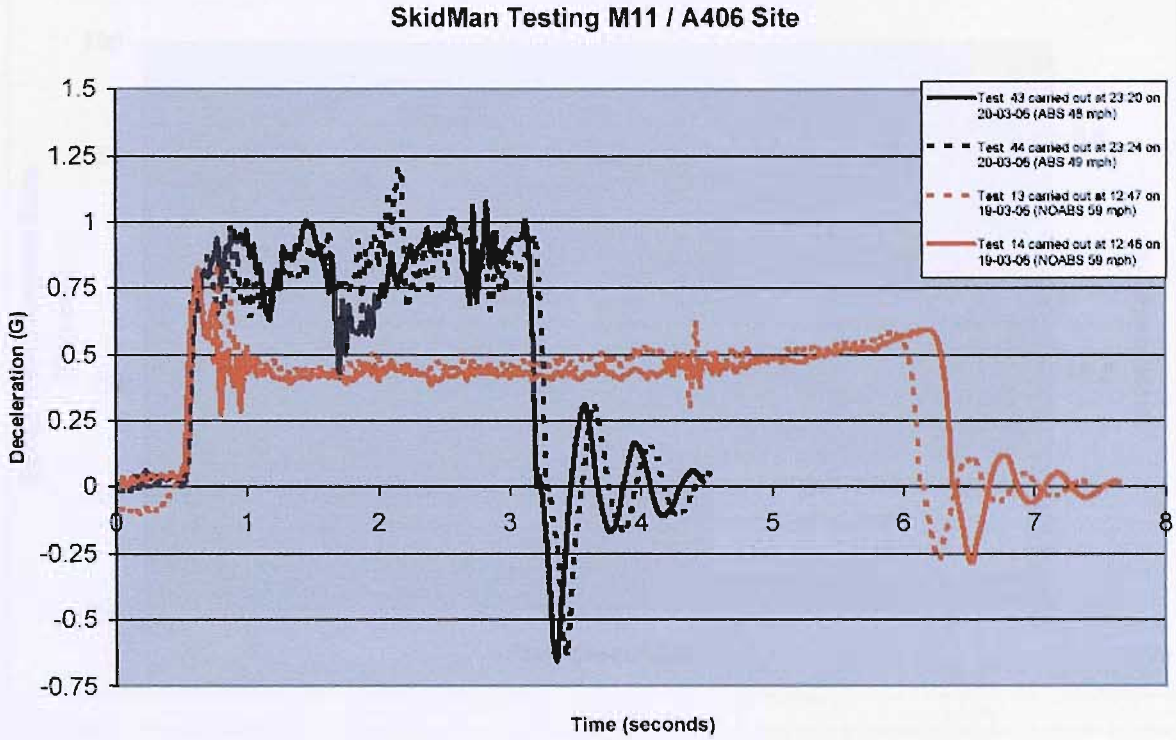
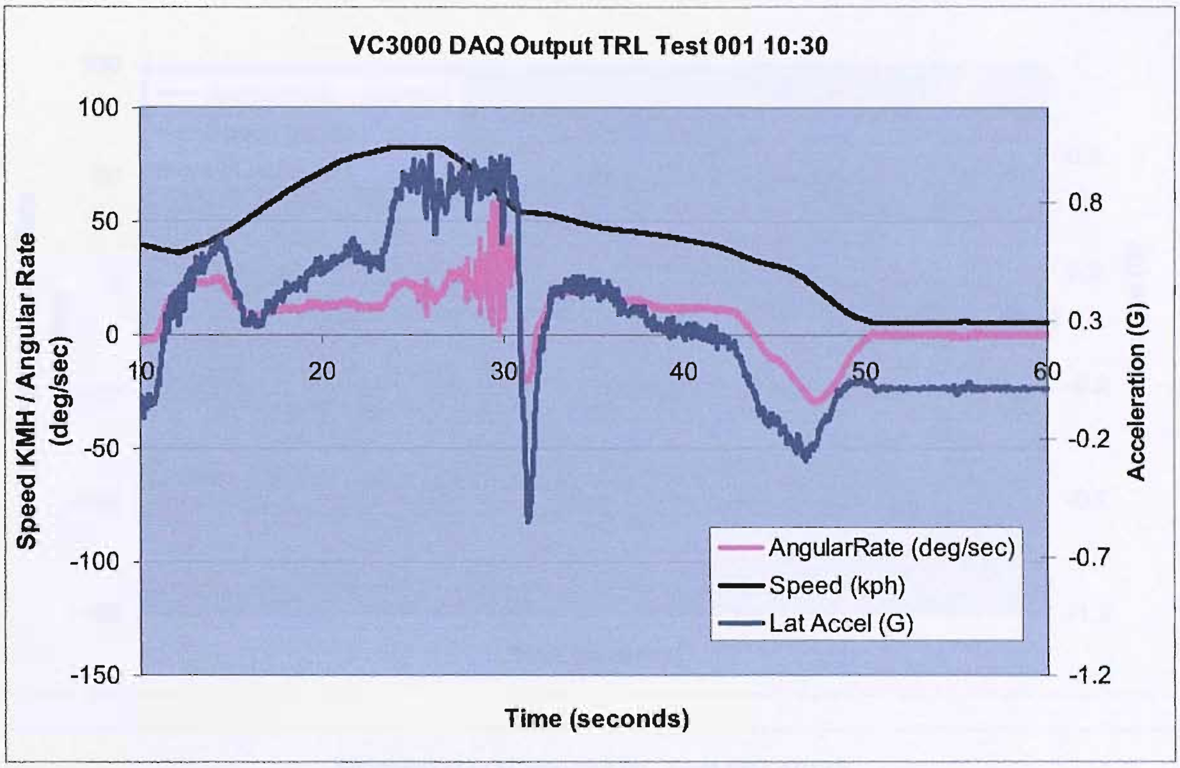


Figure 129 NOABS/ABS test results

Figure 130 The M25/M11 accident scene



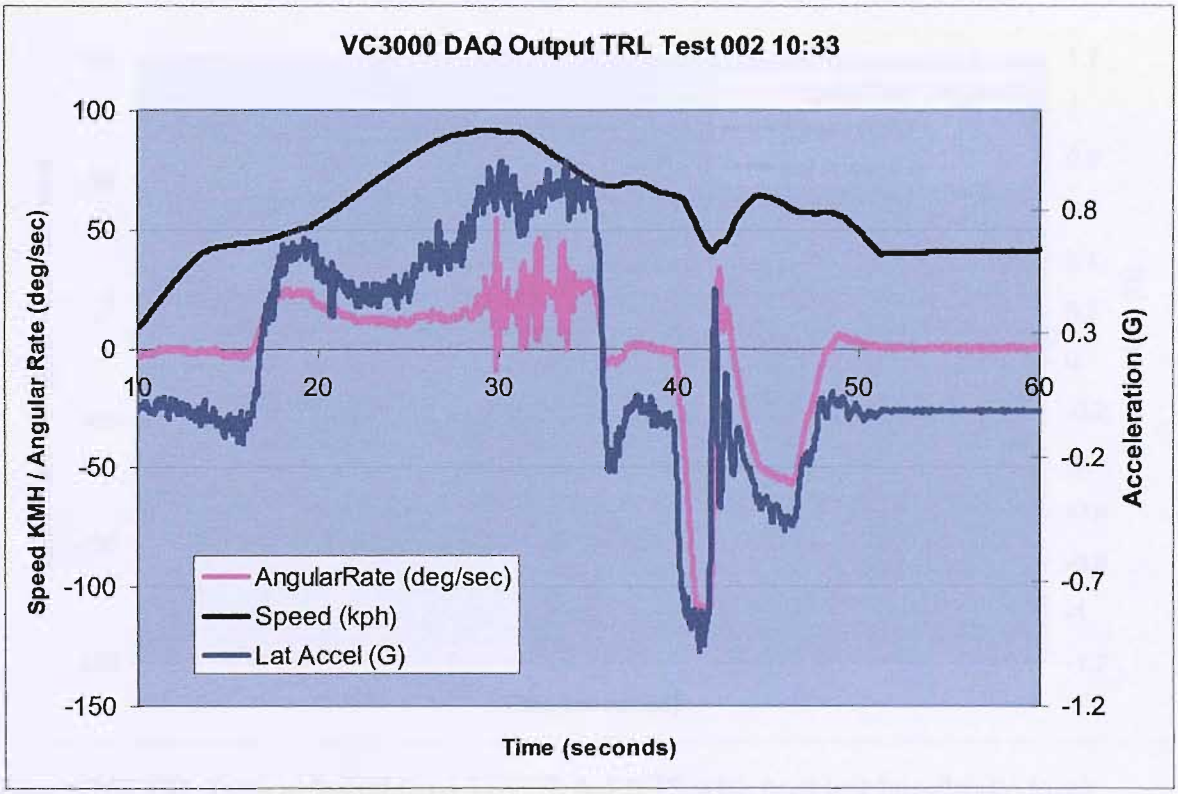


Figure 131 TRL Critical Speed runs 1 (NTS) & 2 (PTS)

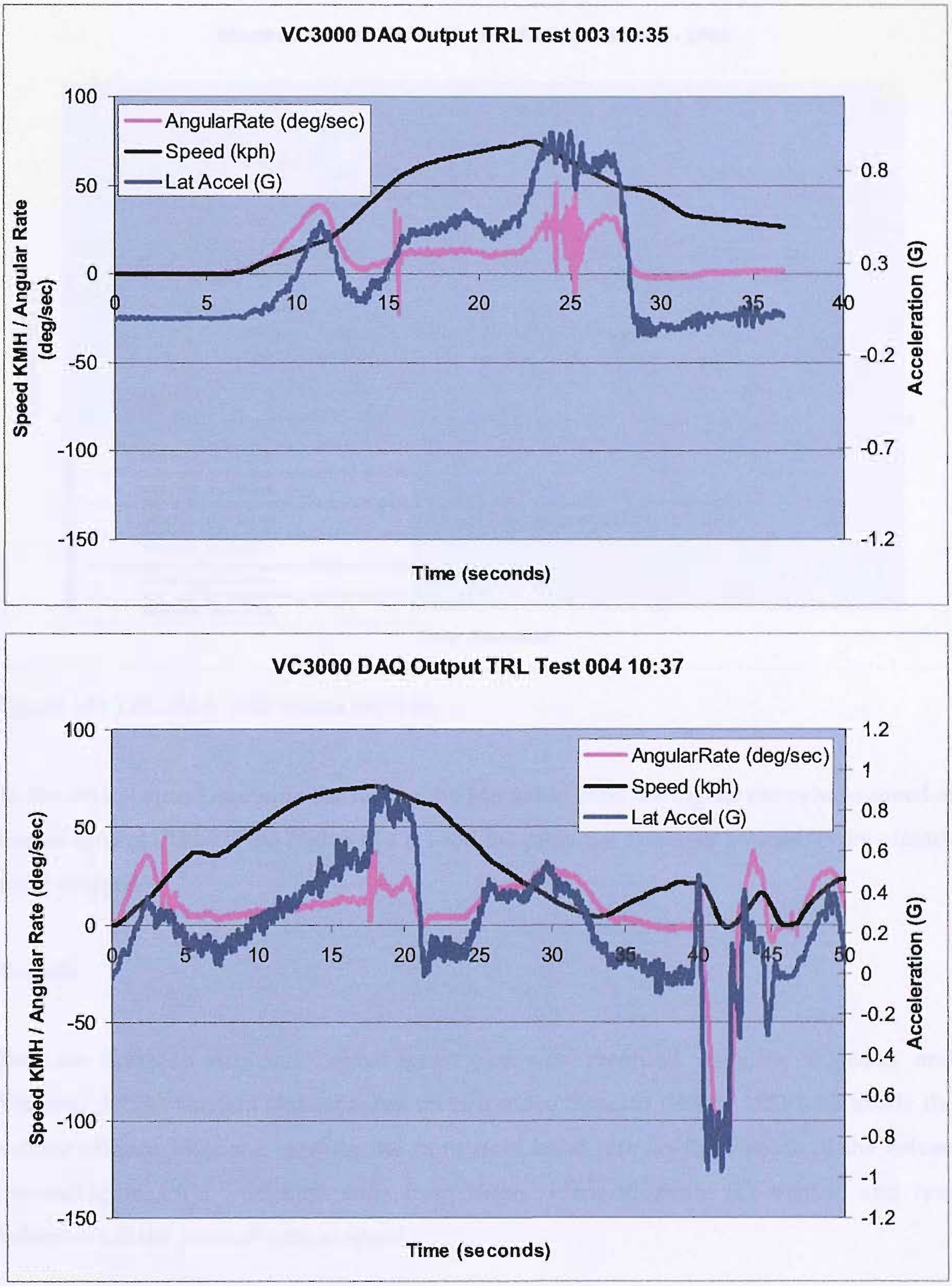


Figure 132 TRL Critical Speed runs 3 (NTS) & 4 (PTS with post test handbrake turn)

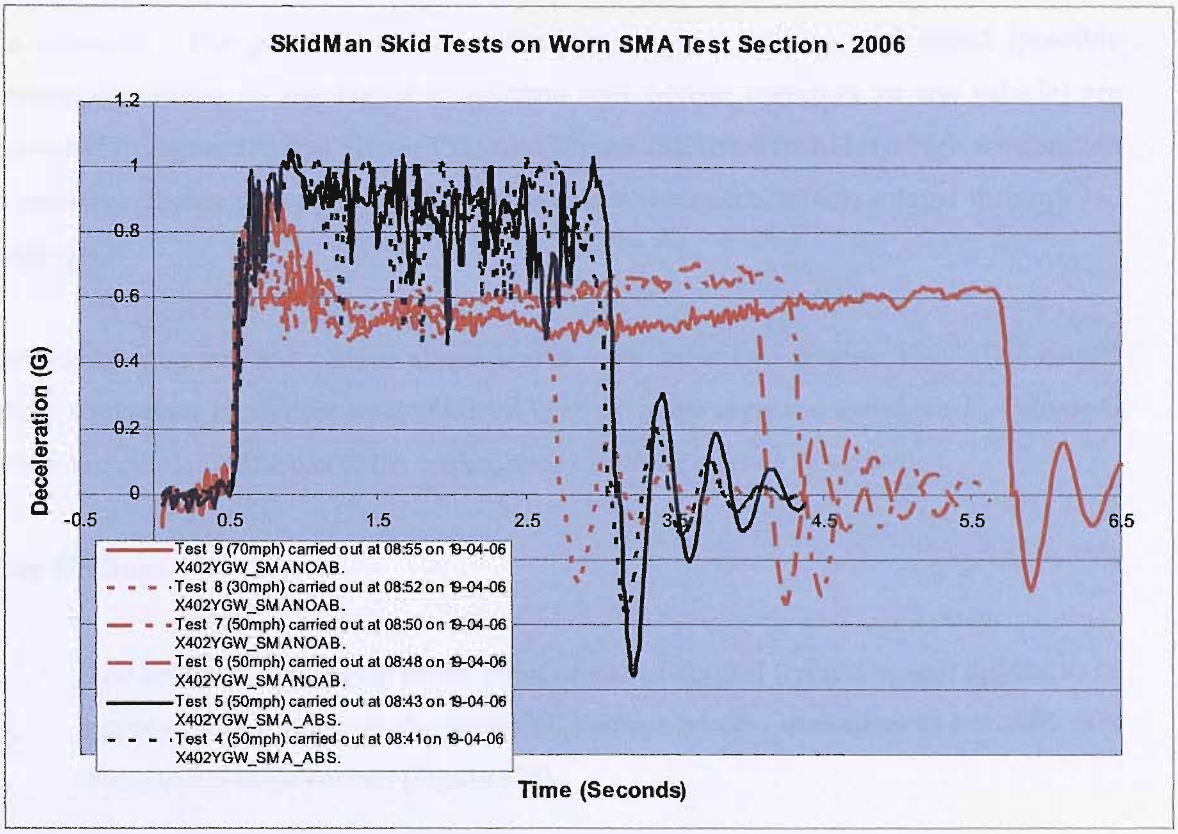


Figure 133 TRL SMA ABS versus NOABS

In the critical speed equation the higher the Mu value used the higher the vehicle speed at loss of control. Thus if too high a Mu is used the potential exists for a more severe offence to be charged.

Results

Both the SkidMan tests and Critical speed runs were recorded using the SkidMan and Vericom decelerometers and captured on two video cameras (Figure 135) (one inside the vehicle (Figure 136), one viewing the front right hand tyre on the outside of the driven curves(Figure 137)). Selected stills from these videos illustrate the vehicle and tyre behaviour at the point of critical speed.

The Vericom was equipped with a rate of rotation sensor (on free loan from Vericom) to augment the forward accelerometer as the side forces on the vehicle would compromise its accuracy. The plots of lateral acceleration, rate of rotation and speed (possibly inaccurate owning to the lateral disposition and curved trajectory of the vehicle) are provided in Figure 131 and Figure 132 (note, Figure 132 Test 4 includes a high acceleration reverse handbrake turn at the end of the sequence where the vehicle rotated through 360 degrees).

Following each run any critical speed marks were measured (Figure 134). The results show a relatively consistent level of lateral G at the point of critical speed, such ultimate G levels are pivotal in the use of the critical speed formula already discussed.

Key Findings

- The levels of lateral grip at the point of loss of control (critical speed) appear to be approximating more to the levels of average friction measured in the ABS skid tests on the same surface (Figure 133).

- There was little difference observed in practice between the Mu/deceleration values obtained from ABS and NOABS SkidMan tests on the HRA and SMA surfaces available and the critical speed values were equally inconclusive.

- The lack of difference between the SMA and HRA at TRL was undoubtedly due to the loss of the bituminous binder film on the SMA materials tested resulting from the cumulative exposure of the SMA to traffic.

- Similar tests undertaken on a new NTS surfaces may well reflect the lower levels of Mu available once wheel lock occurs leading to a lower critical speed. The Author is working with the Metropolitan Police to seek funding from the DFT to investigate the potential for NEW NTS to deliver lower levels of friction at the point of loss of control.

- More work is needed using instrumentation designed to measure lateral acceleration independent of vehicle yaw.

Figure 134 Measurement of Visible Critical Speed Marks

Figure 135 External video camera mounting on skid car

Figure 136 View from Passenger Compartment During Critical Curve Run

Figure 137 View of Outside Front Tyre at Critical Speed during Critical Curve Run

4. Possible mechanisms for the Bituplaning Event

This section partially addresses Question four in Section 1.4: What was the likely mechanism (or mechanisms) responsible for the generation of the low levels of dry friction observed on certain NTS surfaces?

The experiments and statistical analysis undertaken have confirmed the findings of the literature review, NTS exhibit significantly different characteristics to PTS surfaces during dry braking events. ABS braking on NTS has been shown to generate the momentary levels of friction more characteristic of NOABS sliding friction that are responsible for the dash like skid marks seen in the same tests. Dry NTS surfaces have been shown to illustrate peak/slide differences more typical of WET PTS surfaces. Both bituminous material and oily exudates have been seen on the tyre surface following DRY NOABS skid tests on new looking NTS surfaces.

The erosion of the binder film by sliding tyres during locked wheel (NOABS) skidding has been seen in the fluorescence microscopy sections, dynamic shear rheometry tests undertaken on one bituminous material used at a test location showed evidence of low viscosity at temperatures well below the maxima observed between tyre and road in the imaging exercises. The infrared imaging exercises at Madingley showed lower maximum temperatures were being developed on NTS surfaces regardless of whether ABS or NOABS tests were undertaken. A bituplaning event has been captured as a high speed image (1000fps) enabling the sliding of the tyre on the road surface to be observed in slow motion.

Thus, the following observations are valid regardless of the mechanism responsible for generating the bituplaning phenomenon:

- It has been shown via statistical analysis that NOABS tests on dry negative textured surfaces (NTS) give significantly lower deceleration results from those undertaken on dry positive textured surfaces (PTS)

- NOABS tests on dry negative textured surfaces give lower slide/peak ratios than those undertaken on other braking/surface/surface state combinations and those documented in the literature.
- It has been shown that NOABS tests on dry negative textured surfaces give deceleration results lower than those considered typical by trained collision investigators.
- Measurements relating to the deceleration and the thermal environment in close proximity to the tyre/road contact where the bituplaning event takes place, have also been made, these show a lower maximum temperature is developed behind the tyre for NTS tests than for PTS tests.

This combination of the findings resulting from practical experimentation and statistical analysis' along with the associated literature reviews now enables a reasoned argument to be made regarding possible mechanisms responsible for the low levels of dry friction observed during bituplaning events.

By balancing the possible mechanisms against evidence whether the conditions actually exist for the mechanism to manifest themselves, a conclusion may be drawn as to the most likely cause of bituplaning, though sadly a conclusive mechanism can only be established with further research.

4.1 The tyre/road temperature regulation mechanism

The temperature profiles observed from the skid tests at Madingley provide a valuable illustration as to why the assumption has been made that melting is the cause of the bituplaning events; such an assumption is probably the easiest. Without proof, two possible mechanisms exist for the limitation of ultimate temperature that can be reached during skidding.

4.1.1 Melting

Temperature build up during skidding will continue until the friction generating the heat is reduced. If the heat build up produces a low viscosity layer due to melting, this low viscosity layer reduces the friction, reduces heat transfer between tyre and road and the temperature generation ceases or is greatly reduced.

4.1.2 "Another cause"

Temperature build up during skidding may also continue until a change in friction precipitated by an unknown process takes place at the tyre/road interface. Such an unknown process may generate a low viscosity layer in response to some threshold condition being exceeded in other forces associated with the dynamic environment between tyre and road. This low viscosity/friction layer of unknown origin also reduces heat transfer between tyre and road reducing friction and at this point temperature generation ceases or is greatly reduced.

The possible non-melting mechanisms for the low dry friction seen in bituplaning will now be discussed along with the currently assumed melting mechanism.

4.2 Simple Melting as a mechanism for the Bituplaning Event

The mechanism responsible for the generation of the low levels of friction on dry surfaces has always been supposed to be that of simple melting of the bituminous layer between the sliding tyre and the coarse aggregate particles of the road surface ((Roe, 2004, Roe, 2001, Roe, 2003, Roe, 2005, Roe and Lagarde-Forest, 2005, Jutte and Siskens, 1997)) .

Evidence supporting the simple melting theory includes:

- photographic records of bituminous material entrained in the tyre treads where the sliding contact with the road surface took place
- Evidence of bituminous material migration in a lateral direction from the area traversed by the sliding locked tyre (Roe and Lagarde-Forest, 2005)

- Theoretical calculations in the literature estimating the temperature between the tyre and road during sliding contact ((Jutte and Siskens, 1997))
- Actual measurement at Madingley using thermal imaging of the area directly behind the sliding contact patch of tyre during skid car tests on new NTS surfacing confirming the presence of temperatures within the melting region of typical bituminous materials using in NTS.
- Extrapolation of the known viscosity/temperature relationships for bituminous materials to the temperatures measured at the tyre-road interface yield levels of viscosity more associated with oils than bitumen.

Research undertaken by TRL into the effect of surface contamination on road surface friction included measurements undertaken on surfaces contaminated by motor oil and diesel (Lambourn and Viner, 2006). The levels of friction obtained on such oil-contaminated surfaces (Figure 138) appear similar to those obtained for skid car tests undertaken on the surfacing at Madingley (Figure 139). Simplistically one could infer such similarity suggests a surface film generated by the contact patch melting of a liquid of the same viscosity as motor oil may yield similar friction characteristics as oil itself.

Evidence rejecting the simple melting theory:

The observed short-term bituplaning during ABS pulses on the NTS surface at Madingley (Figure 140) are of such short duration as to question how enough time exists for heat transfer to generate melting. The period available for heat to transfer into the bitumen is very limited as at 50 kph the tyre is passing over the road at 13 m/sec and the pulse event lasts for a few thousands of a second.

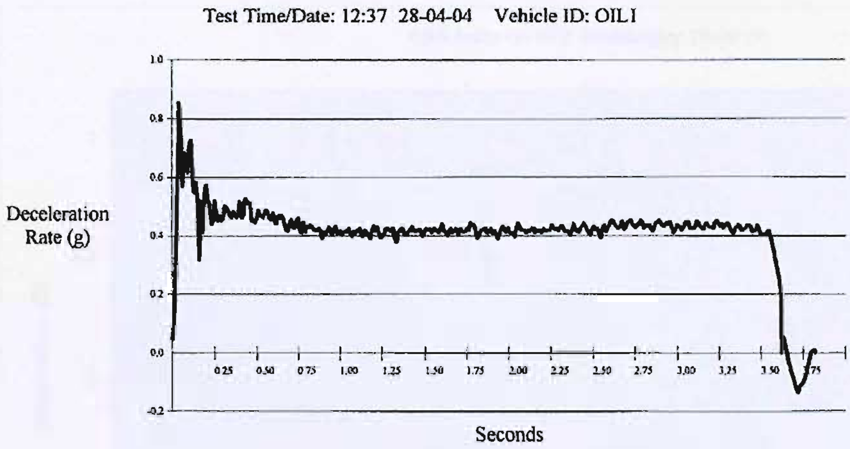


Figure 138 Skid tests on road surface contaminated by used engine oil (Lambourn and Viner, 2006).

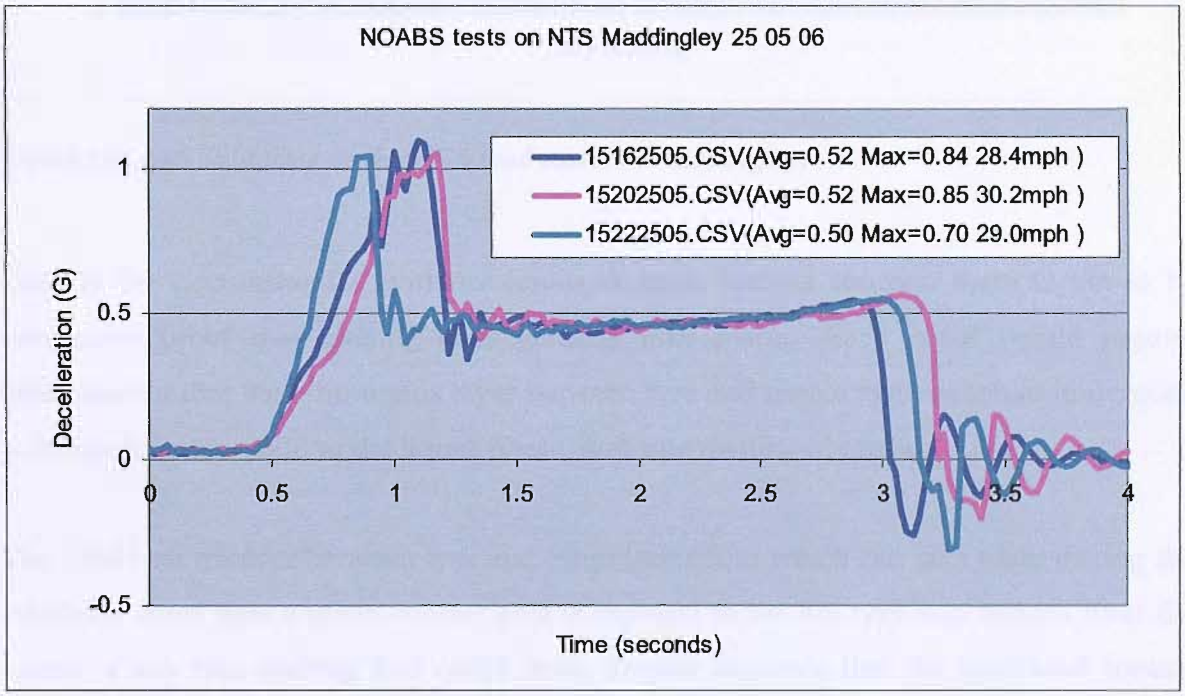


Figure 139 NOABS Skid tests on dry NTS road surface at Madingley.

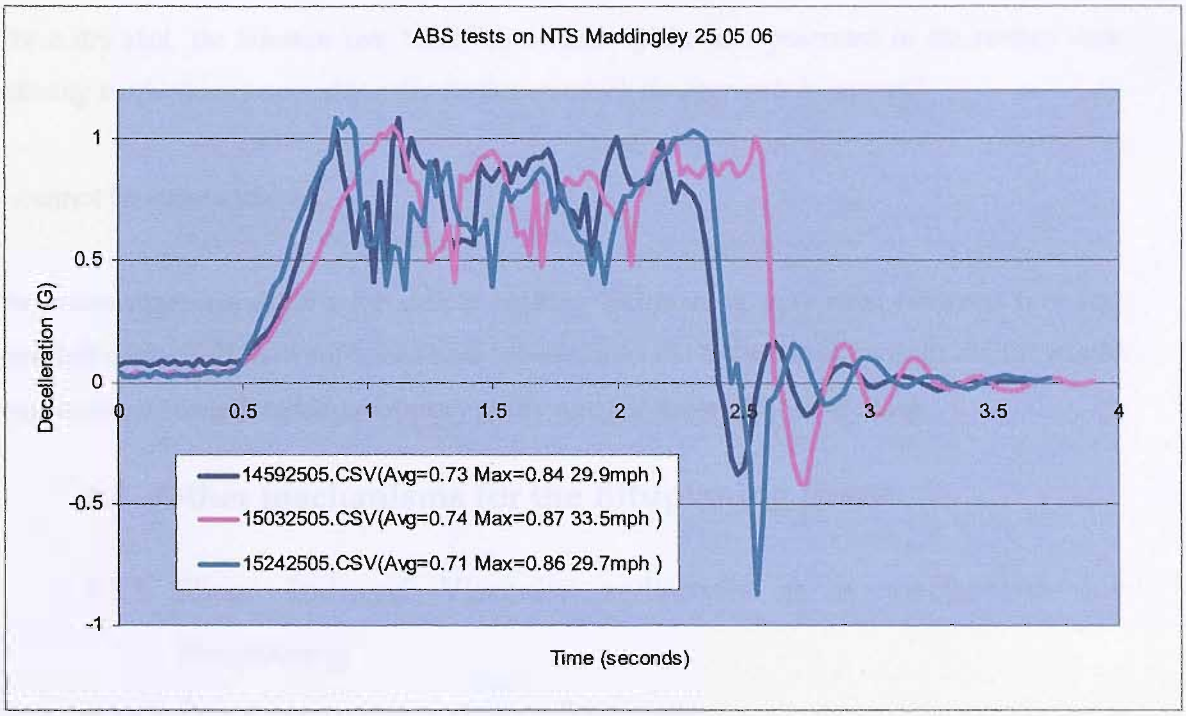


Figure 140 ABS Skid tests on dry NTS road surface at Madingley.

Despite the circumstantial evidence amassed from various sources, there is yet to be conclusive proof that melting does actually take place. Such proof would require confirmation that the bituminous layer between tyre and coarse aggregate had undergone a change from the solid to the liquid phase, that true melting occurred.

The total heat transfer between tyre and bituminous film which can take place during the relatively short time a given contact area is exposed to the hot tyre may indeed limit the extent of any true melting that could occur despite evidence that the tyre/road contact patch increases in temperature during the sliding event .

Since the area of contact between tyre and road surface cannot easily be observed and the thin layer of bituminous material cannot be instrumented using rheometers to confirm that a liquid state has been achieved. Thus , the assumption made by TRL (Roe and Lagarde-Forest, 2005) :

"In a dry skid, the bitumen can "melt" as a result of the heat generated in the contact area, reducing the friction compared to a dry surface on which the aggregate is exposed"

...cannot be substantiated

The momentary conditions for simple melting bituplaning may exist between tyre and road but confirmation of sufficient heat transfer into the bituminous layer to melt it would require proof from detailed laboratory study and/or theoretical modelling

4.3 Other mechanisms for the Bituplaning Event

4.3.1 Shear Induced Viscosity reduction as a mechanism for Bituplaning

The high temperatures which have been measured adjacent to the sliding tyre contact patch, have been generated in a region of tyre road contact which equally experiences high shear rates as the static bituminous film comes in contact with the tyre rubber moving at rates as high at thirteen metres per second.

Regardless of the temperatures measured adjacent to the sliding tyre/road contact, the levels of shear to which the bituminous film is exposed may also be investigated as one possible cause of the generation of a low level of dry friction experienced during "bituplaning" regardless of whether temperature plays a role or not.

Though tenuous, the vibration inherent in the deformation of the tyre contact patch during braking may possibly have a similar effect on the bitumen on the road surface. Vibration can reduce the viscosity of polymer melts in extrusion (Li et al., 2006), though the viscosities involved are at least two orders of magnitude above those likely to be relevant to the bituplaning event.

The High shear behaviour of bitumens as a mechanism for the generation of the bituplaning phenomenon must be explored since bituminous samples can potentially be exposed to high levels of shear under controlled laboratory conditions. However, the limitations inherent in the use of existing test equipment designed for the analysis of bitumens for surfacing use may restrict any investigations extending to the maximum levels of shear experienced by the bitumen film between tyre and road.

4.3.2 Exudative Hardening / Oil Exudation mechanism for Bituplaning

The generation of a film of light grade lubricants in response to the action of the sliding tyre has been observed post-test on a number of separate occasions, Figure 143, Figure 144, Figure 145, and Figure 146 show the "greasy patch" visible following testing on NTS surfaces. The forces necessary to generate the oil exudation (Read and Whiteoak, 2003) may be simply produced during the period of high shear between the tyre and the road surface. The shear induced oil exudation would allow the bituplaning effect to occur even during short-term locked wheel events during ABS NTS skids where the response time of the ABS detection system may be insufficiently quick to react to the sudden evolution of the oil and the associated low friction this causes.

Skid mark dashes associated with ABS braking on NTS surfaces have been noted by a number of collision investigators and the future use of linked imaging and deceleration measurement may be able to confirm the visual/deceleration dynamics of these ABS Dash events. Typical ABS "dashes are shown in Figure 141 and Figure 142. The NTS testing at Madingley resulted in the creation of a number of semi-continuous ABS skid marks consistent with the ABS lock observed in the high-speed video shot at the time.

Appendix 4 \DORSET- ABS ON DASHES VERSUS ABS OFF SKIDS ON NTS shows a video of ABS dashes being generated during an ABS skid test.

No analysis was made of the oily contaminant visible on the post-test tyres. The literature suggests that such a deposit may contain both tyre and road derived components (Roe and Lagarde-Forest, 2005) but more work regarding the transfer of bituminous constituents between the road and the tyre at high temperatures may be appropriate. This transfer of material twixt tyre and road surface is not a simple one, this area having been the subject of some research relevant to the use of recycled tyre rubber in bituminous surfacing. Artamendi (Artamendi and Khalid, 2006) studied the absorption of bitumen components by tyre rubber, bitumen chemistry and more significantly increased temperature influenced the diffusion rate .

4.3.3 Low Hysteresis combined with low Adhesion during Bituplaning

Examination of the high speed bituplaning video taken on a new NTS in the course of NOABS simulated emergency braking at Madingley provides some degree of visible evidence of the reduced friction generated with a reduction in hysteresis.

The ABS tests showed similar momentary minima in the NTS ABS tests. These minima were akin to the extended sliding deceleration in the NTS NOABS tests.

Reduced hysteresis friction combined with low levels of adhesion derived friction (caused by the presence of a thick binder film between tyre and road surfacing aggregate) may possibly combine to generate the low levels of dry friction observed on new NTS surfaces .

The reduced hysteresis friction between tyre and road surfacing aggregate on negative textured road surfaces could potentially generate low levels of dry friction observed on OLDER new NTS surfaces where the binder film has been worn away.

In the case of new NTS surfaces with a thick binder film between tyre and aggregate, the additional influence of this film is therefore sufficient to deliver the levels of low dry friction below that considered "typical".

Figure 141 ABS "dashes" observed on an NTS in Dorset following testing

Figure 142 Semi continuous ABS "dashes" observed on an NTS in Derbyshire following testing

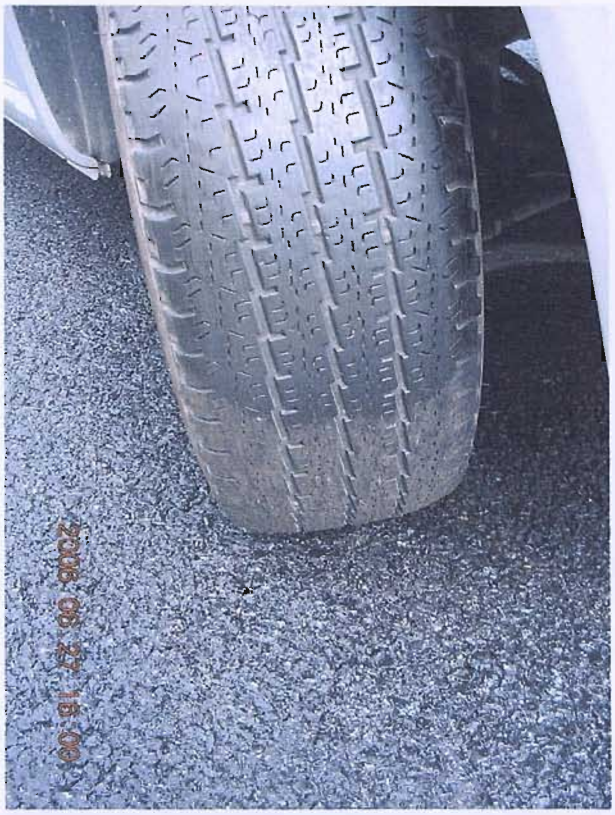


Figure 143 Oily deposit observed following NOABS test at Madingley

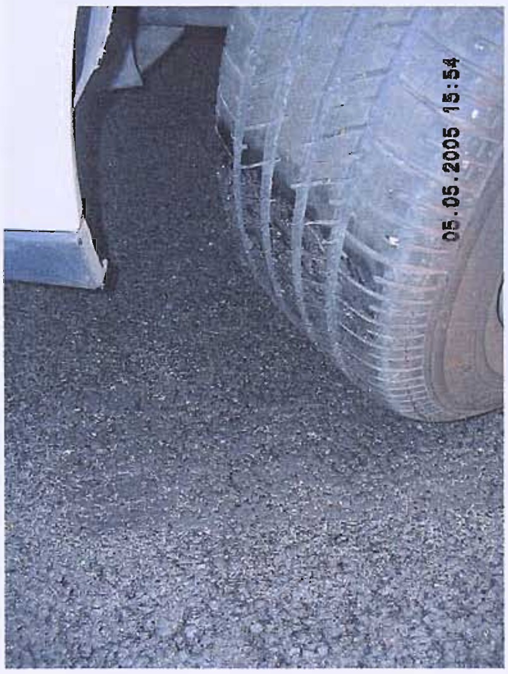


Figure 144 Oily deposit observed following NOABS test In New Zealand

Figure 145 Oily deposit observed following NOABS test on SMA in Devon

Figure 146 Oily deposit and bitumen observed following NOABS test on SMA in Dorset

4.4 The most plausible mechanism in Bituplaning

Without complex measurement, directly at the tyre/road interface of the physical behaviour of the bituminous film, one cannot accept the simple assumption of melting of the binder film being the mechanism behind bituplaning.

The generation of MINIMUM levels of friction in bituplaning synonymous with that of driving on engine oil AND the presence of oily patches on the tyres strongly suggests that oil exudation in response to high shear is the predominant mechanism behind bituplaning.

One must also consider the potential for NTS surfaces to generate lower levels of dry friction BEFORE bituplaning begins as such NTS surfaces may present both reduced hysteresis friction (owing to the uniform texture) and reduced chemical bond friction (from the binder film) .

5. Bituplaning in Accidents

With proof of significant difference in emergency braking on dry surfaces between NTS and PTS surfaces in the dry combined with experimental proof of a difference in the behaviour of the materials under emergency braking, one must ask why this phenomenon has not been implicated in more crashes than the few already discussed. Therefore, it is necessary to establish the reasons why.

Establishing evidence of:

1) The occurrence of Bituplaning events on UK Roads
2) The significant effect of the Bituplaning phenomenon on deceleration

And

3) Gaining a fuller understanding of what takes place during such events

Does not logically lead to the conclusion that:

The bituplaning event in itself poses a significant risk to road users.

It is therefore important to investigate past reports in the literature of the role it may have had in collisions and to investigate if the phenomenon is currently implicated as a factor in collisions now.

Part of this study included an investigation of what factors may limit its documentation in practice even if it does have a role in a crash.

5.1 Actual Evidence of Bituplaning Crashes

A bituplaning crash on NTS in the Netherlands was documented and prompted further research (Bonnot, 1997, Jutte and Siskens, 1997, Swart, 1997, van der Zwan et al., 1997). Shelshear documented a bituplaning crash on an PTS where bituplaning was observed which also prompted more research (Shelshear, 1998, Shelshear, 1986b, Shelshear, 1986?-b, Shelshear, 1986?-a, Shelshear, 1986a).

Derbyshire Police documented two fatal crashes (Constable (1154) Harris, 2001, Constable (1357) Allen, 2001) where low dry friction was found at the scene but bituplaning was shown not to be influential on the crash outcome . The first crash had no witnesses, the casualty was discovered fatally injured later, and the second crash involved a vehicle where adaptation for a disabled driver prevented simultaneous braking and steering. This fact was pivotal in the outcome of the crash.

Two fatal crashes were similarly documented by Dorset Police (Boardman, 2003, Wandless, 2004) where low dry friction was measured but not stated as pivotal in the collision outcome.

Identifying the possible role of Bituplaning in the outcome of a collision does necessitate a high level of specialist knowledge in the attending police officers and others in the investigation process.

Low dry friction (0.529) was identified in the investigation of another fatality in Derbyshire (Constable (1357) Allen, 2002). Simply for the absence of a point of entry from the pavement (into the path of the vehicle involved) of the pedestrian involved, there would have been documented evidence of the role of low dry friction in the severity of injuries to the deceased. Higher mu would have reduced the impact speed between vehicle and the deceased or indeed prevented the impact, as the vehicle may have been able to stop in time.

5.2 Road User Behaviour

Human factors predominate in the contributory factors associated with collisions (Broughton et al., 1998). Road user behaviour plays a major role in the precipitation of collisions. Recent work has shown that drivers commonly fail to recognise or react to signage already in use to alert them to known areas where there is a wet friction deficit (TRL, 2004). This would suggest that any warning sign used to alert the road user of the bituplaning risk is likely to be ignored.

Modification of driver behaviour even to the visible presence of wet road surfaces and poor driving conditions have equally been shown to be small (Edwards, 1999, Edwards, 2002, Leden et al., 1998, Lamm et al., 1990). Figure 147 graphically illustrates this typical lack of response to wet road surfaces.

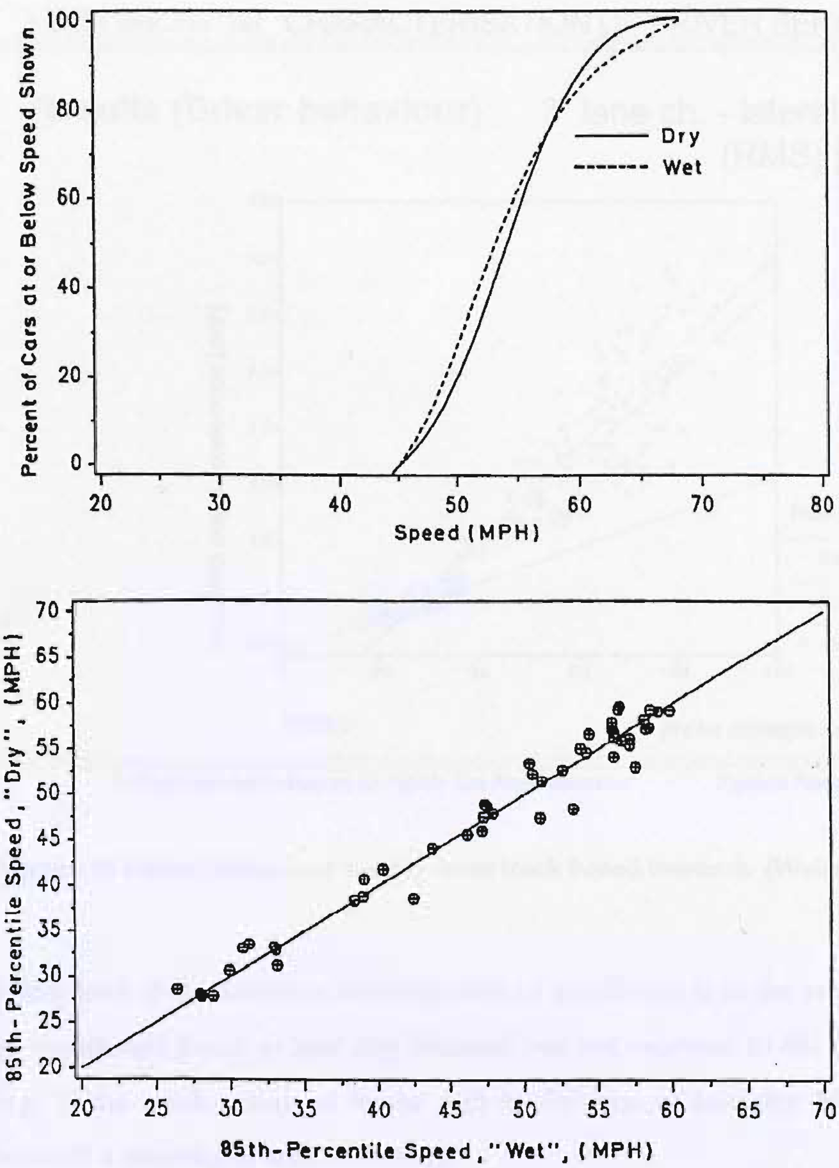


Figure 147 Frequency distribution (top) and 85th percentiles of wet versus dry speeds (Lamm et al., 1990)

Track based research by Weiss et al (Weisse et al., 2000) concluded little evidence of driver behaviour changes between wet and dry conditions, whereas icy conditions resulted in significantly different behaviour (Figure 148).

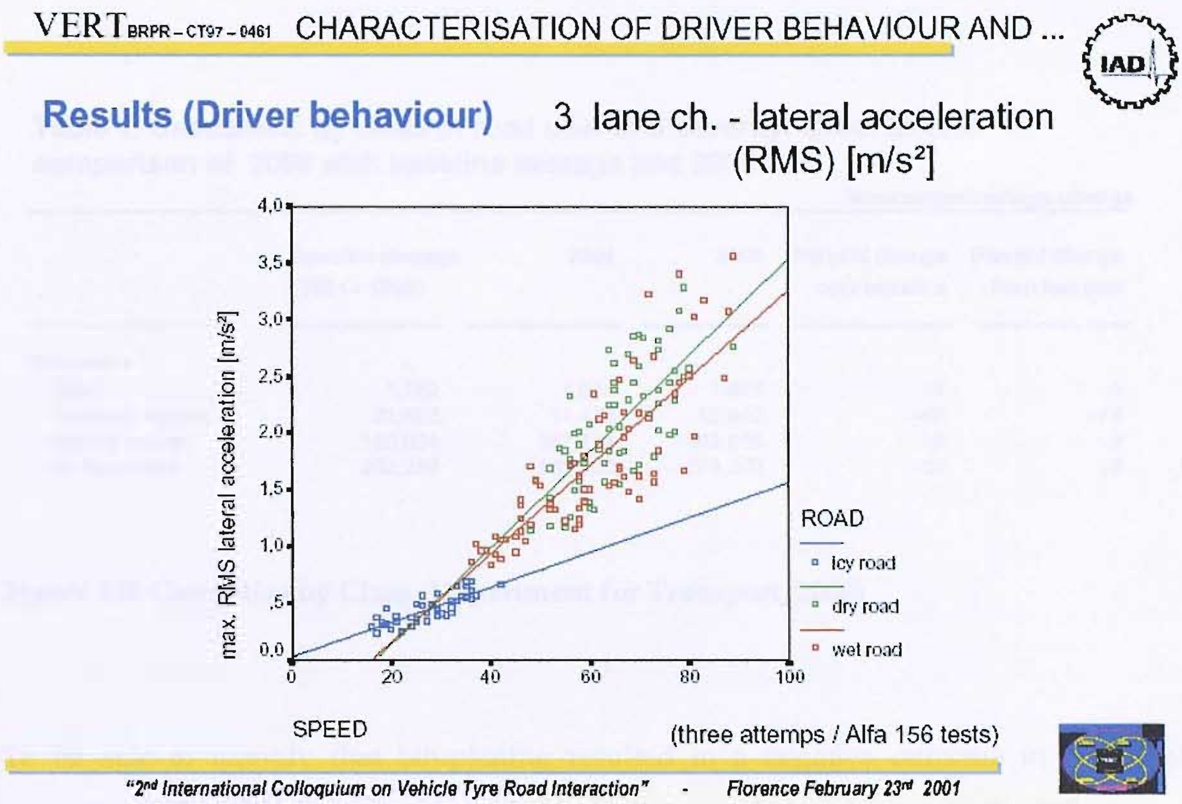


Figure 148 Driver behaviour results from track based research (Weisse et al., 2000)

A key part of the effective investigation of a collision is in the recognition that a factor may be significant (such as low dry friction) but not relevant to the circumstances of the crash (e.g. If the crash occurred in the wet in the case of low dry friction or during daylight hours if a streetlight was defective) .

5.3 Collision Records

Non-fatal or non-near-fatal crashes are seldom investigated by trained collision investigators whereas fatal and near-fatal crashes commonly are. The majority of collisions that take place in the UK (**Figure 149**) fall into this category (Department for Transport, 2006).

Table 1: Casualties: by class of road user and severity: Great Britain comparison of 2005 with baseline average and 2004

Number/percentage change

	Baseline average (1994 - 1998)	2004	2005	Percent change over baseline	Percent change from last year
Car users [3]					
Killed	1,762	1,671	1,675	*-5*	*0*
Seriously injured	21,492	14,473	12,942	*-40*	*-11*
Slightly injured	180,034	167,714	163,685	*-9*	*-2*
All casualties	203,288	183,858	178,302	*-12*	*-3*

Figure 149 Casualties by Class (Department for Transport, 2006)

To be able to identify that bituplaning resulted in a negative outcome in any crash necessitates that the circumstances were actually recorded, evidence of the influence of bituplaning on the collision outcome would require:

(i) Decelerometer readings or other relevant tests were untaken to identify that bituplaning took place during the vehicle manoeuvres.

(ii) A reconstruction of the crash (vehicle movements and interactions etc.) was undertaken to establish that the Bituplaning event actually had a retrograde effect on the ultimate outcome (i.e. It made things worse than if the bituplaning had not taken place).

Since the majority of crashes are non-fatal and non near-fatal, they are documented by individuals without the necessary investigatory skills it is likely the above criteria will not be met.

The existing UK collision database (STATS19) is unlikely to yield any meaningful result in this area, as the skidded field in STATS19 does not identify whether a vehicle skidded.

(a) As a result of deficiency in available skidding resistance during a manoeuvre made at an appropriate speed or

(b) As a result of excessive speed, leading to insufficient skidding resistance to complete safely a braking manoeuvre that began at too high a speed.

5.4 NON ABS Braking and unequal risk

ABS braking has been shown to mitigate the majority of the bituplaning effect (apart from momentary dips in deceleration). All new cars are equipped with ABS however; the legacy of vehicles not fitted with ABS may logically be considered the lower cost, cheaper to insure vehicles that may be likewise equipped with poorer secondary safety features in general. Cheaper cars are invariably driven by those on more likely to result in injury. The following extracts from the "ROSPA Young and Novice Drivers Policy Statements" - May 2002 (http://www.rospa.com/ roadsafety/advice/youngdrivers/policy.htm) provide a valuable summary:

"Young and novice drivers are more likely to be involved in road accidents than more experienced drivers. They are more likely to be involved in high-speed accidents, accidents in the dark, accidents when overtaking and when negotiating bends. They are also more likely than experienced drivers to be at fault for accidents (that take place).

There are many, inter-relating reasons why novice drivers have more accidents.

Age: Younger drivers are more likely to be involved in accidents because they are young, but once they have had one or two years driving experience the effects of age on their accident risk seems to disappear.

Experience: Lack of driving experience is a major reason for the higher accident risk of novice drivers, especially in their first three years of driving. As new drivers gain more driving experience, their accident rate begins to fall. However, the effects of increasing age and increasing driving experience combine, and together they produce even higher reductions in accident risk. Overall, the accident risk of 17-year-old novice drivers reduces by 43% after their first year of driving experience. For 18-year-old drivers, the reduction is 40%, for 19 year olds it is 38%. The accident risk of 25-year-old novice drivers reduces by about one quarter after the first year of driving.

Attitude: Attitude and motivation are perhaps the most difficult factors to address, because they are very closely linked to personal characteristics and general attitudes and beliefs. Young, male drivers are particularly likely to choose to drive in deliberately risky ways, and are also more likely to have accidents. Young drivers consistently rate their own performance as above average and are more likely to equate 'good' driving with the ability to master the controls of the car at higher speeds. They are more willing to break speed limits, drive too close, cut corners, etc than more experienced drivers. There is evidence that poor attitudes towards driving stem from broader personal characteristics and attitudes, and general social deviancy.

Driving Skills: Young drivers tend to have very good vehicle control skills (although for a period, these skills require much of their cognitive attention). However, they are very poor at identifying potential hazards, assessing the risk of the hazard resulting in an accident and tend to over-estimate their ability to avoid the hazard and accident."

5.5 Observations

The fact that few crashes are professionally investigated at the time or skid tests undertaken, it is likely the true role of bituplaning in crashes is grossly under estimated.

5.6 Conclusion

There is conclusive evidence from the literature and from experimentation of the atypical performance of NTS in both NOABS and ABS emergency braking. The analysis of the deceleration database clearly shows statistical proof of the reduction in the available deceleration to an emergency braking vehicle provided by a sample of dry NTS surfaces.

It would be reasonable to suggest if skid tests were undertaken routinely at the scene of all collisions a number of these tests may well confirm the presence of the bituplaning phenomenon and, if followed by a professional collision investigation, identify a proven role of bituplaning in the outcome.

6. Attitudes towards Bituplaning

The findings of any research regarding bituplaning are likely to be viewed differently between groups with different interests in the road surface: road user, road investigator, or road owner. The response of each stakeholder group will vary depending on whether they have:

1) A financial interest to gain or lose from changes in the materials laid on our roads
2) Simply a need to understand the phenomenon as a collision investigator
3) A need to be able to modify their driving behaviour (as users of the road network surfaced using these materials) to avoid the scenarios likely to produce bituplaning

6.1 The UK Surfacing Industry Perspective

The responsibility of the road surfacing materials as suppliers of surfacing materials with the potential to deliver undesirable (or indeed "sub-normal") early life frictional properties is uncertain. Little if any feedback is forthcoming from the Industry to the issues under continuous discussion in local authority circles.

A recent article in the "Asphalt Now" (Anon, 2005d) industry journal attempted to address concerns over safety related issues linked to the use of thin surfacing.

This article stated:

There is "currently no evidence to suggest that roads with SMA-based thin surfacing s are any less safe than those with other types of asphalt surface"

The fact that Devon actually grits all their thin surfacing before opening them to traffic appears to have been omitted from the text relating to Devon county Councils usage of SMAs.

Despite the evidence in the public domain of materials delivering a high percentage of new sections below investigatory level (Bastow et al., 2005), the road surfacing industry in the UK appears to maintain a distance from the investigation of early life friction or disclosing their involvement in such activities, if they are indeed taking place.

One known area of industry involvement is that of Aggregate Industries who are understood to be working with Ulster University to understand more about the early life WET frictional characteristics of their materials. This work has now extended to limited Skidman testing of their surfacing. However, this observation is solely based on a commercial display seen at a recent CSS conference (November 2005, Leamington Spa) rather than on any published work.

Establishing the legal implications for the supplier of providing materials with properties that could subsequently be implicated as having a significant role in collision outcome is beyond the scope of this work. The manufacturers are yet to publish any evidence refuting the findings of both highway engineers and collision investigators alike.

A presentation for the Southern Region Branch of the Institute of Highways and Transportation/ Institution of Highway Incorporated Engineers (IHIE) given by Ringway / Jean le Febre in Tonbridge Wells on the 17th November 2005 suggested that they took a more positive attitude towards the possible increased skidding risks during early life. The gritting of SMA as standard practice in Germany (the application of a 1-3mm graded aggregate to the binder film during rolling) was described in some detail and promoted as a proven method to improve early life friction.

Unpublicised research into the bituplaning phenomenon probably continues behind closed doors, as admission of a problem with a material could assist claims for damages from Local Authorities where early life materials are implicated in collisions.

6.2 The Highway Engineers Perspective

A small number of engineers outside of TRL and the Netherlands have been aware for some time that existing surfaces such as HRA (and Hot Mix Asphalt (HMA) in the case of one report from the US (Kuennen, 2003)) can retain a thin film of bitumen from first trafficking until worn away. They are now placed in the position whereby old and trusted materials that had known shortcomings are being replaced by materials without a proven record of accomplishment in the UK.

Surfacing with negative texture (and in the case of PA interconnected porosity) have generally been seen as the most appropriate replacement for HRA with its problems of rutting (Parker, 2003) and road traffic noise when possessing high macrotexture.

The driving forces behind the widespread adoption of thin surfacing and SMA (negative textured surfacing) have been the perceived benefits they can deliver both during and after laying:

1. During laying the single pass of the paving unit negates the need for the passage of a separate chipping spreader reducing delays for traffic and removing the need for costly diversions where closure of both lanes of a two lane single carriageway to lay a traditional surface would have been required.

2. Roadwork times are further reduced as an NTS can simultaneously regulate an irregular substrate and provide the surface course.

3. Reduced spray and noise are promised by most negative textured surfaces.

Once negative textured surfacing was widely adopted as the "norm", the plant and expertise formerly mobilised to manufacture HRA was lost through natural wastage and/or plant/manpower redeployment on thin surfacing production.

A number of local authorities in the UK are thought to be insisting on using HRA in place of negative textured surfaces, this does lead to an increase in costs per square metres surfaced (as production is less) along with potential delivery delays as HRA is no longer considered "mainstream" by some contractors.

Several workers have observed extended periods of low friction (typically WET friction) for SMA materials (Bastow et al., 2005, Transport SA, 2003).

Devon County Council are investigating the possible hazards to horse riders resulting from the use of SMA surfacing. This issue has received extensive coverage in the equestrian press (Anon, 2003, Khan, 2003, Pettit, 2004, Thorpe, 2003) along with the use of grit to improve early life friction (gritting has been used for some time on new SMA in Germany (Bellin, 1997, EAPA, 1998)).

6.3 The Collision Investigators perspective

The varied response encountered in the day-to-day communications of the Researcher with Police Forces along with the poor response to letters and questionnaires circulated by post or at conferences was considered surprising as it was anticipated all Collision Investigation units would be equally interested in the findings of the research.

Based on questions asked by attendees at presentations made by The Researcher to groups of Collision Investigators (these include ITAI 2005, ITAI AGM 2007, UK Senior Collision Investigators Conference 2003,2004, Thames Valley Police, Greater Manchester Police, Dorset Police., IHT/IHIE Aylesbury 2004), those who are still actively seeking to broaden their Collision Investigation knowledge find the research area of interest. In particular, the Dorset, Derbyshire, and West Midlands Police appear to be attempting to learn more regarding the "early life issue" based on their pro-active input into this research project.

6.4 The General Public (The road user)

Recent research work by TRL suggest that road user behaviour changes little when presented with a slippery road warning sign (Figure 150), indeed nearly as many drivers recalled a non-existent parking sign than the slippery road sign that was actually present. The research was described in the TRL Annual Research Review 2004 (TRL, 2005) (A summary of Whittaker et al. (Whittaker D et al., 2004)).

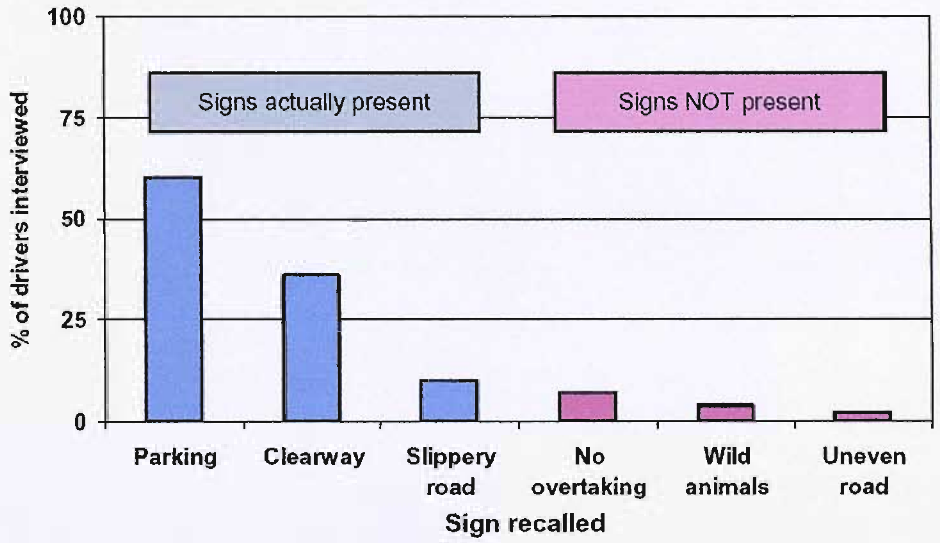


Figure 8 Percentage of drivers reporting having passed each road sign in the previous 2 miles

Figure 150 Sign recognition from Whittaker et al. (Whittaker D et al., 2004)

Notwithstanding the lack of response in road user behaviour to a signed risk of low friction, and the lack of recognition of the warning signs, the media continue to focus on the negative elements of negative textured road surfacing. This negative publicity has been propagated via Television ("The Real Story" with Fiona Bruce BBC1 20th June 2005) and Radio ("File on Four" BBC Radio 4, 22nd February, & 27th February 2005). These programmes delivered a somewhat sensational version of the situation with respect to road surfaces that have been shown to manifest the bituplaning phenomenon.

- The Press continue to present an unbalanced viewpoint where SMA or NTS surfacing has been undertaken and a fatality of serious injury has occurred in a subsequent collision. Numerous articles both online and published in the press have been documented during the course of this study.

- Little or no coverage appears regarding how generally safe the roads in the UK are when compared against those elsewhere in Europe or worldwide.

7. Key Findings of the Research

7.1 Literature Review

- Dry Friction in General: Dry friction is not commonly measured for roads and there is a lack of threshold levels of acceptability for use in routine road testing or road maintenance in the UK.

- World leaders in Dry Friction Measurement: The Netherlands have been identified as leading the world in terms of the identification and measurement of low dry friction in the early 2000's and the lack of reference to their work is evident in the publications made in the UK.

- Grip/Slip: The grip/slip behaviour of road surface in the wet dry and icy states along with what is considered typical dry friction for uncontaminated roads were also established from the literature review for later comparison with field trials.

- Bituplaning deceleration curves: The review of the literature has confirmed the classic form of the deceleration curve for the bituplaning event along with documented occurrences of low dry friction from as far back as 1944.

- Bituplaning in crashes: In the UK, the lack of recognition of the small contribution that bituplaning and low dry friction had in the outcome of the Derbyshire crashes in 2001 was most noticeable, as was the lack of maintained interest in the low dry friction values found on the M4 in the late 1980s. A number of additional cases have also been identified where low dry friction was measured at crash sites but was not considered a factor in the crash outcomes.

- Bituplaning and ABS braking: The role of ABS braking in reducing the effect of low dry friction has been recorded by several researchers but no observations appear to have been made about the momentary levels of low dry friction still experienced by ABS equipped vehicles on these surfaces. The difference between ABS and NOABS sliding friction observed in practice has been reported in the literature. Evidence exists in the literature regarding typical ratios of peak over sliding friction coefficients for NOABS tests to support the testing of whether NOABS tests on Dry NTS deliver significantly lower values of this co-efficient that for tests on Dry PTS The levels of friction generated during brake tests on a road contaminated with engine oil are similar to those generated on DRY NTS.

- Bituplaning and driver behaviour: Evidence was found of the lack of response of drivers to warning signs alerting them to low road surface friction, a lack of recognition of the same signs and of the lack of reduction in speed seen during wet weather conditions.

- Tyre/Road material interaction: The complex interaction between bitumens, polymers, and aggregate and tyre rubber has been documented along with numerous modelling approaches to predict their behaviour in the road and tests and methodologies identified which may be of value in future research.

- Tyre/road friction generation: DRY NTS surfaces may lack the levels of adhesion generated friction and hysteresis generated friction typical of dry PTS surfaces.

- Dry friction on NTS generally improves with time.

7.2 Deceleration Time Series Database Creation

It has been possible to tabulate deceleration time series for subsequent statistical analysis. ASCII Data downloaded from the Skidman device is a more accurate representation of the deceleration characteristics than that from printouts of the SkidCalc package.

7.3 Statistical Testing of the Deceleration Time Series Database

Inaccuracies in the internally generated values of maximum and average deceleration have been found for the Skidman based on comparisons between the internally calculated values and those extracted from the downloaded time series'. The internally calculated value of speed on braking has been verified as approximately correct. Specific findings were:

- A significant difference in average friction in the dry and for the ratio of sliding over peak friction has been established between NTS and PTS surfaces.
- Average sliding deceleration for NOABS tests on DRY NTS are significantly lower than for DRY PTS.
- Average sliding deceleration for NOABS tests on DRY NTS are significantly lower than for DRY PTS.

7.4 Experimental Work

7.4.1 "Typical" Friction Survey

- Values of dry friction has been established for DRY NOABS PTS surfaces that are considered "typical" by collision investigators and this corresponds closely to that found in the literature. Average deceleration values for single surface multi-vehicle testing on DRY PTS compare closely with multiple single vehicle single surface test results.

- Values of dry friction were established for DRY NOABS NTS surfaces that are significantly LOWER than those considered "typical" by collision investigators. These correspond closely to those found in the literature.

7.4.2 Friction Testing / Critical Speed Testing

- Friction Testing: Greasy/Oily patches were observed on the tyre contact patch after many dry NOABS tests on PTS, tests on DRY NOABS NTS surfaces appeared similar to those documented in the literature. Tests on NEW DRY PTS (Hampshire) appeared similar to those undertaken in the literature investigating a low dry friction event on the M4.

- Critical Speed Testing: Evidence has been developed suggesting that, at critical speed, a value of friction closer to that of peak friction rather than that of sliding friction plays a key role in vehicle stability rather than simply the sliding friction value. Well-worn NTS without a binder film may perform almost identically to PTS.

7.4.3 ABS/NOABS comparisons

- Evidence has been produced to suggest the difference between the sliding friction and ABS average friction is proportionally greater for NTS than PTS. Momentary minima in ABS friction time series on NTS approximating to the NOABS sliding friction have been observed, momentary minima seen in ABS tests on PTS have been attributed to surface debris/laitance. ABS tests have been observed to generate "dashes" on the road surface more characteristic of the extended NOAB skids.

7.4.4 Fluorescence Microscopy

- The preparation of thin sections of the road surface and their viewing using fluorescence microscopy techniques appears able to discriminate between the skidded and un-skidded surface. Surface damage caused by the action of a sliding tyre could be seen at high magnification along with the erosion of the binder film at the point of contact between tyre and road. Further work using suitable solvents may enable changes in the bituminous materials, as a result of the passage of a skidding tyre, to be established.

7.4.5 Grip/slip measurements on Gripclean bond coat

- Limited measurements of the grip/slip curve for a DRY smooth bond coat bituminous material suggest that surfaces delivering frictional characteristics similar to those of a bituplaning NTS may possess grip/slip characteristics intermediate in nature between the wet and dry surface models in general use.

7.4.6 Thermal imaging

- The use of thermal imaging technology enabled the heat transfer between tyre, road, and the trailing edge tyre/road contact to be visualised and quantified. Temperatures equivalent to those where bitumen is in a liquid phase have been measured for short periods during both ABS and NOABS dry tests.

- The difference in heat transfer between tyre and road for ABS and NO ABS tests has been quantified. Thermal readings during the transition between rolling and locked wheel phases in NOABS tests along with the "pulses" of activity of Dry ABS tests where wheel lock occurs momentarily have been analysed to extract maximum temperature data during these events. Higher temperatures were observed during Dry PTS tests.

- Temperature build-up during both short period ABS pulses and extended NOABS sliding may be limited by a change in state of the bituminous binder owing to a separate mechanism rather than as has been previously assumed, simply the heat build-up itself triggering melting and loss of friction.

7.4.7 High speed imaging

- A bituplaning event was captured on video. This enables a difference in tyre deformation between NTS and PTS during DRY NOABS testing to be observed. Momentary wheel lock was observed during ABS tests on dry NTS, such events could not be readily observed for DRY PTS.

7.4.8 Acoustic Analysis

- Limited work has shown that the ABS And NOABS phases of a braking event can be discriminated using audio spectrometry. Further work studying bituplaning events would be valuable and easily undertaken.

7.4.9 Changes in dry friction over time

- Repeated tests carried out in three areas of the country all showed that NOABS dry friction improves with time, but not necessarily according to centrally issued guidance, environmental exposure rather than cumulative traffic may be a major factor in this change on less highly trafficked locations.

7.4.10 Dynamic shear rheometry

- Low viscosity behaviour has been generated in a sample of the binder medium used at the Madingley site where low dry friction was observed. Viscosities similar to that of engine oil have been observed. (Relates to Q4 of Section 1.4).

7.4.11 NTS and Accidents

- The lack of professional investigation of the frictional properties of the road surface at the scene of the majority of accidents and the predominance of the influence human factors in collisions may cloak the real role low dry friction on NTS has in collisions. Drivers generally ignore wet roads and low friction warning signs.

8. Key Conclusions Drawn from the Research

8.1 Emergency Braking on NTS and PTS

- **Dry NTS surfaces show levels of sliding friction BELOW the level of dry friction considered TYPICAL by collision investigation professionals and are very similar to those observed in the literature**

- **Levels of dry friction similar to those measured when skid testing on diesel or petrol contaminated surfaces can be delivered on DRY NTS.**

- **Dry NTS surfaces give levels of sliding friction which have been shown to be statistically WORSE than those for DRY PTS surfaces under the same braking conditions: DRY NTS surfaces behave significantly WORSE during NOABS emergency braking in the DRY than DRY PTS surfaces.**

- **ABS braking only partially mitigates the bituplaning effect. ABS brakes on DRY NTS surfaces still fail to prevent the generation of momentary periods of sliding levels of friction manifesting characteristic "dashes".**

DRY NTS surfaces behave significantly **BETTER** during ABS emergency braking in the DRY than DRY PTS surfaces.

DRY NTS surfaces suffering from bituplaning may potentially be driven on at higher speeds than the surfaces they replaced (which may not have shown a risk of bituplaning) if evidence from mainland Europe on PA equally applies to UK NTS

There is a greater difference between ABS and NOABS average friction for DRY NTS than for DRY PTS surfaces .

The ratio of sliding over peak friction is numerically smaller for DRY NTS surfaces than for DRY PTS surfaces in NOABS tests (there is a greater difference between sliding and peak friction for DRY NTS surfaces).

8.2 Imaging/Measuring Bituplaning and possible Bituplaning Mechanisms

- **The behaviour of the tyre can now be observed during NOABS DRY NTS testing and such observations suggest that negative macrotextures may generate fundamentally different frictional behaviours during emergency braking, than for more traditional textures, delivering reduced hysteresis derived friction.**

- **The difference in fundamental friction generation between NTS and PTS surfaces may never have been considered before their widespread introduction.**

- **Melting is not necessarily responsible for the low dry friction as momentary sliding levels of dry friction have been seen during ABS tests.**

- **Oil exudation may provide a mechanism for the generation of low levels of sliding friction**

The measurement at the tyre/road interface of temperatures synonymous of those experienced during the laying process (where the bitumen may be soft or liquid) do not necessarily prove that bituplaning is due to melting since bituplaning has been seen to occur during short period ABS pulses where heat build-up time is limited. Other processes may result in the loss of friction and the cessation of heat transfer between tyre and road rather than the increase in heat generated between them directly causing a material change leading to loss of friction.

Oil exudation may combine with low adhesion and low hysteresis to produce the bituplaning effect; however, more tests are required of surfaces manufactured with binders of known exudation potential.

DRY NTS surfaces show a reduced ability to transfer heat during locked wheel (or ABS near-locked) skidding.

8.3 Dry Friction over Time

- **Existing guidance on the duration of time low dry friction may be an issue, it may grossly underestimate the longevity of the phenomenon if traffic levels are low.**

The variation in dry friction over time seen between only three locations suggests the existing guidance (IAN 49 etc) may not be appropriate outside of the trunk road realm where lower traffic intensities may extend the period of low friction.

8.4 Low Dry Friction and Accidents

- **Bituplaning may not have been identified as having a significant role in collision as a result of insufficient investigation of non-fatal crashes by trained collision investigation professionals.**

- **No research yet exists to refute a claim that smoother quieter (NTS) roads may result in faster road speeds.**

- Drivers ignore wet skidding warning signs and such signs used to warn of DRY friction problems are inappropriate.

- It may be inferred since older, cheaper cars are less likely to be fitted with ABS, Younger, older and less skilled drivers may be LESS likely to drive cars which will not generate bituplaning.

Proper investigation of more non-fatal crashes may reveal the true role of bituplaning in collisions.

Since drivers generally fail to adjust their driving behaviour on wet roads with lower skidding resistance and skidding warning signs, alerting them to a risk of bituplaning may be fruitless.

8.5 Bituplaning and Critical Speed

- **The binder film on new NTS surfaces could result in a change in the maximum safe speed at which a vehicle can safely travel round a bend.**

- **The binder film on new NTS surfaces may result in a change in the characteristics of the in-control/out-of-control transition.**

The bituplaning effect may not influence critical speed on curves where near-lock or locked wheel conditions are not prevalent, however this remains unproven, further work is planned with the Metropolitan Police Service. However, the extreme contrast between peak and sliding friction on dry NTS could be a problem if sliding friction is proven to play a role in critical speed.

Advice and Further Work resulting from the Research

- **Respect the fact all new NTS surfaces may have reduced dry friction when braked on in emergency by a vehicle without ABS.**

- **The wide use of NTS in the UK may require changes in driver training to make them aware of the risk of bituplaning if their vehicle is NOT ABS equipped.**

- **More non-fatal crashes require professional investigation to understand better the manifestation of bituplaning in crashes and its contribution to crash outcome.**

- **A link needs to be either established or discredited between smoother quieter roads and higher road speeds.**

Highway engineers should understand the changes over time in their NTS materials to accommodate differences in traffic levels and climatic effects on the bituminous layers on NTS. Existing advice is too general.

More work is needed to study the influence of DRY NTS friction on critical speed behaviour of these surfaces.

More fluorescence microscopy study is needed of skidded NTS surfaces to find evidence of morphological changes caused by skidding to better understand what hppens to the road surface during bituplaning.

ABS braking models need revision to enable momentary bituplaning to be avoided.

Oil exudation capability should be studied in relationship to bituplaning potential.

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Appendix 1: Conwy Dry Friction Benchmarking.

The following Tables and Figures summarise the Conwy benchmarking exercise of 22 April 2007 undertaken on a length of hot rolled asphalt. Multiple ABS and NOABS tests were carried out using a range of vehicles (Table 19, Figure 153) impounded by North Wales Police. The between-vehicle and between-tester variation is given in **Table 20.**

Test car	S1181 AVG. ABS	B1158 AVG. ABS	S1181 AVG. NOABS	B1158 AVG. NOABS
CV02		0.833	0.654	0.684
TC01	0.732	0.735		
TC02	0.697	0.765		
TC03			0.693	0.673
TC04			0.693	0.677
TC05	0.805	0.797		
TC06			0.718	0.711
TC08			0.788	0.783
TC09	0.820	0.861		
TC10			0.775	0.774
TC11			0.656	0.644
TC12			0.741	0.732
TC13			0.711	0.705
TC14			0.800	0.784
TC15			0.788	0.775
TC16			0.600	0.591
TC17			0.694	0.686
TC18			0.710	0.696
TC19	0.901	0.910	0.679	0.682
TC20			0.733	0.715
TC21	0.825	0.817		
TC22			0.578	0.571
Overall	**0.781**	**0.813**	**0.707**	**0.699**

Test car	S1181 PEAK ABS	B1158 PEAK ABS	S1181 PEAK NOABS	B1158 PEAK NOABS
CV02			0.860	0.880
TC01	0.839	0.771		
TC02	0.950	0.908		
TC03			0.740	0.725
TC04			0.865	0.869
TC05	0.946	0.907		
TC06			0.861	0.828
TC08			0.874	0.866
TC09	0.956	0.946		
TC10			0.868	0.875
TC11			0.682	0.664
TC12			0.865	0.915
TC13			0.732	0.714
TC14			0.890	0.871
TC15			0.916	0.894
TC16			0.674	0.708
TC17			0.742	0.730
TC18			0.735	0.697
TC19	1.026	0.995	0.849	0.848
TC20			0.761	0.738
TC21	0.887	0.841		
TC22			0.653	0.595
Overall	**0.922**	**0.896**	**0.799**	**0.794**

Table 18 Summary Data from Conwy Database

The vehicles were all driven by the same operator, Constable Diane Mann, for whom the exercise was arranged to provide data for the basis of an MSc study pursuant to her role as collision investigators with North Wales Police. Constable Mann kindly provided the test data and photographic records from the days activities for use in this research.

Vehicle Code	Vehicle
CVO2	Police Ford Galaxy (2004)
TC01	Vauxhall Astra 5DR (1999)
TC02	Audi A4 4DR (1998)
TC03	Toyota Yaris 3DR (2000)
TC04	Renault Megane MPV (1998)
TC05	Coupe (1996)
TC06	Maxda MX3 Saloon (1994)
TC08	Ford Sierra 5DR (1992)
TC09	Mercedes 230 5DR Estate (1990)
TC10	Ford Fiesta 5DR (1996)
TC11	Nissan Micra 5DR (1994)
TC12	Maxda 323 5DR (1987)
TC13	Fiat Seicento 3DR (2000)
TC14	Citroen AX 5DR (1995)
TC15	Vauxhall Astra 5DR (1990)
TC16	Fiat Brava 3DR (1998)
TC17	Ford Escort 3DR Van (1991)
TC18	Porsche 911 Coupe (1989)
TC19	Nissan Pathfinder 4x4 (2006)
TC20	Rover Metro 5dr (1996)
TC21	Range Rover (2003)
TC22	Police Transit Van (2002)

Table 19 Vehicle data from Conwy Database

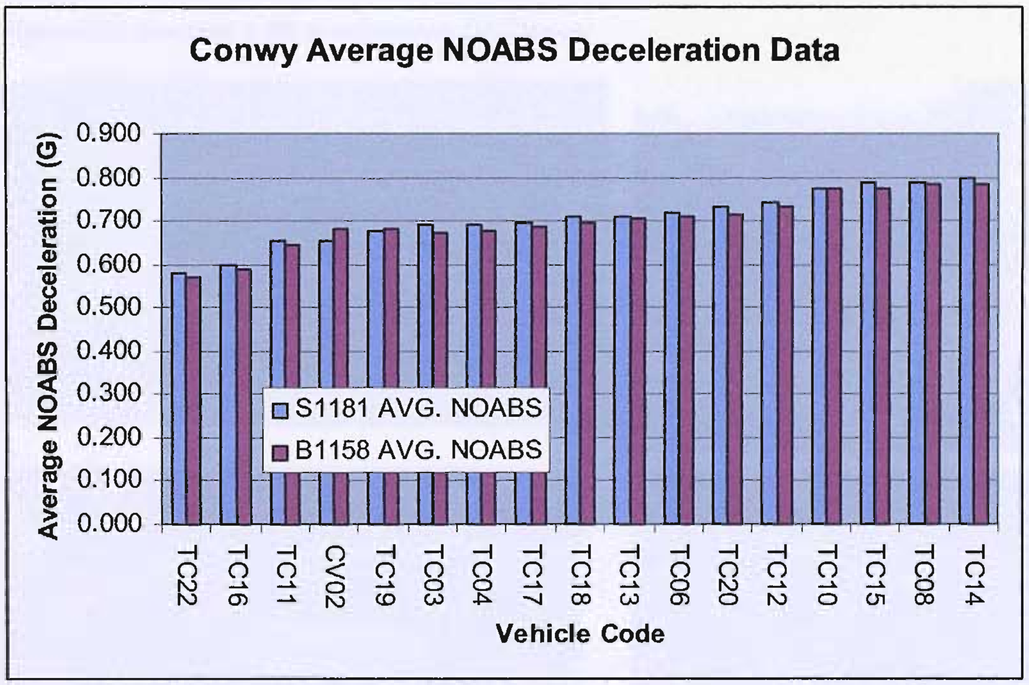

Figure 151 Average NOABS deceleration for Conwy

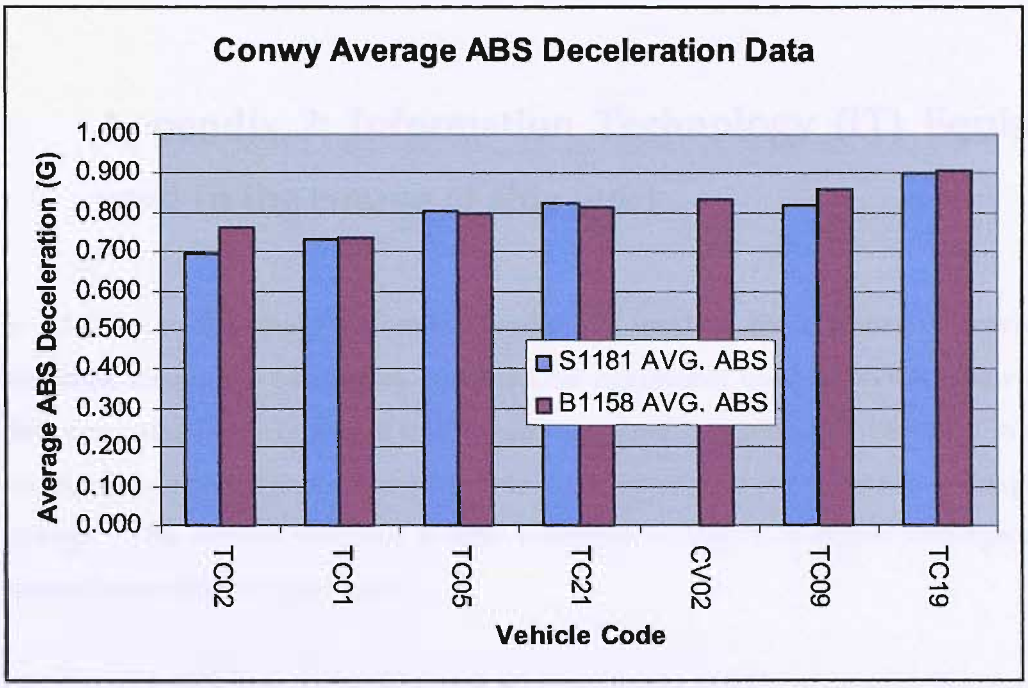

Figure 152 Average ABS deceleration for Conwy

Figure 153 Conwy skid cars TC19 (top left), TC17 (top right), CV02 (bottom left), TC18 (bottom right) (photos North Wales Police Photographic Unit)

Appendix 2: Information Technology (IT) Equipment used in the course of this work.

In addition to the image processing equipment used by the contractors providing the specialist imaging at Madingley and the DSR equipment used by VDOT, the volume of data generated in the course of this research required a significant investment in software and hardware on the part of the Author to process this data and secure its subsequent safe storage. This section provides a brief overview of the IT structure underpinning the research described in this thesis.

The best example of the high data load this research placed on the Researcher is that of the output from the high speed and infrared video cameras:

4) A single four second burst of high-speed video generated an AVI video combining 4000 512 x 512 JPEG images delivering a single file of 2532 frames 1.85GB in size

5) The AVI files output to DV by the infrared camera were typically 100k in size.

6) The FLIR researcher SEQ data files were each 100k to 300k in size, 63 of these files were generated before any analysis took place .

Laptop Computers

Data retrieval from the Skidman device (using the DOS SIMRET application) required the use of a Windows 98 equipped machine offering a COM port for use with the download cable, thus down loading was achieved using a Dell Latitude 5000 laptop from within the TRG computer pool. The Dell laptop was also used in New Zealand to download both the Skidman and the Vericom devices (Vericom via the Profile software) Files downloaded to this device were transferred to floppy disc in the first instance then to CD or DVD media at the earliest possible occasion.

Ongoing analysis and document preparation using Microsoft Office 2003 was undertake using a Clevo M55G Laptop computer running Windows XP Professional SP2 on a generic motherboard using an Intel® 915GM + ICH6-M chipset with 2038 MB of DDR2 memory. A 40GB hard disk was fitted.

Desktop Computer

Ongoing analysis and document preparation using Microsoft Office 2003 was undertake using a desktop PC assembled by the Researcher running Windows XP Professional SP2, an Intel Celeron 4A, 2733 MHz processor mounted on an Asus P4S533-E motherboard (SiS 645DX chipset) and 3072 MB of DDR 400mhz high density memory. The desktop ran four internal IDE disk drives of various sizes from 40GB to 200GB via PCI IDE interface card.

The desktop computer was used to undertake memory and disk intensive graphic manipulations including Minitab analysis, SPSS analysis, FLIR Researcher analysis, MiDAS Player editing and Sony Vegas video editing.

Networking

A NetGear SC101 SAN (Storage Area Network) containing a matched pair of Hitachi 250GB IDE drives provided a RAID based backup service.

The communication between the Clevo laptop and the SAN was achieved either over a 54g wireless connection to a 3Com 3CRWDR100A-72 wireless LAN ADSL router modem or via a 100Mb LAN connection to the same router. The desktop was linked to the SAN via the 100Mb LAN.

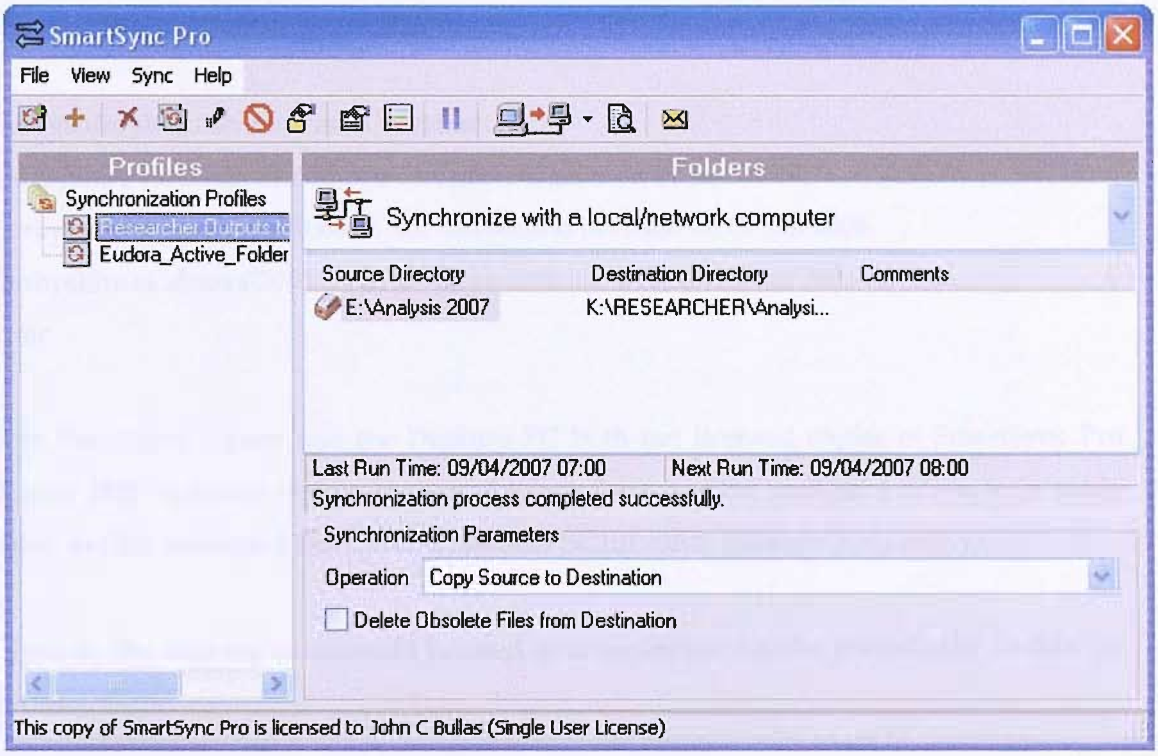

Figure 154 SmartSync Pro screen shot

Data Backup

All data secured in the course of the Research was archived in the form of CD and DVD media however access to these records became difficult owing to the sheer number of individual discs (200 plus) . To enable rapid access to the data, two Seagate USB hard drives (one of 160GB and then a second of 320GB in size) were used to copy the data from CD and DVD onto (Figure 155).

To ensure continuity of changes to documents the SAN array was available to all devices on the LAN via installs of NetGear Storage Central Manager Utility and the SAN version of and file remained the master copy.

Filenames were consistently augmented following revision with the date of modification and a sequence number, for example:

Derbyshire skidman.xls would become:
Derbyshire skidman 010106 .xls on first revision on 01 Jan 2006
Derbyshire skidman 010106v02 .xls on second revision on 01 Jan 2006
Derbyshire skidman020106v12.xls on twelfth revision on 12 Jan 2006
...etc

Both the Clevo laptop and the Desktop PC both ran licensed copies of SmartSync Pro (Figure 154) to enable regular backup of selected areas of the local hard drives to be made either to USB connected storage or a NetGear SC101 SAN (Storage Area Array).

Typically the desktop area would be used as a workspace and be periodically backed up via SmartSync.

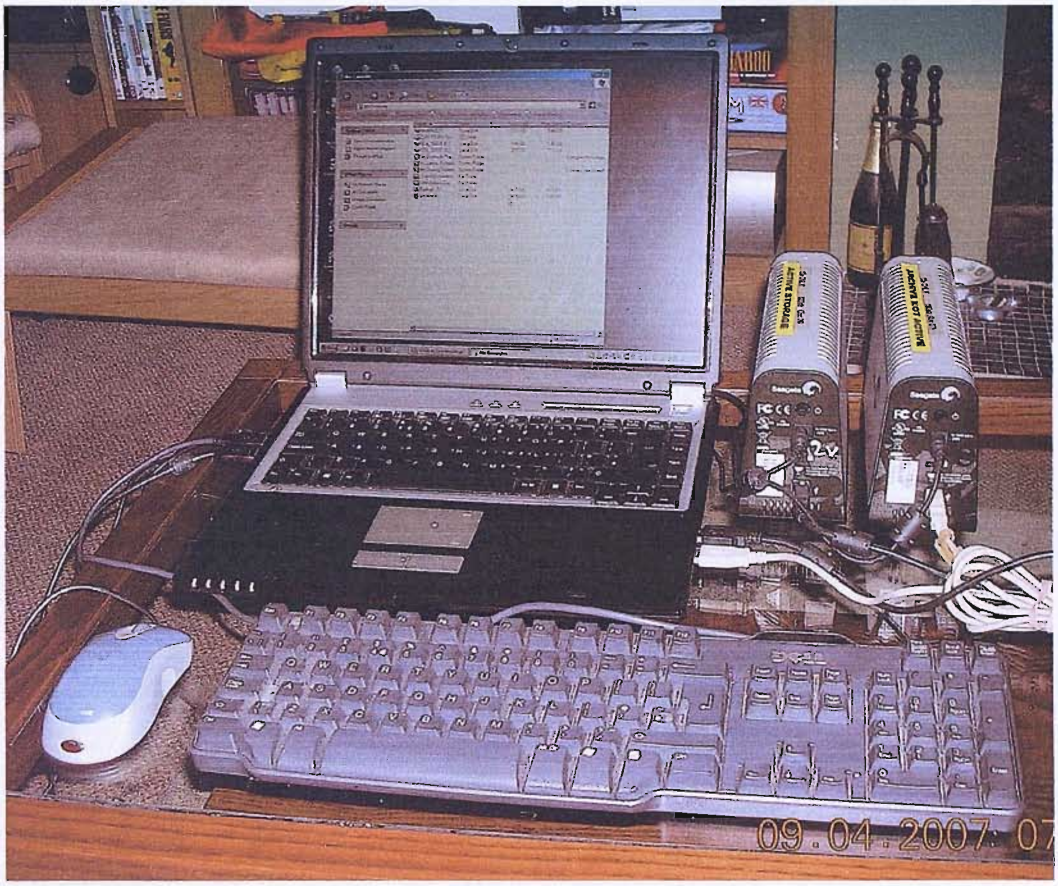

Figure 155 Clevo laptop connected to both Seagate USB IDE drives.

Email

The main medium of communication for this research was via email, Eudora 7.0 (and precursors) was used in addition to web mail services. Eudora offered a simple means to warehouse several thousand emails using a logical directory structure (Figure 156) and also offered a rapid search facility.

The desktop PC was the only device used to download (and therefore delete) emails from mail servers, any other device using a mail client to read emails via POP3 or IMAP had the settings made to ensure the original message was preserved on the server.

Video Transfer / Screen Captures

Video images captured on Mini DV or Movie 8 equipment were transferred to AVI format using Pinnacle Studio 10 software (http://www.pinnaclesys.com/streamfactory/) via a Pinnacle 500-USB video to PC interface.

Screen captures of software in operation (e.g. FLIR Researcher) were recorded using TechSmith Camtasia Studio 3 (http://www.techsmith.com/camtasia.asp).

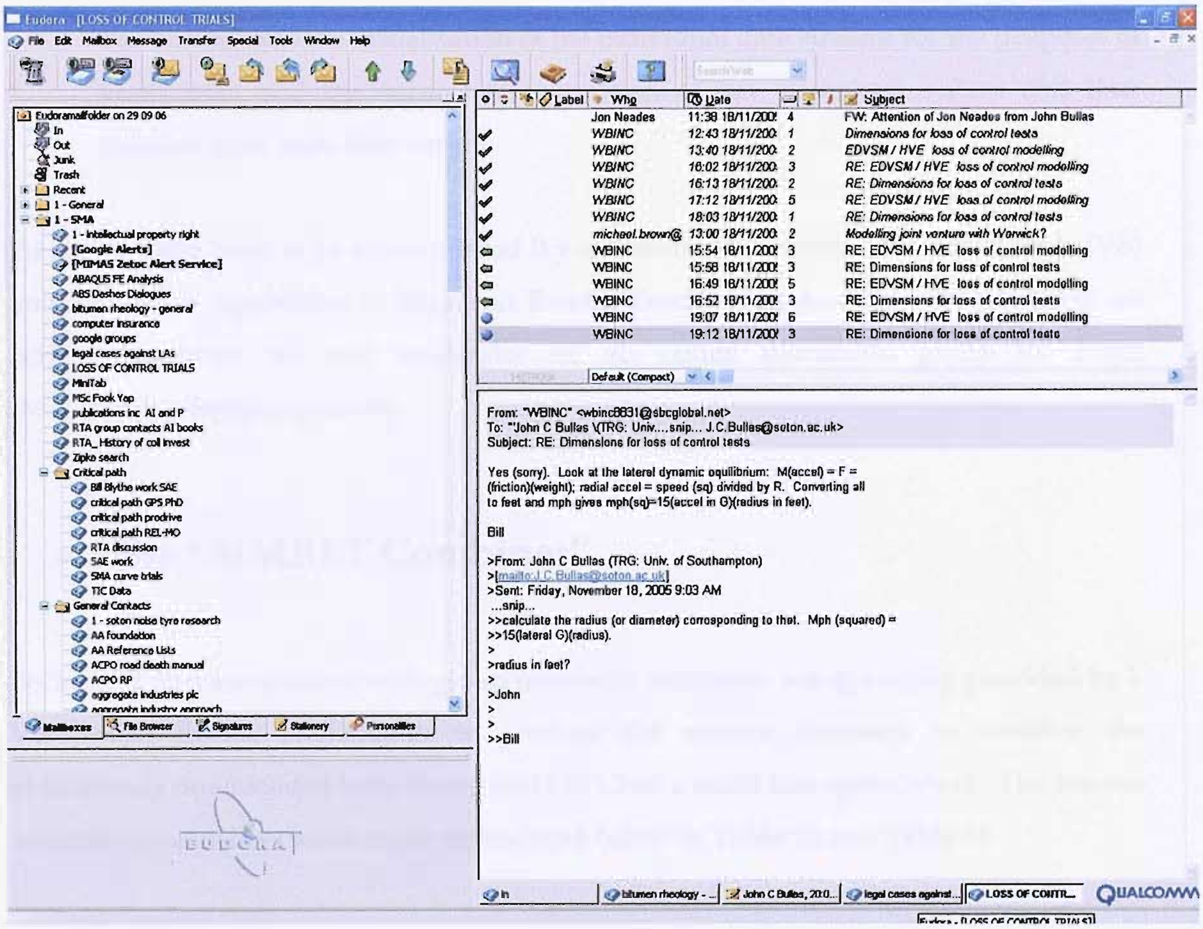

Figure 156 Eudora 7.0 in use

Appendix 3: Listings of custom Microsoft Excel macros and spreadsheets.

Two discrete phases of data processing existed in the assembly of the deceleration time-series database:

- The first was the combination of the individual test sequences into a larger multi line database (from a multi row single test data stream).

- The second was the visualisation of the individual data streams for the purposes of verification and the subsequent extraction of key parameter values and time markers from each data stream.

To enable these tasks to be accomplished it was necessary to harness the Visual Basic (VB) and VB Macro capabilities of Microsoft Excel ("Excel". The Author was fortunately an active contributor to, and moderator of, an online discussion group for Excel (MS_Excel@yahoogroups.com).

• The "SIMRET Combiner"

Because of past associations with group members, assistance was gratefully provided by L Vosslamber in the Netherlands to produce the macros necessary to combine the individually downloaded tests (using SIMRET) into a multi line spreadsheet. The macros from this spreadsheet solution are reproduced below in **Table 20** and **Table 21.**

• The "Visualisation Spreadsheet"

See Appendix4 \SOFTWARE DEMO SCREEN CAPTURES\DECELERATION DATABASE TAGGING.avi for a screen capture video of this application in operation

The visualisation and classification of the test data streams was achieved using a VB spin box enhanced Excel spreadsheet. The initial generic concept for which was converted into a working prototype by Pascal Daulton of Poole in Dorset (another active contributor to the discussion group), this prototype spreadsheet, and VB script was further developed over the course of a number of months into a working spreadsheet solution reproduced in Table 21 below.

General Notes

In the case of both spreadsheet-based solutions, changes were made over time to add extra information from the source data file (in the case of the file combiner) and to generate extra data fields in the case of the visualisation macro.

Table 20 Multipage/ multi column listing of the Visual Basic Macros used in the SIMRET Combiner Spreadsheet

```
Sub AddRecords(CSV As String)
'
' Macro  05 feb 2004 by L. Vosslamber
' changed 05 feb 2004: different lay-out
' changed 10 feb 2004: "decell units and notes" fixed
' changed 29 september 2004 to import filename by jc bullas
'
  RecordsBook = Workbooks("data-v2_bullas.xls").Name
  Windows(RecordsBook).Activate
  'Determine first empty row
  Range("A1").Select
  If Not (IsEmpty(Cells(2, 1))) Then Selection.End(xlDown).Select
  RR = Selection.Row + 1

  'CSV-file
  CSVbook = CSV

  Application.ScreenUpdating = False

  'TESTER
  Windows(CSVbook).Activate
  x = Range("A1").Text
  Windows(RecordsBook).Activate
  Cells(RR, 1) = x

  'Calibrated
  Windows(CSVbook).Activate
  x = Range("A3").Text
  Windows(RecordsBook).Activate
  Cells(RR, 2) = Mid(x, InStr(x, "on") + 3)

  'Test
  Windows(CSVbook).Activate
  x = Range("A5").Text
  Windows(RecordsBook).Activate
  'Cells(RR, 3) = x
  Cells(RR, 3) = Mid(x, 5, InStr(x, "carried") - 6)
  Cells(RR, 4) = Mid(x, InStr(x, "at") + 3, 5)
  ' was Cells(RR, 5) = Mid(x, InStr(x, "on") + 3)
  ' was Cells(RR, 5) = Right(x, 8)
```

```
Cells(RR, 5) = Left(Right(x, 8), 3) & Choose(Mid(Right(x, 8), 4, 2), "Jan", "Feb", "Mar", "Apr", "May", "Jun", "Jul", "Aug", "Sep", "Oct", "Nov", "Dec") & Right(Right(x, 8), 3)

'ID
Windows(CSVbook).Activate
x = Range("A7").Text
Windows(RecordsBook).Activate
Cells(RR, 6) = Mid(x, InStr(x, "ID") + 3)

'Tested by
Windows(CSVbook).Activate
x = Range("A9").Text
Windows(RecordsBook).Activate
Cells(RR, 7) = Mid(x, InStr(x, "by") + 3)

'LEAVE BLANKS HERE FOR IMPORTED LATER NOTES CELL(RR,x) incremented by 5 from here

'File name
Windows(CSVbook).Activate
x = ActiveWorkbook.Name
Windows(RecordsBook).Activate
Cells(RR, 13) = x

'Trigger
Windows(CSVbook).Activate
x = Range("A13").Text
Windows(RecordsBook).Activate
Cells(RR, 14) = x

'Mean EFFORT (g)
Windows(CSVbook).Activate
x = Range("B16").Text
Windows(RecordsBook).Activate
Cells(RR, 15) = x
Windows(CSVbook).Activate
x = Range("C16").Text
Windows(RecordsBook).Activate
Cells(RR, 16) = x

'Peak Value (g)
Windows(CSVbook).Activate
x = Range("B17").Text
Windows(RecordsBook).Activate
Cells(RR, 17) = x
```

```
Windows(CSVbook).Activate
x = Range("C17").Text
Windows(RecordsBook).Activate
Cells(RR, 18) = x

'Braking Time (sec)
Windows(CSVbook).Activate
x = Range("B18").Text
Windows(RecordsBook).Activate
Cells(RR, 19) = x
'Windows(CSVbook).Activate
'x = Range("C18").Text
'Windows(RecordsBook).Activate
'Cells(RR, 15) = x

'Delay
Windows(CSVbook).Activate
x = Range("A19").Text
Windows(RecordsBook).Activate
Cells(RR, 20) = x

'Theshold (%g)
Windows(CSVbook).Activate
x = Range("B20").Text
Windows(RecordsBook).Activate
Cells(RR, 21) = x
Windows(CSVbook).Activate
x = Range("C20").Text
Windows(RecordsBook).Activate
Cells(RR, 22) = x

'Stop Slope %
Windows(CSVbook).Activate
x = Range("B21").Text
Windows(RecordsBook).Activate
Cells(RR, 23) = x
Windows(CSVbook).Activate
x = Range("C21").Text
Windows(RecordsBook).Activate
Cells(RR, 24) = x

'Speed at Braking
Windows(CSVbook).Activate
x = Range("B22").Text
```

```
Windows(RecordsBook).Activate
Cells(RR, 25) = x
Windows(CSVbook).Activate
x = Range("C22").Text
Windows(RecordsBook).Activate
Cells(RR, 26) = x

'Stopping Distance
Windows(CSVbook).Activate
x = Range("B23").Text
Windows(RecordsBook).Activate
Cells(RR, 27) = x
Windows(CSVbook).Activate
x = Range("C23").Text
Windows(RecordsBook).Activate
Cells(RR, 28) = x

'Suspension Tilt
Windows(CSVbook).Activate
x = Range("B24").Text
Windows(RecordsBook).Activate
Cells(RR, 29) = x
Windows(CSVbook).Activate
x = Range("C24").Text
Windows(RecordsBook).Activate
Cells(RR, 30) = x

'Notes
Windows(CSVbook).Activate
x = Range("A28").Text
x = Trim(Mid(x, Len("USER NOTES: ") + 1))
x = Trim(x + " " + Range("A29").Text)
x = Trim(x + " " + Range("A30").Text)
x = Trim(x + " " + Range("A31").Text)
x = Trim(x + " " + Range("A32").Text)
Windows(RecordsBook).Activate
Cells(RR, 31) = x

'Decel
Windows(CSVbook).Activate
x = Range("C34").Text
x = Mid(x, Len("DECEL_") + 1)
Windows(RecordsBook).Activate
Cells(RR, 32) = x
```

```
    'Measures
    y = 35
    col = 33
    Windows(CSVbook).Activate
    While Cells(y, 3) <> "" And col < 257
        x = Cells(y, 3)
        Windows(RecordsBook).Activate
        Cells(RR, col) = x
        Windows(CSVbook).Activate
        y = y + 1
        col = col + 1
    Wend
    'Uncomment next line to see when there is too much data....
    ' If col = 257 Then MsgBox "Readings lost: too many data rows in " + CSVbook, vbCritical
    Workbooks(CSVbook).Close
    Windows(RecordsBook).Activate
    Application.ScreenUpdating = True

End Sub
Sub AddOneFile()
    MsgBox "Choose a CSV-file, the file will be added", vbOKOnly

    f = Application.Dialogs(xlDialogOpen).Show
    If f Then
        n = ActiveWorkbook.Name
        AddRecords (n)
    End If
End Sub
Sub AddMultipleFiles()
    MsgBox "Choose a CSV-file, all files in the same directory will be added", vbOKOnly
    Application.ShowWindowsInTaskbar = False
    f = Application.Dialogs(xlDialogOpen).Show
    n1 = ActiveWorkbook.FullName
    n2 = ActiveWorkbook.Name
    n = Left(n1, Len(n1) - Len(n2))
    ActiveWorkbook.Close

    d = Dir(n + "*.CSV")
    While d <> ""
        Workbooks.Open (d)
        n = ActiveWorkbook.Name
        AddRecords (n)
        d = Dir
```

```
  Wend
  MsgBox "The CSV File importation is complete", vbOKOnly

  Application.ShowWindowsInTaskbar = True

End Sub
Sub test()
  AddRecords ("longcsv.csv")
End Sub
```

Table 21 Multipage/ multi column listing of the Visual Basic scripts used in the "Visualisation Spreadsheet"

```
Private Sub SpinButton1_Change()

End Sub

Private Sub spnBounceCross_Change()

Dim CopyValue As Single

  'copy existing values from DATA to tagging sheets

  With Worksheets("Tagging") ' Tagging worksheet
    CopyValue = .Cells(39, 4).Value 'D39 copy existing bounce crss to spin cell
    .Cells(22, 2).Value = CopyValue 'B26

    CopyValue = .Cells(39, 7).Value 'G39 copy existing slide start spin value to spin cell
    .Cells(10, 2).Value = CopyValue 'B10

    CopyValue = .Cells(39, 8).Value 'H39 copy existing slide end spin value to spin cell
    .Cells(13, 2).Value = CopyValue 'B13

      CopyValue = .Cells(39, 5).Value 'E39 copy existing peak G value to spin cell
    .Cells(19, 2).Value = CopyValue 'B19

  End With

End Sub

Private Sub spnRow_Change() 'reads pre-existing values into spin box cells when row selected changes

Dim CopyValue As Single

  'copy existing values from DATA to tagging sheets

  With Worksheets("Tagging") ' Tagging worksheet
    CopyValue = .Cells(39, 4).Value 'D39 copy existing brake start spin value to spin cell
    .Cells(22, 2).Value = CopyValue 'B22

    CopyValue = .Cells(39, 7).Value 'G39 copy existing slide start spin value to spin cell
    .Cells(10, 2).Value = CopyValue 'B10
```

```
    CopyValue = .Cells(39, 8).Value 'H39 copy existing slide end spin value to spin cell
    .Cells(13, 2).Value = CopyValue 'B13

      CopyValue = .Cells(39, 5).Value 'E39 copy existing peak G value to spin cell
    .Cells(19, 2).Value = CopyValue 'B19

  End With

    'insert statement to copy ranges of Distance values into DISTANCE sheet

Dim lngR As Long, lngR2 As Long
Dim rngCopy As Range, rngDest As Range

  With Worksheets("Tagging")
    lngR = .Range("B34").Value ' Assuming this stores 300. Original
    'lngR = .Range("F12").Value ' Test version
    Set rngCopy = Range(.Cells(lngR, 1), .Cells(lngR, 31)) 'ORIGINAL
    ' Set rngCopy = .Range(.Cells(lngR, 6), .Cells(lngR, 8)) ' test Version
'   Set rngCopy = .Range("A" & lngR & ":AE" & lngR)
  End With


  With Worksheets("DISTANCE")
    lngR2 = lngR
    'lngR2 = .Cells(Rows.Count, 1).End(xlUp).Offset(1, 0).Row
    Set rngDest = .Range(.Cells(lngR2, 1), .Cells(lngR2, 31)) 'ORIGINAL
    ' Set rngDest = .Range(.Cells(lngR2, 1), .Cells(lngR2, 3)) ' test version

  End With

  rngDest.Value = rngCopy.Value

End Sub

Private Sub spnBrakeStart_Change() ' copies spin value of brake start to datasheet

Dim CopyToRow As Integer
  Dim CopyToCol As Integer
  Dim CopyValue As Single

  '========================================

  With Worksheets("Tagging") ' define cell location and value of brakestart spin in Tagging worksheet
    CopyValue = .Cells(22, 2).Value 'B22 OK
```

```
    CopyToRow = .Cells(34, 4).Value 'D34
    CopyToCol = .Cells(35, 4).Value 'D35
  End With

  With Worksheets("DATA") ' copy brakestart spin value to DATA worksheet
    .Cells(CopyToRow, CopyToCol).Value = CopyValue
  End With

  '==========================================

End Sub



Private Sub spnPeakTime_Change() 'copies peak G time info to datasheet from cell in tagging

Dim CopyToRow As Integer
  Dim CopyToCol As Integer
  Dim CopyValue As Single

  '====================

  With Worksheets("Tagging") ' Define Tagging worksheet copy Peak Spin value location and value
    CopyValue = .Cells(19, 2).Value 'B19
    CopyToRow = .Cells(34, 5).Value 'E34
    CopyToCol = .Cells(35, 5).Value 'E35
  End With

  With Worksheets("DATA") ' DATA worksheet
    .Cells(CopyToRow, CopyToCol).Value = CopyValue
  End With

  '======================

  With Worksheets("Tagging") ' Tagging worksheet copy G Max value of peak to DATA
    CopyValue = .Cells(20, 3).Value 'C20
    CopyToRow = .Cells(34, 6).Value 'F34
    CopyToCol = .Cells(35, 6).Value 'F35
  End With

  With Worksheets("DATA") ' DATA worksheet
    .Cells(CopyToRow, CopyToCol).Value = CopyValue
  End With
```

```
End Sub

Private Sub spnSlideSlopeManual_Change()

End Sub

Private Sub spnSlideStart_Change() 'copies value of slide start spin to datasheet
  Dim CopyToRow As Integer
  Dim CopyToCol As Integer
  Dim CopyValue As Single

  With Worksheets("Tagging") ' Define slide START cell in Tagging (location and value)
    CopyValue = .Cells(10, 2).Value 'B10
    CopyToRow = .Cells(34, 7).Value 'G34
    CopyToCol = .Cells(35, 7).Value 'G35
  End With

  With Worksheets("DATA") ' Copy slide START value to DATA
    .Cells(CopyToRow, CopyToCol).Value = CopyValue
  End With

   With Worksheets("Tagging") ' Define slide AVERAGE cell in Tagging (location and value)
    CopyValue = .Cells(36, 9).Value 'I36
    CopyToRow = .Cells(34, 9).Value 'I34
    CopyToCol = .Cells(35, 9).Value 'I35
  End With

  With Worksheets("DATA") ' copy slide average G to DATA worksheet
    .Cells(CopyToRow, CopyToCol).Value = CopyValue
  End With


End Sub

Private Sub spnSlideEnd_Change() 'copies value of slide end spin to datasheet

Dim CopyToRow As Integer
  Dim CopyToCol As Integer
  Dim CopyValue As Single

  With Worksheets("Tagging") ' Define slide END cell in Tagging (location and value)
    CopyValue = .Cells(13, 2).Value 'B13
```

```
    CopyToRow = .Cells(34, 8).Value 'H34
    CopyToCol = .Cells(35, 8).Value 'H35
  End With

  With Worksheets("DATA") ' Copy slide END value to DATA
    .Cells(CopyToRow, CopyToCol).Value = CopyValue
  End With

  With Worksheets("Tagging") ' Define slide AVERAGE cell in Tagging (location and value)
    CopyValue = .Cells(36, 9).Value 'I36
    CopyToRow = .Cells(34, 9).Value 'I34
    CopyToCol = .Cells(35, 9).Value 'I35
  End With

  With Worksheets("DATA") ' copy slide average G to DATA worksheet
    .Cells(CopyToRow, CopyToCol).Value = CopyValue
  End With


End                                                                 S
```

Appendix 4: DVD Media

The attached DVD media contains video content referenced in the body of the text along with the necessary viewing software (free licence versions). The use of the MiDAS viewer is preferred as it enables frame-by-frame and variable speed playback of the videos.