Dr David Woodward

Phillip Millar

Christopher Tierney

Jason Ferguson

Development of a test method to investigate the tyre road interface

Dr David Woodward, Phillip Millar, Christopher Tierney and Jason Ferguson
Belfast School of Architecture and the Built Environment
Ulster University, Northern Ireland

Abstract

This paper considers development of a test to investigate the tyre road interface. The aim was to produce data that could be related to what happens in real life. The resulting Ulster Tyre Road Surface Interface method (UTRSI) was developed in the laboratory and has since been used to measure actual road / tyre interfaces. The method has four main elements i.e. vertical pressure mapping, a modified small wheel tracking device fitted with an ASTM friction tyre and test specimens subjected to slow speed high stress accelerated trafficking that allow changes in time to be assessed. Although the emphasis in development of the UTRSI method has been on friction, the data can be used to better understand other interface properties relating to both the road and the tyre. This paper outlines the development of the UTRSI and uses examples to illustrate how its data may be used to investigate the tyre road interface.

1. Introduction

Investigation of the tyre/surface interface for UK roads can be traced back to the 1930s when Bradley and Allen (1930) considered the slipperiness of road surfaces and determined factors which were conducive to skidding. Their research used a modified motorbike and sidecar, which subsequently became the basis of the sideways force friction measuring device. They identified that the problem of skidding may be subdivided into three parts each of which separately required a solution by the Highway Engineer, the Tyre Manufacturer and the Road-Vehicle Designer.

The 1930 report commented that the Highway Engineer is required to produce a road surface on which the wheels of vehicles can obtain a good grip at all speeds and under all weather conditions, where the curves and contours of the surface are designed to be as safe as possible. The Tyre Manufacturer is required to supply tyres which will offer a resistance to slipping which is as high as possible and independent of the speed and surface conditions. The Road-Vehicle Designer must produce a vehicle of which the weight distribution, drive, and braking arrangements are best adapted to provide safety under all conditions.

Their experiments were made primarily from the Highway Engineer's point of view; the engineer will be concerned to a slight extent with the Tyre Manufacturers' problem and they scarcely consider on the problems which confront the Vehicle Designer. Given that this research was carried out 90 years ago it is unfortunate that the Highway Engineer, the Tyre Manufacturer and the Road Vehicle Designer still appear to be independently investigating their own specific areas.

Tyre/road interface properties have become global issues impacting safety; quality of life for people who live beside noisy roads, to government policies committed to targets of reducing CO_2 emissions. Given the importance of the tyre/road interface, there is little in current British and European asphalt standards and specifications that consider this interface. Aggregate tests such as Polished Stone Value (PSV) offer limited insight into the variation of in-service performance of asphalt roads that can be measured on the road network. PSV is a laboratory test. The aggregate version of Friction after Polishing (FAP) relates to PSV and also offers limited insight of in-service variation around the network. The asphalt version of the FAP test is closer to a real road but there are issues with the method and the equipment used. Both PSV and FAP have limitations replicating the interface enveloping of real tyres in real road conditions.

There is a problem or knowledge gap relating to how a tyre interacts with aggregate used to create textured road surfaces. This knowledge gap led to development of the Ulster Friction Tyre Surface Interface method (UTRSI). The method has evolved over the last 10 years by Undergraduate, Masters and PhD students at Ulster University. The original aim was to produce interface data using a simple, quick method that used available equipment. The objectives were:

- **Produce reliable, robust data that could be used for different types of analysis such as inputs for computer modelling or be used to verify model predictions.**
- **Produce visual representations of complex interface conditions that could be easily understood.**
- **Show how the interface changed with time, similar to asphalt mixtures changing during early life trafficking, reaching equilibrium.**
- **Be able to assess factors related to the tyre and the different materials used in asphalt surfaces.**
- **Evaluate how this interaction would change over the life of the surfacing material due to simulated trafficking.**
- **Be used both in the laboratory and on-site.**

The original aim of producing interface data was achieved by combining four main elements i.e. vertical pressure mapping (z-axis), a modified small wheel tracking device fitted with an ASTM friction tyre and slab specimens subjected to slow speed high stress accelerated trafficking that allow changes in time to be assessed. Although the emphasis in development of the UFTSI method has been on friction, the data can be used to better understand other interface properties relating to noise and rolling resistance. This paper outlines the main development stages and uses examples to illustrate how its data may be used to investigate this interface.

2. Review of literature relating to tyre / asphalt interface measurement

Most studies of the tyre road / runway surface interface have tended to consider three main areas (i) tyre / surface contact patch parameters (ii) variation of contact stress in the x, y and z directions and (iii) computer modelling of interface conditions.

Figure 1 is taken from the 1930

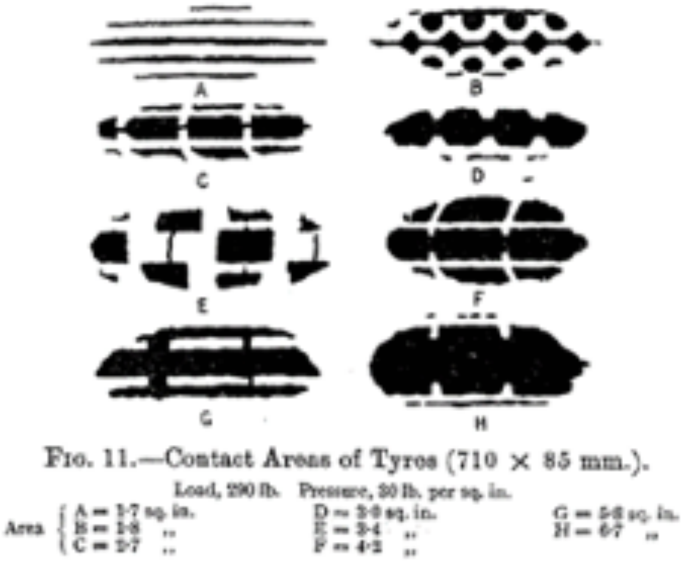


Figure 1. Contact areas of tyres taken from the 1930 Bradley and Allen skidding resistance study

investigation by Bradley and Allen (1930) and shows the contact patch for the tyres evaluated in their study. Ink was applied to the test tyres and pressed against card. The prints illustrate how each tyre interfaced with a smooth surface. This method is still used today. The American ASTM method (ASTM F870-94, 2010) uses ink applied to the tyre which is then loaded against card in the z-axis to create an impression. This allows parameters such as gross contact area, groove or void area, contact length and contact width to be assessed for the tyre / card contact patch.

Studies by Lister and Nunn (1968), Liu (1992), and Siegfried (1998) have used ink or paint impressions to show that the contact patch has a circular shape at higher tyre inflation pressures and lower load. It becomes elliptical at lower tyre inflation pressure and higher load conditions. Contact length tends to increase with load or decreasing inflation pressure with contact width remaining relatively constant. These general relationships apply for most tyres. Although ink impressions can provide useful information, they involve just the tyre interfacing a smooth surface. The ink impression does not quantify values of stress or how it varies within the contact patch for either a smooth surface or the textured surface of road or runway surfacing materials.

The limitations with ink led to research that attempted to quantify variation and distribution of contact stresses generated within the tyre / surface interface. The contact stresses have three main components i.e. vertical contact stress (z) which acts in the normal direction to the running surface of the contact tyre, longitudinal tangential contact stress (x) which acts in the direction of the moving tyre, and transversal tangential contact stress (y) which acts from the centre of the tyre to both its sides within its given contact area. The vertical or z axis tends to be dominate the other 2 components.

Douglas (2009) reviewed tyre / surface contact stress measurement research. This identified three main systems based on strain gauge technologies. The first was the Stress-In-Motion (SIM) system developed in South Africa. This system was used in many studies including de Beer (1997a), de Beer et al (1997b), Weissman (1999), Machemehl et al (2005), Prozzi and Luo (2005) Wang and Machemehl (2006) and de Beer (2008). A second system was developed in Northern Ireland and used in studies by Liu (1992), Siegfried (1998), Woodside et al (1999), Douglas et al (2000, 2003). A third system was developed in New Zealand based on the Irish system and experiences from use of the de Beer SIM system (Douglas, 2009).

The common feature with these three systems was they were designed to investigate truck tyres and to a lesser extent car tyres. The interface was a tyre interacting with instrumented metal pins. In practise, the three systems were demanding to set-up, calibrate and run. Testing was either static or at walking pace. The data files from individual strain gauge had to be post-processed to determine measured strain. The spatial resolution of the data was dependant on the instrumented metal pin spacing. The data related by these systems related to how the tyre and its tread elements interfaced with instrumented metal pins and not actual textured road or runway surfacing materials. Whilst the three systems generated important data relating to trucks they were all fundamentally limited in relation to other interface conditions.

This limitation prompted the need for an alternative approach. The potential of using pressure mapping was identified, as it combined the established principals of ink impression and data related to measured strains. Two main types of pressure mapping were being reported in the literature 10 years ago. The first was the use of pressure sensitive film in studies such as those by Backx (2007), Dunford (2013) and Hamlet et al (2015). Although pressure sensitive film gives detailed information, the images require post-processing to produce useable data. The second type was pressure sensitive sensors subsequently reported in studies by Conville (2010), Friel (2013) and Woodward et. al. (2016). Unlike pressure sensitive film that can only be used a single time, pressure sensitive sensor mapping systems can capture and process data in real-time. Pressure mapping offered measurement of contact parameters such as length, width, area and the distribution and variation phenomena in the z-axis component.

State-of-the-art reviews such as Van der Steen (2007) and Kogbara et. al. (2016) considered tyre-road friction modelling and the many parameters influencing measurement and modelling of skid resistance of asphalt pavements respectively. Studies by Kosgolla (2012, Wang et al (2012), Zhang et al (2013), Srirangam et al (2014) and Srirangam et al (2015) considered different aspects of the interface using computer based modelling. These examples highlighted the need for laboratory derived data that relates to real world interface conditions. Data which can be used as computer model inputs and/ or to confirm modelling predictions and data that can be easily measured in real-time without the need for time-consuming post-processing. This need for data is the knowledge gap addressed in this paper.

3. Development of the UFTSI method

The basic aim was for something simple that could produce meaningful data. The resulting UTRSI method consists of four main elements (i) an ASTM friction tyre (ii) a z-axis pressure mapping system (iii) a device to allow measurement of static or dynamic interface properties and (iv) a device to simulate accelerated trafficking of test specimens.

3.1 ASTM friction tyre

The tyre chosen for this laboratory method is the 254 mm (10 inch) diameter ASTM E1844 (2008) smooth surfaced, pneumatic ASTM friction tyre. This tyre is fitted to the GripTester longitudinal friction device (BS 7941-2 2000). This friction device is used in many countries around the world. The GripTester is a 3-wheel towed trailer that measures skid resistance by simulating the interaction of a fixed slip tyre with a road or runway surface in a longitudinal direction. Better understanding of how this tyre, and the tyres fitted to other friction measurement tyres, interface with the road or runway surface they are assessing is now of significant interest to researchers around the world. Although used for friction testing, the ASTM tyre offered a standard tyre that could be used in other texture/tyre interface studies such a noise and rolling resistance.

3.2 Z-axis pressure mapping system

The interface conditions between the ASTM friction tyre (smooth surface, no tread pattern) and the asphalt surface is quantified using z-axis pressure mapping. Two mapping systems have been used depending on what aspect of the interface is being assessed (XSensor 2020). The first system has 1.15 x 1.15 mm resolution and 65,536 sensing elements mounted on a rigid plexiglass backing. This high resolution rigid system is used for tyre interface measurement only. The second system consists of a flexible mat with 2.54 x 2.54 mm resolution and 16,384 sensing elements. This flexible lower resolution system is used for both tyre interface measurement and tyre/asphalt surface interface measurement, where it can drape over the surface and under the ASTM tyre.

Figure 2 shows an example of pressure pad data for the same treaded tyre at 4 No. inflation pressures. The 4 No. examples are shown to the same scales. This comparison shows contact length to vary more than width. Compared to ink patch testing, variation in vertical z-axis loading is visual going from blue to red with increasing value. The 4 No. patches illustrate how pressure is concentrated under the tyre sidewalls at low inflation pressures and with increasing inflation pressure the contact patch area decreases in size resulting in greater z-axis values being recorded. Similar data could be easily achieved by varying the load instead of inflation pressure.

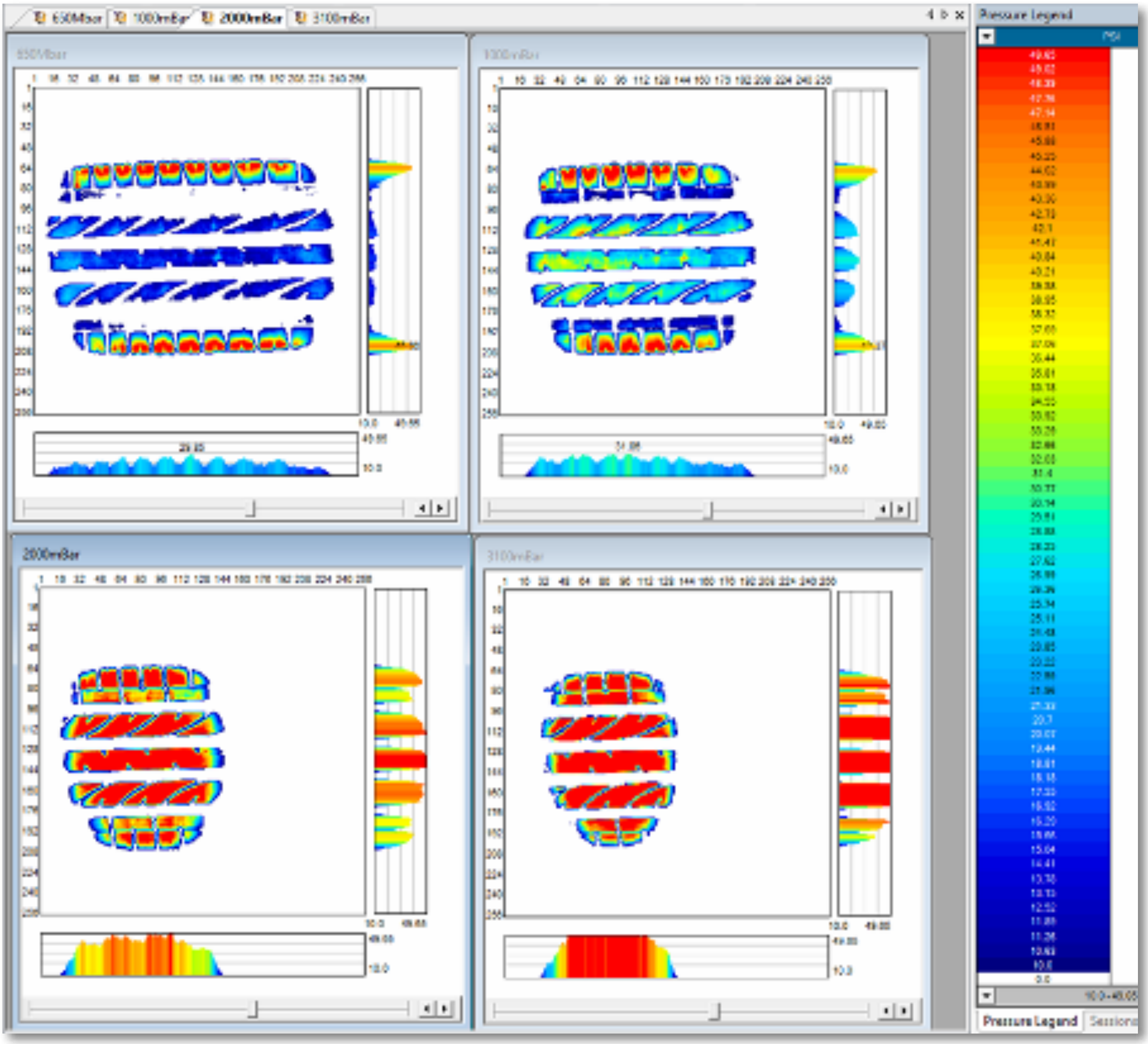


Figure 2. Pressure mapping data for the same tyre at 4 No. inflation pressures.

Both the rigid and flexible pressure mapping systems comprise two grids with parallel conductive strips separated by a thin compressible elastomer. A capacitive node, is formed where two conductive strips intersect. If pressure is applied to a node the elastomer will compress and the conductive strips will be forced closer together causing capacitance at the node to increase. The change in capacitance relates to pressure distribution through a process of calibration. The system is sequenced through each line on the input and output sides of the sensor matrix with the use of multiplexing circuitry which allows for the measurement of the capacitance and thus, the pressure distribution of the whole sensor matrix (XSensor 2020). Proprietary software records and displays real time data from the pressure mapping system. Data is recorded in frames, whereby one cycle of the sensor reading is carried out for every capacitive node in the sensor matrix. The frame rate of the sensor system depends on the sensor pad resolution and size.

When data recording is complete, it can be displayed as individual 2D or 3D frames or as a continuous composite model if the test surface is moved underneath the test tyre during data capture. Pressure data may be exported in comma separated value (csv) format for further analysis or as modelling inputs. Both pressure mapping systems used have a calibrated pressure range of 68.9 to 1378 kPa (10 psi to 200 psi) with a data acquisition rate of up to 16 frames per second during dynamic testing when a test specimen can be moved under the test tyre.

3.3 Device to allow measurement of static or dynamic interface properties

A small wheel tracking device was modified to accommodate the 254 mm (10 inch) diameter ASTM friction measuring tyre. This wheel tracking device has been used to determine resistance to permanent deformation of asphalt materials and is based on the principle of a test specimen moving in a controlled dynamic mode under a loaded tyre. (EN 12697-22 2003, small device). Load on the tyre can be varied using weights attached to the end of a lever arm. The pressure mapping systems are placed under the tyre. The rigid system is used for tyre interface measurements. The flexible system is draped across the textured test specimen surface. This allows static measurements or dynamic measurements when the test specimen is moved under the tyre. The dynamic contact speed is comparable to the de Beer SIM device used for truck and car tyre investigations. **Figure 3** shows the flexible pressure pad draping across the surface of a test specimen located in the modified small wheel tracker fitted with ASTM friction tyre. The computer screen shows real time interface data being recorded.

3.4 Device to subject test specimens to simulated trafficking

The interface conditions of newly compacted asphalt or concrete materials are influenced by coatings on aggregate particles that would be in contact with a tyre. In real-life, early life trafficking starts to remove these coatings. With continued trafficking the exposed aggregate particles begin to polish, wear and ultimately the asphalt may be susceptible to particle loss. Therefore, an important element of the UFTSI method was the need to subject test specimens to accelerated trafficking. This would better simulate what happens in real-life as new surfacing materials are trafficked and their interface conditions evolve until reaching equilibrium.

This was achieved by subjecting test specimens to simulated trafficking under controlled laboratory conditions using the Road Test Machine (RTM) in accordance with Appendix H of TRL 176 (Nicholls, 1997). The RTM has a 2.1 m diameter horizontal table that rotates at 10 rpm. Test temperature is maintained at 10 ºC + / - 2 ºC to avoid permanent surface deformation of the test specimen during trafficking. A maximum of ten test specimens can be fixed to the table and subjected to slow speed high stress simulated trafficking using two vertically mounted 195/70R14 tyres each applying a load of approximately 5 kN. Nicholls (1997) estimated that 100,000 wheel passes is equivalent to 5 to 8 years of trafficking.

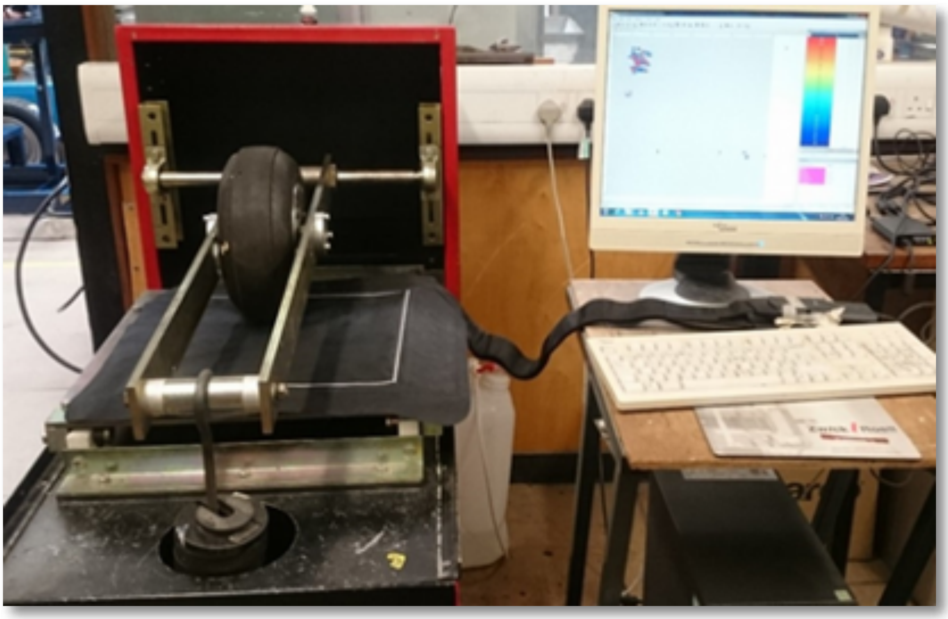


Figure 3. Flexible pressure pad resting on a test specimen located in the modified small wheel tracker fitted with ASTM friction tyre.

Test specimens can be 305 mm x 305 mm x 50 mm roller compacted slabs, 150 mm diameter cylinders prepared using gyratory compaction or cores extracted from a road or runway. This adaptability allows different aggregate/bitumen/compaction/mixture combinations to be quickly assessed without the need for full-scale road trials. Simulated trafficking is stopped periodically to measure parameters such as macrotexture and wet skid resistance. Photographs can be taken for 3d photogrammetry modelling for determination of areal parameters. This flexibility allows change in a wide range of contact patch areal parameters to be compared with pressure mapping derived interface data.

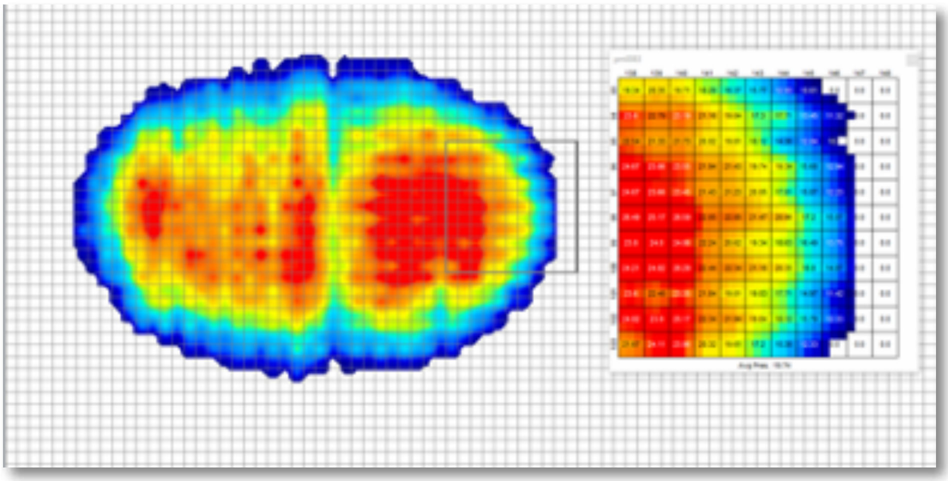
4. Use of the UTRSI method to investigate the friction tyre/surface interface

The UTRSI method facilitates different types of interface investigation. The remainder of this paper uses examples to illustrate its flexibility. They illustrate how its laboratory derived data can be related to real in-service conditions. The examples considered are:

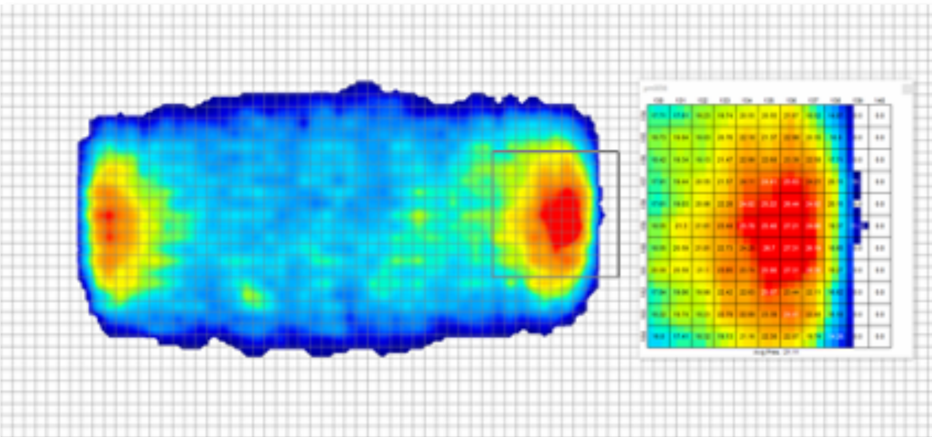
- **The ASTM friction tyre interface.**
- **Merging frames to create a composite contact patch image.**
- **The friction tyre/asphalt test specimen interface.**
- **Comparison of asphalt material contact patch areas.**
- **Comparison of different types of surface dependant data.**
- **Evaluating an idealised runway grooved surface.**
- **Evaluating coarse aggregate nominal size.**

4.1 The ASTM friction tyre interface

The first example illustrates basic interface data for the ASTM 1844 friction tyre using a high resolution pressure pad with individual measurement cell resolution of 1.15 x 1.15 mm. **Figure 4a** shows the contact patch 2D image measured at the standard tyre inflation pressure of 137.9 kPa (20 psi) for a new tyre. **Figure 4b** shows the contact patch 2D image for a badly worn tyre measured at 137.9 kPa (20 psi) inflation pressure. The legend scale in both images' ranges from 68.9 to 172 kPa (10 to 25 psi). Both images show a selected portion of individual cell pressure measurements that can be exported for further analysis. The images are visually quite different illustrating how the tyre interfacing the surface being measured will change as the tyre wears. Contact area remains similar for both tyres. The distribution of load changes from roughly circular and central to being concentrated under the sidewalls.



(4.a. New ASTM friction tyre)



(4.b. Worn ASTM friction tyre)

Figure 4. Comparison of z-axis contact pressure variation for new (4.a) and worn (4.b) ASTM friction tyres at 137.9 kPa (20 psi) inflation pressure (high resolution pressure pad with individual cell size 1.15 x 1.15 mm).

The two static contact patches were measured in real time and did not require post-processing. Therefore, it is possible to quickly investigate different scenarios related to their tyre foot-print. For example, the effect of tyre inflation pressure on contact patch dimensions. The relationships between tyre inflation pressure with contact width, contact length and contact area for a new tyre are shown in **Figure 5**. This illustrates how tyre inflation pressure influences contact length and contact area, with contact width remaining relatively constant. These simple contact patch relationships agree with the ink based studies reported by Lister and Nunn (1968), Liu (1992), and Siegfried (1998). However, unlike these earlier ink studies, the testing shown in **Figure 5** took approximately one hour to complete, with all its data at a cell resolution of 1.15 x 1.15 mm exportable for further analysis.

Under controlled laboratory test conditions i.e. similar mass on the ASTM friction tyre, inflation pressure and number of merged individual frames; it is possible to compare interface properties at similar time periods of simulated trafficking for different types of road or runway surfacing material. As the test specimens are subjected to simulated trafficking, change in interface conditions such as contact area or pressure distribution can be evaluated.

4.2 Merging frames to create a composite contact patch.

The contact patch for a static ASTM friction tyre resting on a smooth surface is quite small compared to a car or truck tyre. In real-life, the ASTM friction tyre will interface with different types of macrotexture associated with different types of asphalt or concrete surfacing materials. The amount of actual contact within the contact patch can be much smaller. A function of the proprietary pressure pad software is to merge individual contact patch frames recorded during dynamic testing to form a single composite image.

This gives the opportunity to increase the length of the contact patch and obtain more representative interface data. **Figure 6** illustrates how individual contact patch frames can be merged to create a larger composite contact patch under dynamic test conditions, which is more representative of a test specimen surface. **Figure 6** a shows 7 No. individual frames representing 7 No. locations along the tracked length of a smooth glass plate test specimen. **Figure 6 b** shows the single composite image formed by merging 50 of these individual frames.

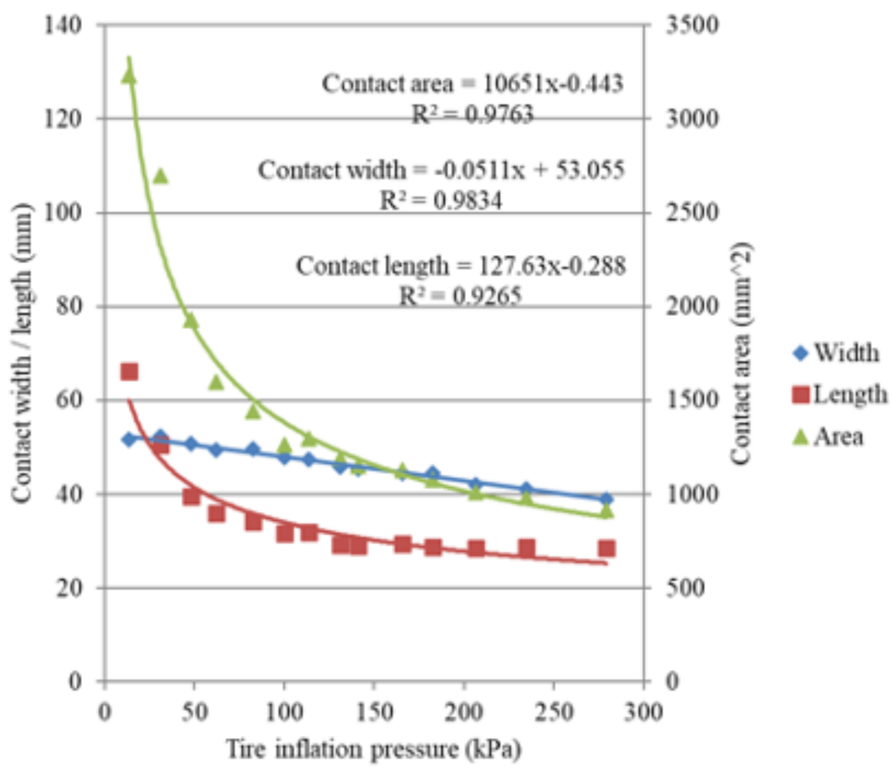
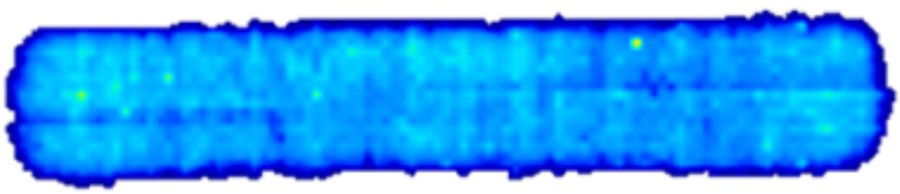


Figure 5. Tyre inflation pressure v. contact width, contact length and contact area for a new ASTM friction tyre.

(6.a. Image capture of individual frames)



(6.b. Composite contact patch made by merging 50 frames)

Figure 6. Images captured from the pressure mapping system software showing how individual frames (6 a) can be merged to make a composite contact patch (6 b).

4.3 The friction tyre / asphalt test specimen interface.

The merged composite frame technique can be used to investigate how the ASTM friction tyre interfaces with the textured surface of an asphalt surfacing material. **Figure 7** illustrates a composite merged image for a 10 mm Stone Mastic Asphalt (SMA10) made in accordance with EN 13108-5 (2008). The image illustrates the actual tyre interface between the ASTM friction tyre and the surface of the SMA 10 test specimen.

The SMA10 test specimen had been prepared in the laboratory as a 305 x 305 x 50 mm roller compacted slab. It had been subjected to 10,000 passes of simulated trafficking in the RTM to initially wear off interface bitumen, expose the underlying aggregate skeleton and cause some wear of the asphalt mixture. The ASTM friction tyre inflation pressure is 137.9 kPa, mass on the tyre 25kg with 50 individual frames merged to form a composite image.

The use of colour thresholding shows the variation and distribution of z-axis contact pressure variation. In this example the z-axis contact pressure legend ranges from 68.9 to 344.7 kPa (10 to 50 psi). The use of colour thresholding shows how z-axis contact pressure varies in relation to how and where the ASTM friction tyre is interfacing with the 10 mm SMA surface texture. Pressure data for individual cells is also shown in the image. With an individual cell size of 2.54 x 2.54 mm, interface data at this resolution was not possible using the instrumented strain gauge based methods of investigation. The individual cell data can be exported to MS-Excel or similar for further analysis.

4.4 Comparison of asphalt material contact areas.

Under controlled laboratory test conditions i.e. similar mass on the ASTM friction tyre, inflation pressure and number of merged individual frames, it is possible to compare interface properties at similar time periods of simulated trafficking for different types of road or runway surfacing material. As the test specimens are subjected to simulated trafficking, change in interface conditions such as contact area or pressure distribution can be evaluated.

Figure 8 compares the merged contact area for 4 No. different asphalt materials expressed as a percentage of the merged contact area for a smooth glass plate. The measured contact area for the glass plate is assumed to be 100 % representing full contact. The measured contact areas for each of the asphalt materials is expressed as a percentage of this value for the glass plate.

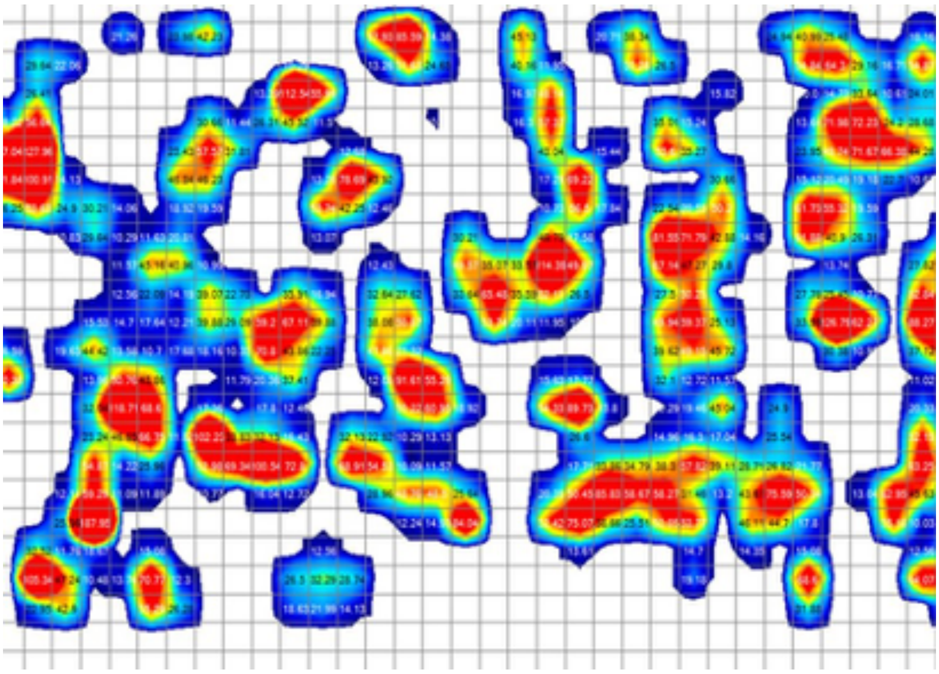


Figure 7. Composite image showing contact area and z-axis pressure distribution for SMA10 (flexible pressure pad with individual cell size of 2.54 x 2.54 mm).

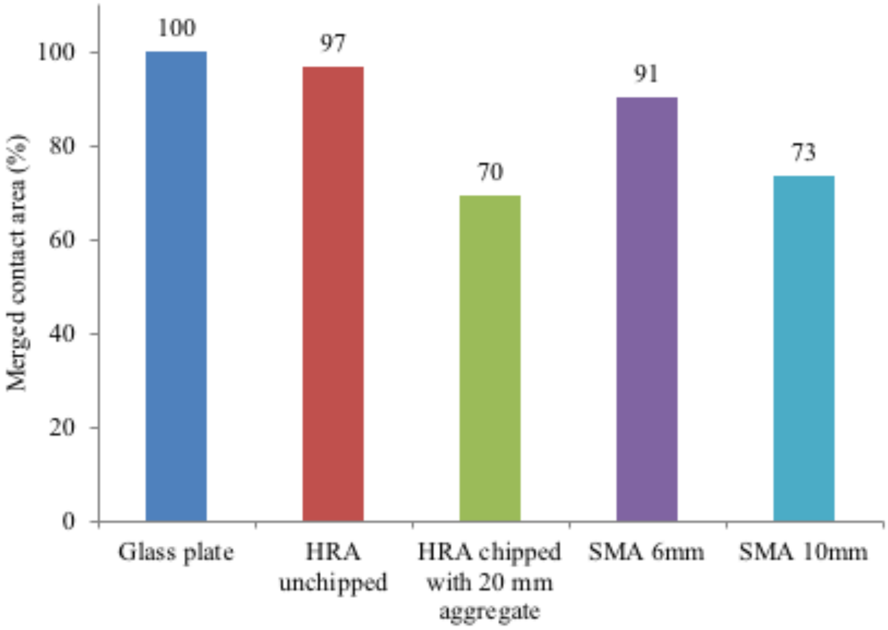


Figure 8. Variation of proportion of merged contact area for different asphalt mixes compared to a glass plate with 100 % contact area (HRA - Hot Rolled Asphalt, SMA – Stone Mastic Asphalt).

In this example the data comes from 305 mm x 305 mm x 50 mm test specimens made with the same aggregate source.

The 4 No. types of asphalt material are unchipped and chipped hot rolled asphalt (EN 13108-4, 2006), 10 mm and 6 mm stone mastic asphalt (EN 13108-5, 2008). This example is from a study that considered why different values of skid resistance were found for different road materials made with the same aggregate (Friel, 2013). The test specimens in this example have been subjected to 10,000 wheel passes of simulated trafficking using the RTM.

The greatest percentage of contact area was found for the unchipped hot rolled asphalt. This was a very low textured material consisting of approximately 35 % coarse aggregate with the remainder being a mortar of sand, filler and bitumen. It had almost no macrotexture and is not used as a surfacing material for major roads. 20 mm chippings must be rolled into its surface during compaction to create macrotexture. By creating a macrotexture, contact area with the ASTM friction tyre was found to reduce from 97 to 70 % contact for this laboratory prepared HRA. The SMA mixes had 91 % contact for the 6 mm nominal size and 73 % contact for the 10 mm nominal size.

This example illustrates that the nominal size of the coarse aggregate in contact with the ASTM friction tyre for the three textured asphalt mixes influenced contact area i.e. as nominal particle size increases contact area tends to decrease. This effect may offer partial explanation why measured road surface skid resistance changes for different types of surfacing material made with the same aggregate.

4.5 Relating texture to contact patch, friction and macrotexture.

The texture scales of a road surface influence its properties and what it offers to the tyre interface. Figure 8 illustrates how merged composite contact area for roller compacted slabs can be compared with macrotexture measured using the volumetric patch technique (EN 13036-1, 2010) and wet skid resistance measured using the Pendulum Test (EN 13036-4, 2011). **Figure 9** shows an increase in percentage merged contact area to correlate with an increase in wet skid resistance and a decrease in texture depth for these laboratory trafficked test specimens. This dataset relates to measurements taken from 305 mm x 305 mm x 50 mm asphalt test specimens that had been made with the same PSV aggregate and subjected to 100,000 wheel passes of simulated trafficking using the RTM. This laboratory investigation took 2 weeks during which the test specimens were subjected to approximately 5 to 8 years of simulated in-service trafficking.

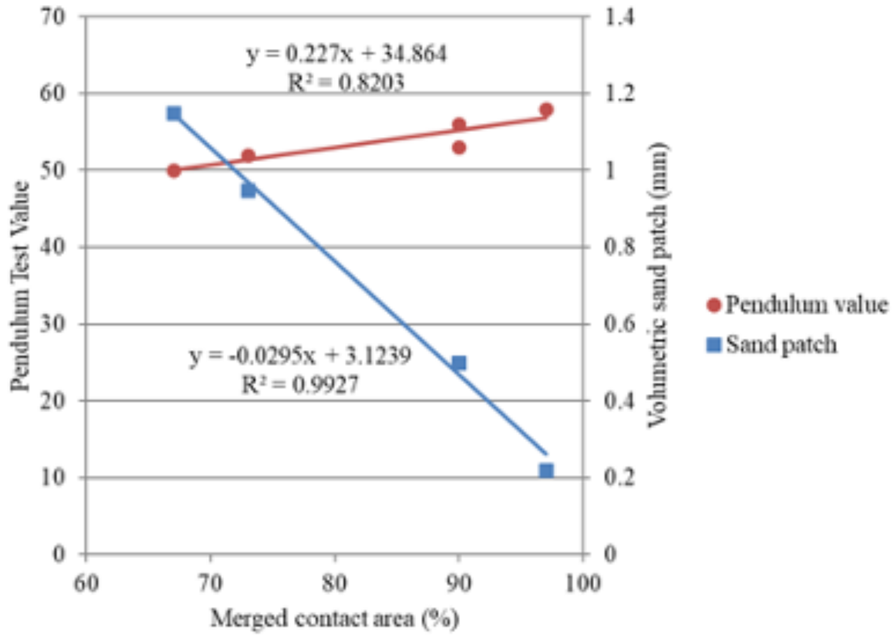


Figure 9. Relationships between merged contact area, pendulum test value and volumetric sand patch after 100 000 wheel passes of simulated trafficking.

4.7 Evaluating coarse aggregate nominal size

The SMA10 example in **Figure 7** illustrates the complexity of its surface interface with what may be regarded as a simple smooth tyre. **Figure 8** compared the contact areas for different textured asphalt materials. To simplify the relationships between nominal particle size, contact area, variation and distribution of z-axis stress, **Figures 11** and 12 compare two idealised road surfaces where the coarse aggregate has been simulated by a tile surface of standard dimension.

In **Figure 11** the tiles are 22.5 mm x 22.5 mm in size with a 2.5 mm spacing between adjacent tiles. In **Figure 12** the tiles are 10.5 x 10.5 mm in size with a 2 mm spacing between adjacent tiles. The 22.5 x 22.5 mm tiles have a flat surface and slightly rounded top edges. The 10.5 x 10.5 mm tiles have a slight convex surface and rounded top edges. Each idealised surface was covered with the flexible pressure pad and the ASTM friction tyre pushed slowly over its surface. Approximately 50 individual frames have been merged to form the composite images. In each figure the grid spacing is 2.54 x 2.54 mm. Pressure thresholding is the same for

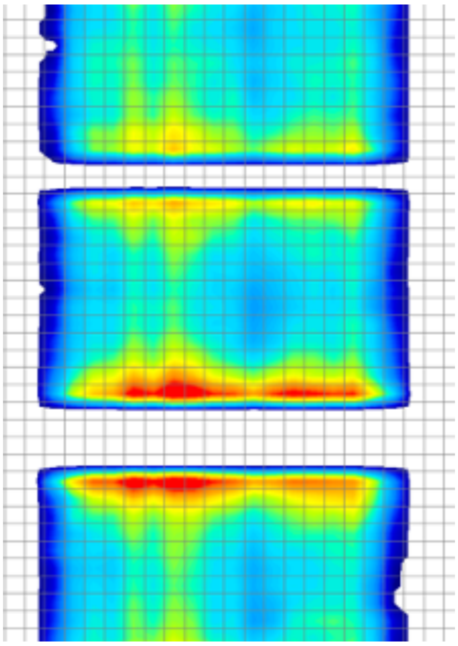


Figure 10. Difference in z-axis data due to simulated groove width (flexible pressure pad with individual cell size of 2.54 x 2.54 mm).

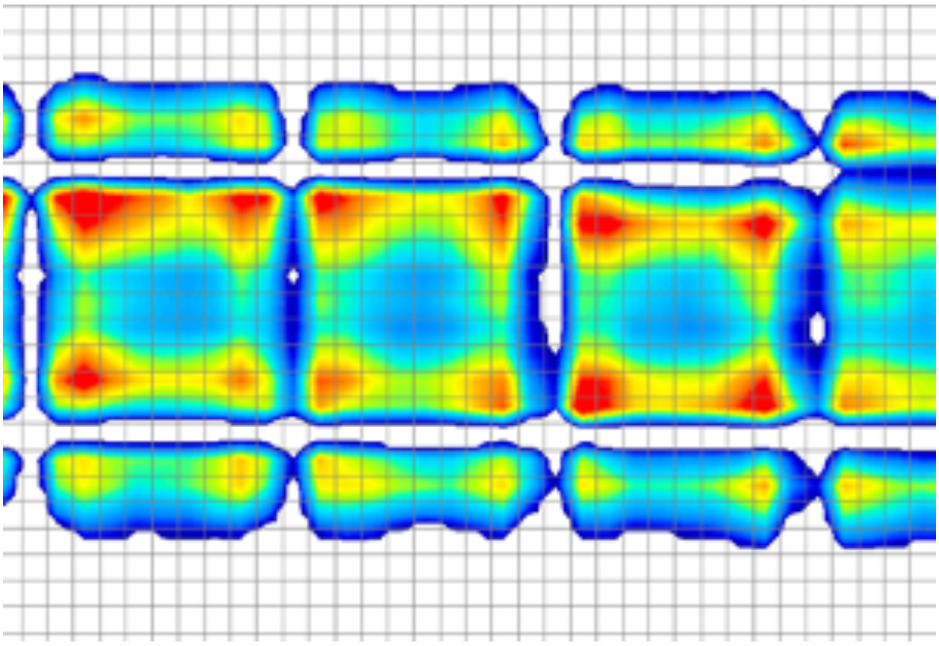


Figure 11. Variation in z-axis contact for idealised coarse aggregate particles 22.5 mm x 22.5 mm in size with 2.5 mm spacings (flexible pressure pad with individual cell size of 2.54 x 2.54 mm).

4.6 Evaluating an idealised grooved runway surface

Compared to the real tyre/surface interface, the use of idealised surfaces makes it easier to understand what might be happening at the interface. Figure 10 illustrates the effect of groove width for an idealised grooved runway surfacing. The test surface was a steel plate with a 5 mm and a 10 mm wide groove cut into the surface. The grooved steel plate was covered with the flexible pressure pad and the ASTM friction tyre pushed slowly over its surface. The merged composite image shown in **Figure 10** illustrates how the ASTM friction tyre behaves differently when traversing the wider groove. The measured contact data is greater and concentrated along the edges of the wider groove. Cell data from the pressure pad can be exported into Excel for analysis or act as modelling inputs.

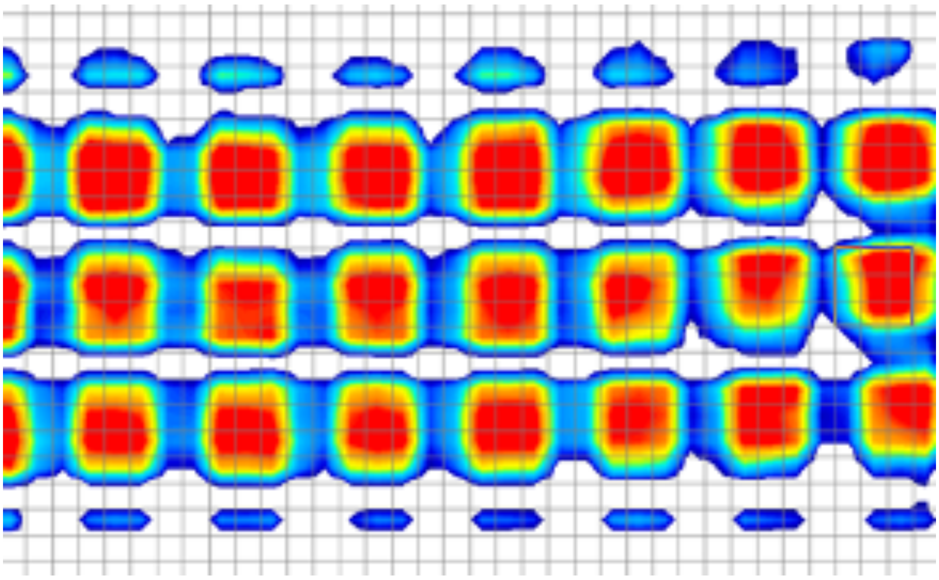


Figure 12. Variation in z-axis contact for idealised coarse aggregate particles 10.5 mm x 10.5 mm in size with 2 mm spacings (flexible pressure pad with individual cell size of 2.54 x 2.54 mm).

both images covering the range 68.9 to 413.6 kPa (10 to 60 psi). Comparison of the two images shows considerable interface variation for the same test conditions. Contact pressure is concentrated at the corners of the larger 22.5 x 22.5 mm tiles compared to their centres. The slightly convex surface of the 10.5 x 10.5 mm tiles is taking most of the vertical loading over a much smaller contact area. These images may help explain why 20 mm chippings rolled into HRA tend to wear away at their corners eventually becoming more rounded. The higher skid resistance values that tend to be measured for SMA10 may be explained by their greater contact stresses.

5. Conclusions

This paper has considered development of a method to investigate the interface between a standard tyre (ASTM friction tyre) and road/runway surfacing materials. The original aim of developing the UTRSI method was to produce data that could be related to measured properties related to skid resistance, noise and rolling resistance. The examples given in this paper mark stages along this development process as the method was used in different investigations. The simple examples illustrate its versatility to produce data. The data shows agreement with previous research such as the ink impression studies highlighted in the literature review. The examples illustrate relationships between inflation pressure and contact area parameters. They illustrate that it is possible to investigate the complex distributions of z-axis interface pressure within the contact patch of real and idealised surfaces as they evolve over the life of a road. As with any test method, there are limitations with the UTRSI method i.e. it only measures the vertical z-axis contact stress at slow speeds. But in terms of impact, rigour and significance, this simple cheap method using existing equipment offers scope for continued understanding and modelling of tyre/surface interface phenomena.

6. References

ASTM F870-94, 2010. Standard practise for tread footprints of passenger car tyres groove area fraction and dimensional measurements.

ASTM E1844-08, 2008. Standard Specification for a Size 10 x 4–5 Smooth-Tread Friction Test Tyre.

Backx, P.W., 2007. Tyre/road contact measurement using pressure sensitive films. Thesis (Bachelor). Technische Universiteit, Eindhoven.

Bradley, J. and Allen, R. F. 1930. Factors Affecting the Behaviour of Rubber-Tyred Wheels on Road Surfaces. 1930-31 Proc. Institute of Automobile Engineering, Vol.25, p. 63.

Conville, S., 2010. The measurement of contact phenomena under a GripTester tyre. Thesis (MSc), University of Ulster.

De Beer, M. and Fisher C., 1997a. Contact stresses of pneumatic tyres measured with the Vehicle-Road Surface Pressure Transducer Array (VRSPTA) system for the University of California at Berkeley (UCB) and the Nevada Automotive Test Center (NATC) Volume 1. Contract Research CR-97/053, TRANSPORTEK, CSIR.

De Beer, M., Fisher, C., Jooste, F. J., 1997b. Determination of pneumatic tyre/pavement interface contact stresses under moving loads and some effects on pavements with thin asphalt surfacing layers. Proceedings of the 8th International Conference on Asphalt Pavements (ICAP '97), Seattle, Washington, August 10-14.

De Beer, M., 2008. Stress-In-Motion (SIM) - A new tool for road infrastructure protection? Proceedings of the International Conference on Heavy Vehicles (HV Paris 2008 - ICWIM5), WIM Session 7, Paris/Marne-la-Vallée, France, May 19-22.

Douglas, R.A., Woodward W.D.H. and Woodside, A.R., 2000. Road contact stresses and forces under tyres with low inflation pressure. Canadian Journal of Civil Engineering, 27:1248–1258.

Douglas R.A., Woodward W.D.H. and Rogers R.J., 2003. Contact pressures and energies beneath soft tyres: modelling effects of central tyre inflation-equipped heavy-truck traffic on road surfaces. Transportation Research Record 1819, Washington, DC: Transportation Research Board, 221–227.

Douglas, R.A., 2009. Tyre/road contact stresses measured and modelled in three coordinate directions. NZ Transport Agency Research Report 384, Golder Associates Ltd, Mississauga, Ontario, Canada.

Dunford, A., 2013. Friction and the texture of aggregate particles used in the road surface course. Thesis (PhD), University of Nottingham.

BS 7941-2, 2000. Surface friction of pavements – Part 2: Test method for measurement of surface skid resistance using the GripTester braked wheel fixed slip device.

EN 12697-22, 2003. Bituminous mixtures – Test methods for hot mix asphalt – Part 22 : Wheel tracking.

EN 13036-1, 2010. Road and airfield surface characteristics – Test methods – Part 1 : Measurement of pavement surface macrotexture depth using a volumetric patch technique.

EN 13036-4, 2011. Road and airfield surface characteristics – Test methods – Part : 4: Method of measurement of slip / skid resistance of a surface: The pendulum test.

EN 13108-4, 2006. Bituminous mixtures – Material specifications – Part 4: Hot Rolled Asphalt.

EN 13108-5, 2008. Bituminous mixtures – Material specifications – Part 5: Stone Mastic Asphalt.

Friel, S., 2103. Variation of the friction characteristics of road surfacing materials with time. PhD Thesis, University of Ulster.

Hamlet, S., Hammoum, F. and Kerzreho, J.P. 2015. Evaluation of the distribution of local pressures and the real contact area between the tyre and the road surface. International Journal of Pavement Engineering, Vol. 16, Nos 9-10, 832-841.

Kogbara, R.B., Masad, E.A., Kassem, E., Scarpas, T. and Anupam, K. 2016. A state-of-the-art review of parameters influencing measurement and modelling of skid resistance of asphalt pavements. Construction and Building Materials Volume 114, Pages 602-617. http://dx.doi.org/10.1016/j.conbuildmat.2016.04.002

Kosgolla, J.V., 2012. Numerical simulation of sliding friction and wet traction force for a smooth tyre sliding on a random rough pavement. PhD thesis, University of South Florida.

Lister, N.W. and Nunn D.E., 1968. Contact Areas of Commercial Vehicle Tyres. Transport and Road Research Laboratory, RRL Report LR 172.

Liu, G.X., 1992. The area and stresses of contact between tyres and road surface and their effects on road surface. Thesis (DPhil) University of Ulster.

Machemehl, R.B., Wang F. and Prozzi J.A., 2005. Analytical study of effects of truck tyre pressure on pavement with measured tyre-pavement contact stress data. Transportation Research Record 1919. Washington DC: Transportation Research Board, 111–120.

Nicholls J.C., 1997. Laboratory tests on high-friction surfaces for highways, TRL Report 176.

Prozzi, J.A. and Luo, R., 2005. Quantification of the joint effect of wheel load and tyre inflation pressure on pavement response. Transportation Research Record 1919. Washington DC: Transportation Research Board, 134–141.

Srirangam, S. K., Anupam, K., Kasbergen, C., and Scarpas, A., 2014. Development of a Thermomechanical Tyre-Pavement Interaction Model, International Journal of Pavement Engineering, DOI: 10.1080/10298436.2014.946927, Taylor & Francis.

Srirangam, S. K., Anupam, K., Kasbergen, C., Scarpas, A., Cerezo, V. 2015. Study of Influence of Operating Parameters on Braking Friction and Rolling Resistance. TRB 94th Annual Meeting.

Siegfried, 1998. The study of contact characteristics between tyre and road surface. Thesis (DPhil). University of Ulster.

Van der Steen, R. (2007) Tyre-Road Friction Modelling: Literature Survey. PhD Thesis, Eindhoven University of Technology.

Wang, F. and Machemehl, R.B., 2006. Mechanistic-empirical study of effects of truck tyre pressure on pavement: measured tyre-pavement contact stress data. Transportation Research Record 1947. Washington DC: Transportation Research Board. 136–145.

Wang, H., Al-Qadi, I., and Stanciulescu, I., 2012. Simulation of tyre–pavement interaction for predicting contact stresses at static and various rolling conditions. International Journal of Pavement Engineering, Volume 13, Issue 4, 310-321.

Weissman, S.L., 1999. Influence of tyre-pavement contact stress distribution on development of distress mechanisms in pavements. Transportation Research Record 1655. Washington DC: Transportation Research Board, 161–167.

Woodside, A.R., Woodward, W.D.H., and Siegfried, 1999. The determination of dynamic contact stress. Paper no. CS5-2, Proceedings of the International Conference on Accelerated Pavement Testing, Reno, Nevada, 18–20.

Woodward, D., Millar, P., Lantieri, C., Sangiorgi, C. and Vignali, V. 2016. The wear of Stone Mastic Asphalt due to slow speed high stress simulated laboratory trafficking. Construction and Building Materials Volume 110, Pages 270-277. http://dx.doi.org/10.1016/j.conbuildmat.2016.02.031.

Zhang, L., Ong, G., and Fwa, T., 2013. Developing an Analysis Framework to Quantify and Compare Skid Resistance Performance on Porous and Nonporous Pavements. Transportation Research Record: Journal of the Transportation Research Board, 10.3141/2369-09, 77-86.

XSENSOR Technology Corp, 2020. www.xsensor.com