Northumbria Research Link

Citation: Edmondson, Vikki, Woodward, John, Lim, Michael, Kane, Malal, Martin, James and Shyha, Islam (2019) Improved non-contact 3D field and processing techniques to achieve macrotexture characterisation of pavements. Construction and Building Materials, 227. p. 116693. ISSN 0950-0618

Published by: Elsevier

URL: https://doi.org/10.1016/j.conbuildmat.2019.116693 <https://doi.org/10.1016/j.conbuildmat.2019.116693>

This version was downloaded from Northumbria Research Link: http://nrl.northumbria.ac.uk/40452/

Northumbria University has developed Northumbria Research Link (NRL) to enable users to access the University's research output. Copyright © and moral rights for items on NRL are retained by the individual author(s) and/or other copyright owners. Single copies of full items can be reproduced, displayed or performed, and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided the authors, title and full bibliographic details are given, as well as a hyperlink and/or URL to the original metadata page. The content must not be changed in any way. Full items must not be sold commercially in any format or medium without formal permission of the copyright holder. The full policy is available online: http://nrl.northumbria.ac.uk/policies.html

This document may differ from the final, published version of the research and has been made available online in accordance with publisher policies. To read and/or cite from the published version of the research, please visit the publisher's website (a subscription may be required.)

CUSTOMER SERVICE EXCELLENCE CSE UniversityLibrary

Northumbria
University
NEWCASTLE

Improved non-contact 3D field and processing techniques to achieve macrotexture characterisation of pavements

Vikki Edmondson[a], John Woodward[a], Michael Lim[a], Malal Kane[b], James Martin[a], and Islam Shyha[a]

[a] Department of Mechanical and Construction Engineering,
Northumbria University
Ellison Place
Newcastle Upon Tyne
NE1 8ST
United Kingdom

[b] IFSTTAR-Nantes,
Institut Français des Sciences et Technologiques des Transports, de l'Aménagement et des Réseaux
Allée des Ponts et Chaussées
Route de Bouaye - CS4
44344 Bouguenais Cedex, France

Authors Email Addresses:
vikki.edmondson@northumbria.ac.uk
john.woodward@northumbria.ac.uk
michael.lim@northumbria.ac.uk
malal.kane@ifsttar.fr
James.e.martin@northumbria.ac.uk
islam.shyha@northumbria.ac.uk

Full contact details of corresponding author:
Vikki Edmondson
Northumbria University
Ellison Place
Newcastle Upon Tyne
NE1 8ST
United Kingdom
Tel 0191 349 5930
Email: vikki.edmondson@northumbria.ac.uk

Abstract

Macrotexture is required on pavements to provide skid resistance for vehicle safety in wet conditions. Increasingly, correlations between macrotexture measurements captured using non-contact techniques and tyre-pavement contact friction are being investigated in order to enable more robust and widescale measurement and monitoring of skid resistance. There is a notable scarcity of research into the respective accuracy of the non-contact measurement techniques at these scales. This paper compares three techniques: a laser profile scanner, Structure from Motion photogrammetry and Terrestrial Laser Scanning (TLS). We use spectral analysis, areal surface texture parameters and 2D cross-correlation analysis to evaluate the suitability of each approach for characterising and monitoring pavement macrotexture. The results show that SfM can produce successful measures of the areal root mean square height (*Sq*), which represents pavement texture depth and is positively correlated with skid resistance. Significant noise in the TLS data prevented agreement with the laser profiler but we show that new filtering procedures result in significantly improved values for the peak density (*Spd*) and the arithmetic peak mean curvature (*Spc*), which together define the shape and distribution of pavement aggregates forming macrotexture.

However, filtering the TLS data results in a trade-off with vertical accuracy, thus altering the reliability of *Sq*. Finally, we show the functional areal parameters *Spd* and *Spc* are sensitive to sample size. This means that pavement specimen size of 150 mm x 150 mm or smaller, when used in laboratory or field observations, are inadequate to capture the true value of areal surface texture parameters. The deployment of wider scale approaches such as SfM and spectrally filtered TLS are required in order to successfully capture the functional areal parameters (*Spc* and *Spd*) for road surfaces.

Keywords

Pavement texture; Macrotexture; Skid resistance; Structure from Motion (SfM); Terrestrial Laser Scanning (TLS)

---

1. Introduction

Adequate texture on the surface of a pavement is required to provide skid resistance or friction at the tyre/road interface for vehicle safety in wet conditions [1,2,3,4]. Skid resistance is also influenced by temperature, presence of contaminants, speed and tyre tread thickness [5]. Friction forces generated from the contact of the tyre with texture are a consequence of the viscoelastic deformation of the tyre, and increase in dry conditions with adhesion [6]. Pavement texture is defined as the deviation of the pavement surface from a true planar surface [7] and has been characterised at different scales according to the wavelengths of the deviations [8]. Microtexture suspected to induce adhesion, represents the texture components with wavelengths from less than 0.5mm and peak amplitude from 0.001 to 0.5mm. Microtexture correlates to the asperities upon the surface of coarse road aggregates [9], and also to the fine particles present in the mixture constituting the wearing course of the pavement. In wet conditions, adhesion is reduced by the phenomenon of viscoplaning [6], where a degree of tyre contact is lost with the pavement due to the presence of a thin water film (in the order of a tenth of a millimetre or less). Macrotexture, suspected to induce hysteresis response in the viscoelastic tyre, represents the texture components with wavelengths from 0.5 mm to 50 mm and amplitude of 0.1 mm to 20mm mm (formed by the shape, size and gradation of road aggregates on a pavement surface). Macrotexture acts also to disperse water, under wet conditions, through the gaps in between the road aggregates [10]. Thus, macrotexture, has been shown to influence the way skid resistance reduces with increasing speed in wet conditions [11]. Generally, with equal microtexture, pavement surfaces with higher macrotexture offer more friction resistance as speed increases than pavements with lower macrotexture under the same contact conditions [12, 13].

Thus, the preservation of adequate skid resistance requires the monitoring of macrotexture [1] to ensure sufficient texture remains on the pavement to prevent skidding. Standard monitoring techniques involve either a sand patch test [14] or a direct measurement of the frictional resistance through a rubber pad [15] or test wheel making contact with a wetted pavement [16,17]. Kogbara *et al.* [18] provide a full summary of devices and their operating principles. These contact devices are known to be susceptible to seasonal variation [19]. This phenomenon has been attributed to a number of factors: the sensitivity of rubber resilience to temperature change [20]; changes induced by temperature in the viscosity of the test water of a device [21]; and differential polishing of the aggregate microtexture throughout the year [22]. Survey results obtained from these devices require statistical interpretation [1,23,] with individual devices requiring harmonisation with the rest of a fleet [24]. Friction measurements from rubber contact base devices are also known to be susceptible to changes in travel speed [25]. Direct comparison between different devices adopted in particular countries is also difficult, as measurements are influenced by machine operating conditions such as the load, speed, slip ratio and the composition of the rubber.

The problems associated with contact measurement techniques, make a reliable non-contact technique desirable. Accurate non-contact macrotexture measurement is one step towards the estimation of pavement friction values via analytical modelling [5,26,27,28]. Researchers have successfully deployed contactless techniques under laboratory conditions to measure texture; typically to a size of 100 x 100 mm [29,30]. At present, there are also a number of in-situ proprietary spot contactless techniques available for use in the field, including the Circular Texture Meter [31], the Model 9300 laser texture scanner [32] and close-range stereo photogrammetry [33,34,35], which requires a minimum of three images taken from different perspectives to reconstruct a 3D pavement surface. These techniques offer an alternative to the simple sand patch test [14,36,37], where a measured volume of fine material is spread in a circular motion into a road’s surface depressions to find the mean texture depth, for in-situ localised pavement texture assessment. Recent research, focused on the development of a prototype test rig [38] adopting a laser range finder, that uses triangulation, to measure texture in the field or to detect defect on pavements [39], but is still restricted to a localised area comparable to that of a sand patch test. The minimum texture profile height measured by the rig was limited to 0.032 mm, with a spatial sampling frequency of about 4 mm^{-1}, thus meeting only part of the range needed for macrotexture. 3D handheld scanners [40, 41], using triangulation principles, have also been deployed to capture macrotexture in-situ [42]. These scanners are designed for metrology applications, and having a limited field of view, lack scalability. Advances in 'off-the-shelf' laser and photogrammetry technology and point cloud post-processing applications means there is now the potential to capture macrotexture over larger areas, potentially more representative areas using contactless techniques. Terrestrial Laser Scanning (TLS) offers rapid, full 3D high resolution reconstruction of a highway surface as a point cloud [43] and Structure from Motion (SfM) photogrammetry [44,45] offers a low-cost method utilising digital images to generate a 3D dense point cloud data of surfaces.

This paper introduces a method to characterise macrotexture using TLS and SfM over a typical full lane width. Recent research [34] suggests that frictional resistance is sensitive to certain areal parameters [46,47] (Table 1). Particularly, to the density of peaks within the macrotexture of a highway surface, *Spd*, and to the pointiness or arithmetic mean of the principal curvature of the same peaks *Spc*; which together characterise the shape and size of the road aggregates. Furthermore, the areal parameters root mean square of surface departures, S_q, as the standard deviation of peak height from an average plane, is spatially equivalent to mean profile depth [48]. Mean profile depth represents the averaged values over an overall 2D profile length, of the difference within a lateral distance (typically in the order of a tyre/pavement contact) between the profile and a horizontal line through the top of the highest peak. This paper explores the accuracy of the scalable TLS and SFM approaches to determining these measurements in comparison to measurements achieved using a 3D Smart Laser Profile Sensor [49]. The 3D Smart Laser Profile Sensor was selected as an accurate well-constrained controlled dataset of 2D profile macrotexture measurements from which to formulate a 3D surface, as such laser profile sensors are well-understood have been deployed widely previously to capture 2D profile measurements of macrotexture [50, 51, 52]. This paper will first introduce the methods applied to capture point cloud data in the field using the three techniques, before rigorously considering the accuracy of results obtained through the application of spectral analysis, areal parameters and 2D cross-correlation.

2. Methods

2.1. Remote sensing technology

2.1.1. Terrestrial Laser Scanning

The TLS data were collected using the Faro Focus 3D X Series phase-based laser scanner on a tripod mounted inverted as shown in Figure 1a. The static scanner was set-up at a height of 1 m above the pavement surface on a levelled tripod, and the desired scanning parameters were entered on the instrument's home screen. Figure 2 details the workflow for programming the scanner's settings prior to completing a scan. To retain a practical completion time for the survey, a resolution of 1/5 and quality of 6x was adopted, providing a scan time of 22.38 minutes. The scanner stores data on a SD memory card, and this was post processed using Faro Scene 7.1 software to extract, register and align the point cloud.

INSERT FIGURE 1 and FIGURE 2 HERE

2.1.2. Structure from Motion photogrammetry

Static digital images (5472 x 3648 pixels) were captured at the test location using a digital single-lens reflex camera with 50 mm fixed focal length, mounted on a camera tripod and dolly (refer to Figure 1b). Following the method of [34] a minimum of 60% forward overlap and 30% sideways overlap between photographs was maintained. Previous research [45] has demonstrated that capturing flat surfaces using SfM with predominantly parallel images, and adopting self-calibration of camera locations can cause deformation of the point cloud typified by 'doming' effects. To prevent these affects, over lapping photographs, were captured at three heights (500 mm, 600 mm and 750 mm) above the pavement surface, across the width of the highway (Figure 3a).

Agisoft Photoscan version 1.3.4.5067 software 6 was used to post process the images enabling reconstruction of the overlapping photographs into a 3D point cloud. The software determines the position and orientation of cameras automatically using a scale invariant feature transform (SIFT) [44]. The SIFT matches up identified features across the image set, to establish their 3D co-ordinates and generate a sparse cloud. The sparse cloud is then densified into a dense point cloud by the software using Multi View Stereo techniques [53]. Figure 3 illustrates the key stages of the construction of a point cloud from the camera images. Using this approach, an area equivalent to the width of a standard road lane (3.65 m) was successfully reconstructed without deformation.

INSERT FIGURE 3 HERE

2.1.3. 3D Smart Laser Profiling

The 3D Smart Laser Profile Sensor, an LMI Technologies Gocator 2350, was mounted upon a trolley at a height of 500 mm (Figure 1c) and powered by a 60-volt battery. One trolley wheel made contact with a digital quadrature encoder fitted to a 200 mm circumference measuring wheel. The digital encoder was wired to provide a pulse signal to the 3D Smart Sensor, being programmed to produce 40,000 pulses per rotation of the measuring wheel. Each pulse equates to a travel distance of 0.005 mm and this information is used to enable 3D surface profiles to be captured at variable speed. The 3D Smart Laser Profile Sensor's settings where programme using Gocator Emulator version 4.6.7.17 software, installed on a conventional laptop. Figure 2b details the workflow for programming the 3D Smart Laser Profile Sensor's settings prior to completing a scan. The data were collected at walking speed every 201 pulses or 1.005 mm over a 3 m section, with the 3D Smart Laser Profile Sensor operating at a typical field of view width of 300 mm. The 3D Smart Laser Profile Sensor, is equipped with the capacity to view the laser points forming the profile line on the highway surface in 'real-time'. This facilitates adjustment of the laser exposure level and active measurement area to accommodate ambient light levels, stray light and variability of highway surface reflectivity. The surface profiles extracted from the 3D Smart Laser Profile Sensor were post processed using Gocator_Emulator version 4.6.7.17 and kCSvConveter software to an ASCII xyz file format suitable for point cloud post processing [54].

2.2. Test location

To test the three techniques a field site was selected that contained three standard types of pavement surface within close proximity (Figure 4), allowing for the same ambient conditions to be assumed over the surfaces. The site included a close graded dense bitumen macadam (DBM), and a gap graded hot rolled asphalt (HRA), as well as surface dressing (SD). Test were undertaken on the dry pavement surfaces with permanent ground control points being installed to demarcate each surface using 16 mm survey nails.

2.3. Deriving macrotexture parameters from non-contact survey techniques

The 3D point cloud data for the DBM, HRA and SD surfaces were captured consecutively on the same day using the three different techniques. The point clouds obtained from each technique were then aligned utilising the installed reference ground control points in Cloud Compare v 2.10 software [55], to facilitate direct comparison between the surfaces. Subsequently, 150 mm x 150 mm sample areas (representing a typical laboratory specimen size) were clipped for each surface from the aligned point clouds for analysis.

These clipped point clouds were then loaded into MountainsMap Premium version 7.4 and the software used to remove any transverse or longitudinal slope by method of least squares, and to calculate the standard areal parameters as listed in Table 1, to characterise the macrotexture. Areal parameters were adopted, in contrast to 2D profile parameters [56], as these are recognised as providing a more complete description of a surface [46], capturing height with respect to both the 'x' and 'y' direction to characterise functional aspects such as texture, shape and direction. In sampling the point cloud data to make successful areal measurements it is important that Nyquist values be smaller than the smallest desired surface macrotexture requiring characterisation. Nyquist sampling theorem states that the shortest wavelength that can be defined from a digital dataset is two digital sample intervals long. Therefore, the wavelength or sample length available to characterise pavement texture areal parameters, is defined by the relationship between point cloud density and sample size.

INSERT TABLE 1 HERE

2.4. Deriving 2D wavenumber amplitude spectra from non-contact techniques and filtering

Image datasets can be analysed by MATLAB software to transform them to the wavenumber domain, allowing images to be characterised by spatial frequency. Accordingly, 2D Kx-Ky wavenumber spectral analyses of the samples [56] were calculated in MATLAB to determine the areal wavenumber characteristics of the surfaces captured using the different techniques. To prevent spectral leakage caused by discontinuities at the edges of each measured sample area, the amplitude of the signal at the outer edges was attenuated using a cosine taper Tukey window that extended for 10% from the extreme edges of the sample line [57]. The resulting 2D wavenumber spectra enabled the wavenumber content of the data to be determined, which facilitated the selection of an appropriate 2D wavenumber filter to attenuate high wavenumber noise from the macrotexture signal.

Examining the spectra for each non-contact technique the 3D Smart Laser Profile Sensor was the lowest resolution technique, containing wavenumbers not greater than 0.1 mm^{-1}. Consequently, to achieve conformity of the wavelengths for areal parameter analysis across techniques a wavenumber filter of 0.1 mm^{-1} was applied to the SfM and TLS data. A low pass zero phase Butterworth wavenumber filter [57] was then designed to remove high wavenumber noise components from the data, up to the Nyquist wavenumber [58]. The filter was applied in a two-pass process, firstly for every trace in the x-direction and then the y-direction, thus creating a 2D filtered data set. Normalised 2D autocorrelations and cross-correlation plots of the filtered surface data were then prepared as a means of measuring image spatial similarity (as the macro-texture scale pushes the limit of conventional differencing techniques adopted for identifying similarity and change in point cloud analysis [56]).

3. Results and discussion

Nyquist values are given in Table 2. The 3D Smart Laser Profile Sensor minimum Nyquist wavelengths mean that the technique is unable to measure a small part of the lower range of macrotexture wavelengths between 0.5 and 1 mm. The SfM and TLS Nyquist wavelengths mean the techniques can measure the full range of macrotexture wavelengths and have the potential to also measure some part of microtexture below 0.5 mm, this capability should be explored as part of a further research study. The Nyquist wavelengths vary between samples, possibly because the techniques are sensitive to pavement surface albedo, environmental conditions, and edge effects. Given technique sensitivity, oversampling to ensure a sufficiently fine Nyquist wavelength is beneficial and in this regard adopting a higher resolution technique such as TLS is advantageous. The Nyquist wavelength for a TLS, will increase with distance from the laser source, because of the elongation of the beam, as the angle of incidence with a surface increases. Therefore, the optimal location to acquire TLS data with an 'off-the-shelf scanner', is within a narrow cone of incidence directly in line with the laser source, with data captured using an inverted head tripod set-up.

Surface height plots for each surface scanning technique are illustrated in Figure 5. For the DBM greater similarity is evident between Figure 5(a) and Figure 5(b) as the 3D Smart Laser Profile Sensor and SfM techniques have similar resolution. The higher resolution of the TLS is evident in the finer granularity of plot Figure 5(c). All the techniques are able to capture the voids between aggregates (e.g. i) and aggregate features (e.g. ii) on the DBM surface at the same locations. Equally, for the HRA surface there is greater similarity between Figure 5(e) and Figure 5(f), the data captured with the 3D Smart Laser Profile Sensor and SfM techniques. The higher resolution of the TLS is evident again in the finer granularity of the edges of the red chipping aggregate (Figure 5g). Finally, although the SD aggregate chippings are the smallest for the three surfaces, all the techniques have still collectively identified areas of void between aggregates in blue Figure 5(J) to (l)(e.g. vi) and areas of elevated macrotexture in orange located to the right and left edge of each plot. Again there is greater similarity between Figure 5(j) and Figure 5(k), the data capture with the 3D Smart Laser Profile Sensor and SfM technique. The higher resolution of the TLS is evident in the finer granularity of plot (l). The degree of similarity between the techniques has been characterised using areal parameters and 2D correlation analysis discussed in Section 3.1 and 3.2 respectively.

INSERT FIGURE 5 AND TABLE 2 HERE

3.1 Unfiltered areal parameters

The areal parameters derived for each technique are given in Table 2. *Sq* is spatially equivalent to the mean profile depth that is used at present to evaluate macrotexture. Table 2 shows that *Sq,* for the 3D Smart Laser Profile Sensor and SfM are within 0.002 mm agreement for the DBM, 0.013 mm for the SD and 0.09 mm for the HRA. This presents the 3D Smart Laser Profile Sensor and SfM, as an alternative method to capture texture depth. The TLS obtained results for *Sq* are very different, with differences in comparison with the 3D Smart Laser Profile Sensor value ranging from 0.139 mm to 0.394 mm; the largest value being obtained for the SD surface. The value for *Sp* and *Sv,* the maximum peak and pit heights, demonstrate greater agreement between the SfM and 3D Smart Laser Profile Sensor results, than the TLS technique. The variance in TLS derived parameters is because of the higher resolution nature of the data. Values for *Spd* and *Spc*, which have previously been shown to have positive correlations with skid resistance [34], are typically different by an order of magnitude for all the techniques and surfaces considered. The variability of *Spd* and *Spc* suggests the parameters are also sensitive to resolution and limits the potential to adopt unfiltered data in ‘universal’ across technique parametric comparison studies with friction. For *Ssk*, the parameter defining skewness (thus indicating whether texture is positive or negative), all three unfiltered techniques were able to identify the positive texture of the surfaces. The skewness is sensitive to the spatial sampling resolution of the technique, with closer agreement demonstrated between the SfM and 3D Smart Sensor technique.

3.2 2D Correlation analysis

Areal parameters only characterise discrete functions of surface roughness. Therefore, 2D cross-correlation analysis to measure x-y and z plane similarity between images was completed. Perfect correlation is characterised by a strong central peak with a value of 1. The normalised 2D cross-correlation plots are shown in Figure 6. For the DBM surface a central peak is evident of 0.4492 and 0.3515 for similarity between the 3D Smart Laser Profile Sensor and SfM, and 3D Smart Laser Profile Sensor and TLS respectively (Figure 6 (a) and Figure 6 (d)); defining positive correlation and symmetry (or lack of shift) between the wavelength frequencies. To the left of the central peak there is a dominating positive feature on both plots, depicted as the yellow to red zone (e.g. Figure 6 (a)(i)), representing an area of higher macrotexture departure from the surface. For the SD surface, no central peak is evident with elongated bands of positive and negative agreement being visible (Figure 6 cii and ciii) for similarity between both the 3D Smart Laser Profile Sensor and SfM, and 3D Smart Laser Profile Sensor and TLS. The bands arise as the macrotexture of the SD surface is dominated by a repeating texture feature.

Overall, the best correlation is achieved between the 3D Smart Laser Profile Sensor and SfM measurement technique for the HRA surface Figure 6(b). The plot has a clear strong centralised peak of 0.729, demonstrating an alignment or lack of lateral shift between the wavelength frequencies of the two techniques. The rest of the plot is generally blue indicating a general lack of secondary dominating features on the surface. This can be attributed to the parity of resolution between two techniques and the larger wavelength features of the HRA surface. The 2D cross-correlations affirm the areal parameter results with greater agreement between the unfiltered 3D Smart Laser Profile Sensor and SfM surface measurements. The 2D cross-correlation plots comparing similarity between the 3D Smart Laser Profile Sensor and TLS demonstrate less agreement. The normalised cross-correlation peaks are either not present or where present are lower being 0.3515 for the DBM (Figure 6(d)). This confirms the influence of the higher resolution shorter wavelengths within the unfiltered data, which cause the reduction in the normalised peak, and reduced agreement. After the application of a 0.1 wavenumber filter the heights of the normalised 2D cross- correlation peaks increase by 16.6 to 25% demonstrating stronger agreement between the 3D Smart Laser Profile Sensor and the other two techniques.

INSERT FIGURE 6 HERE

3.3 Filtered areal parameters

Surface height plots for each filtered surface scanning technique are illustrated in Figure 7. For all three

INSERT Figure 7 Here

surfaces after the application of a 0.1 mm^{-1} wavenumber filter there is greater visual similarity between all three techniques. The filter has reduced the resolution of the TLS data, removing the finer granularity, to reveal the macrotexture more clearly. Furthermore, post-filtering increased agreement was achieved for areal parameters *Spd* and *Spc,* previously shown to have a positive correlation with skid resistance*.* The filtered areal parameters are shown in Table 2. The filtered *Spc* (arithmetic mean peak curvature) values, related to the shape of the road aggregates, measured using the 3D Smart Laser Sensor and SfM are within 0.013 mm $^{-1}$ for the DBM and 0.067mm^{-1} for the SD. The filtered values of *Spc* for the HRA do not demonstrate agreement. The filtered *Spd* (peak density) values, related to the distribution of road aggregates upon a pavement surface, measured using the 3D Smart Laser Sensor and SfM are within 0.00087mm^{-2} for the DBM, 0.01417 mm^{-2} for the HRA, and 0.00044 mm^{-2} respectively for the SD. The filtered *Spd* (peak density) values measured using the 3D Smart Laser Sensor and TLS are within 0.00059 mm^{-2} for the DBM, 0.01747 mm^{-2} for the HRA, and 0.00054 mm^{-2} for the SD. The filtered *Spd* values measured using the SfM and TLS are within 0.00028 mm^{-2} for the DBM, 0.0033 mm^{-2} for the HRA, and 0.0001 mm^{-2} for the SD. Although an increased agreement has been achieved for *Spd* and *Spc*, importantly for practical pavement characterisation of surface height departures, for the 3D Smart Laser Profile Sensor and SfM techniques this is at the expense of the accuracy of *Sq,* which experiences magnification at a range of four to ten times. Therefore, filtering improves spatial agreement, but at the cost of vertical measurement, a factor that should be considered by researchers seeking correlations between non-contact texture measurements and skid resistance. Moreover, the filtered values of *Sq* obtained from the TLS whilst closer to the original unfiltered 3D Smart Laser Profile Sensor, demonstrate at best ten percent accuracy; being in 0.213 mm agreement for the DBM, 1.928 mm agreement for the HRA and 0.063 mm agreement for the SD. The TLS technique does offer the best balance between the vertical and spatial areal functions post-filtering, fundamentally because it enables oversampling of the surfaces, with correspondingly the shortest Nyquist wavelength. However, the improved resolution of the technique still does not lead to sufficiently accurate measurement of *Sq*, the vertical departure heights from a pavement surface. Greater technique resolution does not necessarily equate to sufficiently improved accuracy for some measurements.

3.4 Spectral analysis

The spectra in Figure 8 illustrate the areal wavenumber characteristics of the three surface materials in the ’x’ and ‘y’ plane [55]. As wavenumber is the reciprocal of wavelength, the plots serve to demonstrate differences in macrotexture characteristic between the surfaces. The spectra are sensitive both to the scale of the macrotexture and the technique of measurement. The TLS has the largest spectral cloud of the three techniques for all surfaces, illustrating that it is consistently the highest resolution technique. Considering the SfM spectral plots, it is clear that the HRA surface has the largest wavelength features represented by the brightest spectral cloud centre; whilst the DBM contains the smallest wavelength features represented by the largest cloud. As a high pass filter was not applied to the cloud data, the larger wavelengths in the centre of the spectral plots represent the unevenness of the surfaces. The spectra reveal for the SfM technique that for the HRA the wavelengths features are typically 4 mm or larger; the SD 3.5 mm or larger and DBM 2.6 mm or larger. Finally, greater similarity is generally evident between the unfiltered spectra for the SfM and 3D Smart Laser Profile Sensor, as the techniques have similar resolution and accuracy.

INSERT FIGURE 8 Here

3.5 Spatial variability

The spatial variability of *Sq, Ssk, Sp, Sv, Spd* and S*pc* for seventy-two 150 mm x 150mm samples and eighteen 300 mm x 300 mm samples captured using SfM were considered for a 1.8 m x 0.9 m area of HRA in Figure 9 and 10.

INSERT FIGURE 9 and 10 Here

The computed parameters (*Sq, Ssk, Sp, Sv, Spd* and S*pc*) for each individual sample, were divided into a percentage of the overall maximum for each considered areal parameter, with the discrete colour contrasts representing 20% . Thereby each colour represents a 20th percentile in the overall maximum parameter value, and thus illustrates the variability of the parameters across the 1.8 m x 0.9 m HRA surface . The 150 mm x 150 mm sample size for *Sp,* maximum peak height, reflects the distribution of red aggregate chippings across the HRA surface. Lower peaks are encountered near the top edge of the sample, where the surface is predominantly bituminous binder. Some discrete squares of increased peak height are shown in dark green, representing the higher texture height of isolated red chippings. Principally, the peak height values *Sp* are within the percentile range of 1.85 mm to 3.65 mm. The 150 mm x 150 mm sample size for *Sv*, maximum pit height, demonstrated limited variability between separate sample areas, with 87.5% of the HRA surface being within 4.4 mm to 7.4 mm. This consistency most likely reflects the method of laying HRA, with the precoated red aggregate chippings being scattered across the surface of the previously laid asphalt binder and rolled into the surface at a constant pressure, resulting in more consistent pit heights. For vertical macrotexture characterisation parameters, such as *Sv* , *Sp* and *Sq* spatially equivalent to the mean profile depth used at present to evaluate macrotexture, there is some similarity between the location of darker colour contrast for both the 150 mm x 150 mm and 300 mm x 300 mm sample sizes.

There is a lack of parity between the surface characterised using the 150 mm x 150 mm sample and the 300 mm x 300 mm sample for *Spd*; with an increase in sample size appearing to 'smooth' the density of peaks removing altogether the highest percentile range 3.42 x 10^{-3} mm^{-2} to 4.06 x 10^{-3} mm^{-2} from the 300 mm x 300 mm plot. The 150 mm x 150 mm samples reflect the distribution of red chippings across the surface, with the lower peak densities recorded near the top and edge of the HRA surface where there is predominantly bituminous binder present. The *Spd* parameter also demonstrates the greatest variability between different 150 mm x 150 mm samples. *Spd* has previously been shown as being important to skid resistance, with positive correlation achieved with friction measurements. However, the variability of *Spd* values, means picking a representative 150 mm x 150 mm sample to characterise the whole surface to correlate with friction is difficult. *Spd* represents the number of peaks in a unit area and is sensitive to sample size. Figure 11 considered the influence of upscaling the sample size for areal parameters (*Sq, Ssk,* *Sp, Sv, Spd* and S*pc*) on the HRA surfacing capture using SfM with the point cloud extended to 1.05 m x 1.95m. For *Spd* the optimum sample size for the HRA surface was found to be 1050 mm x 1050mm. For the vertical macrotexture parameters, the optimum sample size was found to be 750 mm x 750 mm for *Sv* , 1050 mm x 1200 mm for *Sp,* and 1050 mm x 1650 mm for *Sq*.

INSERT FIGURE 11 Here

For S*pc* mean curvature of peaks, the optimum sample size was discovered to be 450 mm x 450 mm for the HRA surface. S*pc* was found to have the smallest sample size of all the parameters considered perhaps reflecting its general lack of heterogeneity. The 150 mm x 150 mm sample size demonstrating the least variability across the HRA surface of any of the areal parameters considered by the study; with 80% of the samples falling within the 20% range 0.58 $mm^{-1}$to 0.88 mm^{-1}.

Whilst *Sq*, *Sp, and Sv* just capture the overall height and depth of peak and pit surface departures, *Ssk* gives the location (or skewness) above and below the mean plane; consequently, providing an indication of the distribution of texture available to contribute to skid resistance. For *Ssk*, both the 150mm x 150 mm and 300mm x 300 mm sized samples confirm that the HRA has positive texture. The split of the contrasting light and dark blue squares for *Ssk*, is similar for each sample size, with the predominant number of darker squares below the white diagonal line bisecting the 1.8 m x 0.9 m area (refer to Fig 10). However, the location of the mean plane was determined to be sensitive to sample size, with the value of *Ssk* varying. A sample size of 1050 mm x 1200 mm of smaller was found in the upscaling analysis to have a negative texture confirming a positive texture, but above this size *Ssk* was shown to have a positive value indicating a skew to negative texture. The change in *Ssk* can be attributed to the influence of the variability of peak height with changing sample area, on the location of the mean plane. Overall reviewing individual areal parameters typically used to characterise friction (*Sp, Sv, Spd* and S*pc*) optimal sample size, suggests that a suitable sample size of 1050 mm x 1200mm is appropriate to characterise HRA; this being established from the maximum size of the individual parameters

Further research should be conducted to explore the efficiency of sample sizes for areal parameters for different pavement textures. As contact friction devices are known to be susceptible to seasonal variation and machine operating conditions such as load, speed slip ratio and the composition of rubber, using reliable non-contact areal parameter data to be able to analytically model a relationship with friction is desirable. Moreover, higher resolution does not always equate to greater accuracy. It was found that whilst SfM photogrammetry successfully provides an alternative method to the 3D Smart Laser Profile Sensor to capture vertical pavement measurement *Sv, Sp and Sq* for mean profile depth estimation and correlation with friction, the higher resolution TLS data contained significant inaccuracies. Furthermore, the values of *Spd* and S*pc*, which together define the shape and distribution of pavement aggregates and have previously been proven to have positive correlation with friction [34], are sensitive to resolution, incurring order of magnitude differences. A 2D low pass wavenumber filter achieved improved agreement with the 3D smart profiler for *Spd* and S*pc* parameters. Optimising such filters consistently across a range of non-contact techniques is needed to achieve a ‘universal’ correlation between these parameters and to model relationships with skid resistance. Further, as the application of such a filter has the potential to impact on vertical accuracy of measurement (*Sq, Sp,* and *Sv*) for some high resolution techniques, findings of this study indicate the filter should be applied only to the *Spd* and S*pc* spatial parameters.

4. Conclusions

In conclusion, the study has compared the measurement of macrotexture using three different techniques. The study makes a first contribution to the establishment of reliable standardised texture measurements using point cloud derived data to inform analytical prediction methods for tyre-pavement contact friction without the influences of seasonal variation, measuring devices and their operating conditions. Results from the analysis of the data lead to the following conclusions:

- Unfiltered close field SfM photogrammetry provides values of *Sp, Sv* and *Sq,* within an acceptable degree of tolerance to those obtained from the 3D Smart Laser Profile Sensor, so as SfM photogrammetry is an effective, readily scalable alternative method to capture mean profile depth for pavement evaluation.
- The parameters *Spc* and *Spd,* for which previous studies have established an important correlation with pavement friction, are sensitive to technique resolution and a 2D low pass wavenumber filter needs to be applied to obtain a 'universal' measurement for pavement friction assessment.
- A 2D zero-phase wavelength filter of 0.1 mm^{-1} improves S*pd,* for the TLS and SfM techniques.
- The Nyquist wavelengths of TLS and SfM techniques mean they have the potential to measure microtexture wavelengths below 0.5mm.
- TLS data are significantly improved for macrostructure surveys after 2D low pass wavenumber filtering.
- Where 150 mm x 150 mm industry sample sizes are used to determine parameters from point clouds data derived from non-contact techniques, these are not sufficient to correctly characterise functional areal parameters to describe the spatial variability of macrotexture upon a pavement. This study suggests a suitable sample size of 1050 mm x 1200mm is appropriate to characterise HRA.

References

[1] Design Manual for Roads and Bridges, HD28/15: Skid Resistance. Norwich: The Stationary Office, Office of Public Sector Information. Volume 7, Section 3, Part 1, 2015. [Online] Available at: http://www.standardsforhighways.co.uk/ha/standards/dmrb/vol7/section3/hd2815.pdf (Accessed 27th January 2018)

[2] D.F. Moore, The Friction of Pneumatic Tyres, Elsevier, New York (1975) ISBN 0444413235

[3] M.Klüppel, G.Heinrich, Rubber Friction on Self Affine Road Tracks, Rubber Chemistry and Technology, 73 (2001) pp. 578–606. https://doi.org /10.5254/1.3547607

[4] B.N.J. Persson, Sliding Friction: Physical Principles and Applications. Springer-Verlag, Berlin (2001) ISBN 978-3-662-04283-0

[5]M.Kane, V.Edmondson, Modelling the bitumen scour effect: Enhancement of a dynamic friction model to predict the skid resistance of rubber upon asphalt surfaces subject to wear by traffic polishing, Wear, 400-401 (2018) pp100-110 https://doi.org/10.1016/j.wear.2017.12.013

[6]M.T.Do, V.Cerezo, Road Surface Texture and Skid Resistance, Surface Topography: Metrology and Properties, 3 (2015) pp1-16 https://doi.org/10.1088/2051-672X/3/4/043001

[7] J.W.Hall, K.L.Smith, L.Titus-Glover, J.C.Wambold, T.J.Yager, Z.Rado, Guide for Pavement Friction: Final Report for National Cooperative Highway Research Program (NCHRP) Project) 01-43, Transport Research Board of the National Academies, Washington, D.C, 2009. [Online] Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.464.9481&rep=rep1&type=pdf (Accessed 27th January 2018)

[8] PIARC, Report of the committee on surface characterisation, in: Permanent International Association of Road Congress (PIARC) XVIII World Road Congress, Brussels, 1987 [Online] Available at: https://www.piarc.org/en/publications/Congress-Proceedings/Brussels-1987/technical-committee-report.htm (Accessed 27th January 2018)

[9] A.Dunford, Friction and the texture of aggregate particles used in the road surface course PhD thesis, University of Nottingham, UK, 2013. [Online] Available at: http://eprints.nottingham.ac.uk/13412/ (Accessed 27th January 2018)[10] A. Dunford, Road Surfaces, chapter in Leach, R. The Characterisation of Areal Surface Texture. Teddington: Springer pp 337-348 (2013) ISBN-13:978-3-642-36457-0

[11] G.Flintsch, E. De Leon, K.McGhee, I.Al-Qadi, Pavement Surface Macrotexture Measurement and Applications, Transport Research Record, 1860, (2013) https://doi.org/10.3141/1860-19 [12] R.G.Roe, R.Sinhal, The polished stone value of aggregates and in service skidding resistance, TRL report 322, TRL, Crowthorne, UK , 1998 [Online] Available at: https://trl.co.uk/reports/TRL322 (Accessed 27th January 2018)

[13] Z.Rado, M.Kane, An initial attempt to develop an empirical relation between texture and pavement friction using the HHT approach, Wear, 309, 1-2 (2014) pp 233-246. https://doi.org/10.1016/j.wear.2013.11.015

[14] BS EN 13032-1:2010, Road and airfield surface characteristics – Test method. Part 1: Measurement of pavement surface macrotexture depth using volumetric patch techniques. British Standard Institute. London ISBN-13: 9780580685613

[15] British Standards Institute, BS EN 13036-4:2011: Road and airfield surface characteristics of slip/skid resistance of a surface: The pendulum test. London: British Standards Institute (2011). ISBN-13:9780580812606

[16] British Standards Institute, BS7941-1: 2006 Method of measuring the skid resistance of pavement surfaces. Sideway-force coefficient routine investigation machine. London: British Standards Institute (2006). ISBN-10: 0580489973

[17] British Standards Institute, BS7941-2:2000: Method of measuring the skid resistance of pavement surfaces. Test method for measurement of surface skid resistance using the Grip Tester braked wheel fixed slip device. London: British Standards Institute (2000). ISBN-10: 0580332101

[18] R.B.Kogbara, E.A.Masad, E.Kassem, A.T.Scarpas, K.Anupam, A state-of-the-art review of parameters influencing the measurement and modelling of skid resistance of asphalt pavements, Construction and Building Materials, 114, (2016) pp602-617 https://doi.org/10.1016/j.conbuildmat.2016.04.002 [19] W.Bijsterveld, M.A.de Val, Towards quantification of seasonal variation in skid resistance measurement, Road Materials and Pavement Design, 17, (2) (2016) pp 477-486 http://dx.doi.org/10.1080/14680629.2015.1090909

[20] J.R.Hosking, G.C.Woodford, TTRL Report 738, Measurement of skidding resistance Part II. Factors effecting the slipperiness of a road surface. Crowthorne: Transport and Road Research Laboratory (1967) [Online] Available at: https://trl.co.uk/reports/LR738 (Accessed 27th January 2018).

[21] M.A.Kahasawneh, R.Y.Laing, Temperature effects on the frictional properties of HMA at different polishing stages, Jordan Journal of Civil Engineering, 6 (1) (2012) p39-53 [Online] Available at: http://www.iiste.org/Journals/index.php/JJCE/article/view/17985/18362 (Accessed 27th January 2018)

[22]R.H.Smith, Analysing Friction in the Design of Rubber Products and their Paired Surfaces, CRC Press (Taylor and Francis Group), Boca Raton, Florida, 2008 ISBN-13:9780849381379

[23] C. Plati, K. Georgouli, A. Loizos, Utilising the seasonal variations of skid resistance to plan preventative maintenance, in: M.Losa, T.Pagagiannakis (Eds), Sustainability, Eco-Efficiency and

Conservation in Transportation Infrastructure Asset Management , CRC Press (Taylor and Francis Group), Boca Raton, Florida, 2014, pp509-518, ISBN-13:9781138001473

[24] P.D.Sanders, S.McRobbie, J.Gopaldas,H.E.Viner, Report Number PPR771 Development of a reference surface for the assessment of pavement skid resistance measurement devices, Transport Research Laboratory, Crowthorne (2015) [Online] Available at: https://trl.co.uk/reports/PPR771 (Accessed 27th January 2018)

[25] A. Dunford, PPR315 Measuring skid resistance without contact, Transport Research Laboratories, Crowthorne (2008) [Online] Available at: https://trl.co.uk/reports/PPR315 (Accessed 27th January 2018)

[26]M.Kane, M.T.Do, V.Cerezo, Z.Rado, C.Khelfi, Contribution to pavement friction modelling an introduction to the wetting effect, International Journal of Pavement Engineering (2017) p1-12

[27] M.Kane, V.Cerezo, A contribution to tire/road friction modelling: From a simplified dynamic friction contact model to a 'Dynamic Friction Tester' model, Wear, (342-343) 2015 p163-171

[28] A.Ueckermann, D.Wang, M.Oeser, B.Steinauer, Calculation of skid resistance from texture measurements, Journal of Traffic and Transportation Engineering (English Edition), 2 (1) (2015) p3-16 https://doi.org/10.1016/j.jtte.2015.01.001[29] X.Zhang, T.Liu, C.Liu, Z.Chen, Research on skid resistance of asphalt pavement based on three-dimensional laser-scanning technology and pressure-sensitive film, Construction and Building Materials, 69 (2014) pp49-59 http://dx.doi.org/10.1016/j.conbuildmat.2014.07.015

[30] V.M.C. Araujo, I.S.Bessa, V.T.F Castelo Branco, Measuring skid resistance of hot mix asphalt using the aggregate image measurement system (AIMS), Construction and Building Materials, 98 (2015) pp476-481 http://dx.doi.org/10.1016/j.conbuildmat.2015.08.117[31]B.Prowell, D.Hanson, Evaluation of Circular Texture Meter for measuring surface texture of pavements, Transport Research Record: Journal of the Transportation Research Board 1929, https://doi.org/10.3141/1929-11

[32] S.Li, S.Noureldin, K.Zhu,Y.Jaing, Pavement surface microtexture: Testing characterisation and frictional interpretation, in B.Choubane (Ed.) Pavement Performance: Current Trends, Advance and Challenges; ASTM STP 1555, American Society for Testing Materials (ASTM), West Conshohocken, PA, 2012 pp59-76 http://dx.doi.org/10.1520/STP104426

[33] A.Shalaby, A.El Gendy, Digital Image Analysis: Current Practice of Pavement Texture Measurement , 8th International Transportation Speciality Conference, Winnipeg, Manitoba, June 9th to 12th (2010) pp1313 to 1321 [Online] https://www.researchgate.net/publication/290284577_Digital_image_analysis_Current_practice_of_pavement_texture_measurement (Accessed 27th January 2018)

[34] R.B. Kogbara, E.A. Masad, D.Woodward, P.Millar, Relating surface texture parameters from close range photogrammetry, Construction and Building Materials, 166 (2018) pp227-240 https://doi.org/10.1016/j.conbuildmat.2018.01.102

[35] M.N.Alamdarlo, S.Hasami, Optimization of the photometric stereo method for measuring pavement texture properties, Measurement, 127 (2018) pp406-413 https://doi.org/10.1016/j.measurement.2018.05.109

[36] F.G.Pratico, A.Astolfi, A new and simplified approach to assess the pavement surface micro- and macrotexture, Construction and Building Materials, 148 (2017) pp 476-483. https://doi.org/10.1016/j.conbuildmat.2017.05.050

[37] L.Gao, M.Lui, Z.Wang, J.Xie, S.Jia, Correction of texture depth of porous asphalt pavement based on CT scanning technique,Construction and Building Materials, 200 (2019) pp 514-520. https://doi.org/10.1016/j.conbuildmat.2018.12.154

[38] W.Wang, X.Yan,H.Huang,X.Chu, M.Abdel-Aty, Design and verification of a laser based device for pavement macrotexture measurement, Transport Research Part C, 19 (2011) p682-694

[39] D.Zhang, Q.Zou, H.Lin, X.Xu, L.He, R.Gui, Q.Li, Automatic pavement defect detection using 3D laser profiling technology, Automation in Construction, 96 (2018) pp 350-365 https://doi.org/10.1016/j.autcon.2018.09.019

[40]Creaform (no date) HandyScan 3D, The truly portable metrology grade 3D-Scannar, [Online] Available at: https://www.creaform3d.com/sites/default/files/assets/brochures/files/handyscan3d_brochure_en_hq_21032017_2.pdf (Accessed 27th January 2018)

[41] Z Corporation (no date) Z Scannar ® 800 High Resolution Handheld Scannar, [Online] Available at: http://www.agile-manufacturing.com/files/products/zscanner-800.pdf (Accessed 27th January 2018)

[42] L.Hu, D.Yun, Z.Lui, S.Du, Z.Zhang, Y.Bao, Effect of three-dimensional macrotexture characteristics on dynamic frictional coefficient of asphalt pavement surface, Construction and Building Materials, 126 (2016) pp720-729 http://dx.doi.org/10.1016/j.conbuildmat.2016.09.088

[43] A.Abellan, M.Jaboyedoff, T.Oppikofer, J.M.Vilaplana, Detection of millimetric deformation using a terrestrial laser scanner: experiment and application to a rockfall event, Natural Hazards and Earth System Sciences, 9 (2009) pp365-372 https://doi.org/10.5194/nhess-9-365-2009

[44] N.Micheletti, J.H.Chandler, S.N.Lane, Structure from Motion (SfM) Photogrammetry, Geomorphological Techniques, Chapter 2.2 (2015) ISSN 2047-0371 [Online] http://geomorphology.org.uk/geomorph_techniques (Accessed 27th January 2017)

[45] M.R.James, S.Robson, Straightforward reconstruction of 3D surfaces and topography with a camera: Accuracy and geoscience application, Journal of Geophysical Research, 117 (2012) pp1-17 http://dx.doi.org/10.1029/2011JF002289

[46] Leach, R. Introduction to surface topography, chapter in R.Leach (eds) Characterisation of Areal Surface Texture, London, Springer, (2013) pp1-13 ISBN-13:978364236457

[47] G.Boscaino, F.G.Praticò A classification of surface texture indices of pavement surfaces [Classification et inventaire des indicateurs de la texture superficielle des revêtements des chaussées], Bulletin des Laboratoires des Ponts et Chaussees 234 (2001), pp. 17-34+123+125+127. ISSN: 1269-1496.

[48] ISO 13473-1: Characterisation of pavement texture by the use of surface profiles – Part 1: determination of mean profile depth. Geneva, Switzerland: International Organization for Standardization (2019) [Online] Available at https://www.iso.org/obp/ui/#iso:std:iso:13473:-1:ed-2:v1:en (Accessed 3rd July 2018)

[49] LMI Technologies (ND), Gocator 2300 series all in one smart profile sensor, Available at: https://www.stemmer-imaging.co.uk/media/uploads/vision-systems/lmi/81/81688-LMI_Gocator_2300.pdf (Accessed 18th March 2018)

[50] H.Yaacob, N.A.Hassan, M.R.Hainin, M.F.Rosli, Comparision of sand patch test and multi laser profiles in pavement surface measurement, Jurnal Teknologi, 70 (4) (2014) pp 103-106 http://dx.doi.org/10.11113/jt.v70.3497

[51] ISO 25178 Part 2, Geometrical product specification (GPS) – Surface texture: areal part 1: terms, definitions and surface texture parameters. International Organisation of Standardisation. (2012) [Online] Available at: https://www.iso.org/standard/42785.html (Accessed 27th January 2018)

[52] ISO 4288. Geometrical Product Specification (GPS) -- Surface texture: Profile method -- Rules and procedures for the assessment of surface texture. Geneva, Switzerland: International Organization for Standardization (1996) [Online] Available at https://www.iso.org/standard/2096.html (Accessed 3rd July 2018)

[53] Y.Furukawa, J.Ponce, Accurate, dense, and robust multiview stereopsis, IEEE Transactions on Pattern Analysis and Machine Intelligence, 32 (2010) pp 1362-1376, http://dx.doi.org/10.1109/TPAMI.2009.161

[54] LMI Technologies, Gocator Firmware 4.6, The Latest Features and Tools (ND), Available at: https://lmi3d.com/products/gocator/firmware (Accessed 27th April 2018)

[55] Girardeau-Montaut, D. Cloudcompare 3D point cloud and mesh processing software – open source project, Available at: http://www.danielgm.net/cc/ (Accessed 27th April 2018)

[56] Gubbins, D. Time Series Analysis and Inverse Theory for Geophysicists, Cambridge: Cambridge University Press (2004) ISBN-10:0521819652

[57] ISO 4287, Geometrical product specification (GPS)- Surface texture: profile method – terms, definitions and surface texture parameters. International Organisation of Standardisation. (1997) [Online] Available at: https://www.iso.org/standard/10132.html (Accessed 27th January 2018)

[58] Bloomfield, P. Fourier Analysis of Time Series: An introduction. New York: Wiley-InterScience (2000) ISBN-10:0471889482