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

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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)

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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].

89

90   Thus, the preservation of adequate skid resistance requires the monitoring of macrotexture [1] to ensure

91   sufficient texture remains on the pavement to prevent skidding. Standard monitoring techniques involve

92   either a sand patch test [14] or a direct measurement of the frictional resistance through a rubber pad

93   [15] or test wheel making contact with a wetted pavement [16,17]. Kogbara *et al.* [18] provide a full

94   summary of devices and their operating principles. These contact devices are known to be susceptible to

95   seasonal variation [19]. This phenomenon has been attributed to a number of factors: the sensitivity of

96   rubber resilience to temperature change [20]; changes induced by temperature in the viscosity of the test

97   water of a device [21]; and differential polishing of the aggregate microtexture throughout the year [22].

98   Survey results obtained from these devices require statistical interpretation [1,23,] with individual devices

99   requiring harmonisation with the rest of a fleet [24]. Friction measurements from rubber contact base

100   devices are also known to be susceptible to changes in travel speed [25]. Direct comparison between

101   different devices adopted in particular countries is also difficult, as measurements are influenced by

102   machine operating conditions such as the load, speed, slip ratio and the composition of the rubber.

103

104   The problems associated with contact measurement techniques, make a reliable non-contact technique

105   desirable. Accurate non-contact macrotexture measurement is one step towards the estimation of

106   pavement friction values via analytical modelling [5,26,27,28]. Researchers have successfully deployed

107   contactless techniques under laboratory conditions to measure texture; typically to a size of 100 x 100

108   mm [29,30]. At present, there are also a number of in-situ proprietary spot contactless techniques

109   available for use in the field, including the Circular Texture Meter [31], the Model 9300 laser texture

110   scanner [32] and close-range stereo photogrammetry [33,34,35], which requires a minimum of three

111   images taken from different perspectives to reconstruct a 3D pavement surface. These techniques offer

112   an alternative to the simple sand patch test [14,36,37], where a measured volume of fine material is

113   spread in a circular motion into a road's surface depressions to find the mean texture depth, for in-situ

114   localised pavement texture assessment. Recent research, focused on the development of a prototype

115   test rig [38] adopting a laser range finder, that uses triangulation, to measure texture in the field or to

116   detect defect on pavements [39], but is still restricted to a localised area comparable to that of a sand

117   patch test. The minimum texture profile height measured by the rig was limited to 0.032 mm, with a

118   spatial sampling frequency of about 4 mm^{-1}, thus meeting only part of the range needed for macrotexture.

119   3D handheld scanners [40, 41], using triangulation principles, have also been deployed to capture

120   macrotexture in-situ [42]. These scanners are designed for metrology applications, and having a limited

121   field of view, lack scalability. Advances in 'off-the-shelf' laser and photogrammetry technology and point

122   cloud post-processing applications means there is now the potential to capture macrotexture over larger

123   areas, potentially more representative areas using contactless techniques. Terrestrial Laser Scanning (TLS)

124   offers rapid, full 3D high resolution reconstruction of a highway surface as a point cloud [43] and Structure

125   from Motion (SfM) photogrammetry [44,45] offers a low-cost method utilising digital images to generate

126   a 3D dense point cloud data of surfaces.

127

128   This paper introduces a method to characterise macrotexture using TLS and SfM over a typical full lane

129   width. Recent research [34] suggests that frictional resistance is sensitive to certain areal parameters

130   [46,47] (Table 1). Particularly, to the density of peaks within the macrotexture of a highway surface, Spd,

131   and to the pointiness or arithmetic mean of the principal curvature of the same peaks Spc; which together

132   characterise the shape and size of the road aggregates. Furthermore, the areal parameters root mean

133   square of surface departures, S_q, as the standard deviation of peak height from an average plane, is

134   spatially equivalent to mean profile depth [48]. Mean profile depth represents the averaged values over

135   an overall 2D profile length, of the difference within a lateral distance (typically in the order of a

136   tyre/pavement contact) between the profile and a horizontal line through the top of the highest peak.

137   This paper explores the accuracy of the scalable TLS and SFM approaches to determining these

138   measurements in comparison to measurements achieved using a 3D Smart Laser Profile Sensor [49]. The

139   3D Smart Laser Profile Sensor was selected as an accurate well-constrained controlled dataset of 2D

140   profile macrotexture measurements from which to formulate a 3D surface, as such laser profile sensors

141   are well-understood have been deployed widely previously to capture 2D profile measurements of

142   macrotexture [50, 51, 52]. This paper will first introduce the methods applied to capture point cloud data

143   in the field using the three techniques, before rigorously considering the accuracy of results obtained

144   through the application of spectral analysis, areal parameters and 2D cross-correlation.

145   **2. Methods**

146   *2.1. Remote sensing technology*

147 *2.1.1. Terrestrial Laser Scanning*

148 The TLS data were collected using the Faro Focus 3D X Series phase-based laser scanner on a tripod

149 mounted inverted as shown in Figure 1a. The static scanner was set-up at a height of 1 m above the

150 pavement surface on a levelled tripod, and the desired scanning parameters were entered on the

151 instrument's home screen. Figure 2 details the workflow for programming the scanner's settings prior to

152 completing a scan. To retain a practical completion time for the survey, a resolution of 1/5 and quality of

153 6x was adopted, providing a scan time of 22.38 minutes. The scanner stores data on a SD memory card,

154 and this was post processed using Faro Scene 7.1 software to extract, register and align the point cloud.

155 INSERT FIGURE 1 and FIGURE 2 HERE

156 *2.1.2. Structure from Motion photogrammetry*

157
158 Static digital images (5472 x 3648 pixels) were captured at the test location using a digital single-lens reflex

159 camera with 50 mm fixed focal length, mounted on a camera tripod and dolly (refer to Figure 1b).

160 Following the method of [34] a minimum of 60% forward overlap and 30% sideways overlap between

161 photographs was maintained. Previous research [45] has demonstrated that capturing flat surfaces using

162 SfM with predominantly parallel images, and adopting self-calibration of camera locations can cause

163 deformation of the point cloud typified by 'doming' effects. To prevent these affects, over lapping

164 photographs, were captured at three heights (500 mm, 600 mm and 750 mm) above the pavement

165 surface, across the width of the highway (Figure 3a).

166 Agisoft Photoscan version 1.3.4.5067 software 6 was used to post process the images enabling

167 reconstruction of the overlapping photographs into a 3D point cloud. The software determines the

168 position and orientation of cameras automatically using a scale invariant feature transform (SIFT) [44].

169 The SIFT matches up identified features across the image set, to establish their 3D co-ordinates and

170 generate a sparse cloud. The sparse cloud is then densified into a dense point cloud by the software using

171 Multi View Stereo techniques [53]. Figure 3 illustrates the key stages of the construction of a point cloud

172 from the camera images. Using this approach, an area equivalent to the width of a standard road lane

173 (3.65 m) was successfully reconstructed without deformation.

174 INSERT FIGURE 3 HERE

175
176
177 *2.1.3. 3D Smart Laser Profiling*

178   The 3D Smart Laser Profile Sensor, an LMI Technologies Gocator 2350, was mounted upon a trolley at a

179   height of 500 mm (Figure 1c) and powered by a 60-volt battery. One trolley wheel made contact with a

180   digital quadrature encoder fitted to a 200 mm circumference measuring wheel. The digital encoder was

181   wired to provide a pulse signal to the 3D Smart Sensor, being programmed to produce 40,000 pulses per

182   rotation of the measuring wheel. Each pulse equates to a travel distance of 0.005 mm and this information

183   is used to enable 3D surface profiles to be captured at variable speed. The 3D Smart Laser Profile Sensor's

184   settings where programme using Gocator Emulator version 4.6.7.17 software, installed on a conventional

185   laptop. Figure 2b details the workflow for programming the 3D Smart Laser Profile Sensor's settings prior

186   to completing a scan. The data were collected at walking speed every 201 pulses or 1.005 mm over a 3 m

187   section, with the 3D Smart Laser Profile Sensor operating at a typical field of view width of 300 mm. The

188   3D Smart Laser Profile Sensor, is equipped with the capacity to view the laser points forming the profile

189   line on the highway surface in 'real-time'. This facilitates adjustment of the laser exposure level and active

190   measurement area to accommodate ambient light levels, stray light and variability of highway surface

191   reflectivity. The surface profiles extracted from the 3D Smart Laser Profile Sensor were post processed

192   using Gocator_Emulator version 4.6.7.17 and kCSvConveter software to an ASCII xyz file format suitable

193   for point cloud post processing [54].

194   *2.2. Test location*

195   To test the three techniques a field site was selected that contained three standard types of pavement

196   surface within close proximity (Figure 4), allowing for the same ambient conditions to be assumed over

197   the surfaces. The site included a close graded dense bitumen macadam (DBM), and a gap graded hot

198   rolled asphalt (HRA), as well as surface dressing (SD). Test were undertaken on the dry pavement surfaces

199   with permanent ground control points being installed to demarcate each surface using 16 mm survey

200   nails.

201   *2.3. Deriving macrotexture parameters from non-contact survey techniques*

202   The 3D point cloud data for the DBM, HRA and SD surfaces were captured consecutively on the same day

203   using the three different techniques. The point clouds obtained from each technique were then aligned

204   utilising the installed reference ground control points in Cloud Compare v 2.10 software [55], to facilitate

205   direct comparison between the surfaces. Subsequently, 150 mm x 150 mm sample areas (representing a

206   typical laboratory specimen size) were clipped for each surface from the aligned point clouds for analysis.

207 These clipped point clouds were then loaded into MountainsMap Premium version 7.4 and the software

208 used to remove any transverse or longitudinal slope by method of least squares, and to calculate the

209 standard areal parameters as listed in Table 1, to characterise the macrotexture. Areal parameters were

210 adopted, in contrast to 2D profile parameters [56], as these are recognised as providing a more complete

211 description of a surface [46], capturing height with respect to both the 'x' and 'y' direction to characterise

212 functional aspects such as texture, shape and direction. In sampling the point cloud data to make

213 successful areal measurements it is important that Nyquist values be smaller than the smallest desired

214 surface macrotexture requiring characterisation. Nyquist sampling theorem states that the shortest

215 wavelength that can be defined from a digital dataset is two digital sample intervals long. Therefore, the

216 wavelength or sample length available to characterise pavement texture areal parameters, is defined by

217 the relationship between point cloud density and sample size.

218   INSERT TABLE 1 HERE

219 *2.4. Deriving 2D wavenumber amplitude spectra from non-contact techniques and filtering*

220 Image datasets can be analysed by MATLAB software to transform them to the wavenumber domain,

221 allowing images to be characterised by spatial frequency. Accordingly, 2D Kx-Ky wavenumber spectral

222 analyses of the samples [56] were calculated in MATLAB to determine the areal wavenumber

223 characteristics of the surfaces captured using the different techniques. To prevent spectral leakage caused

224 by discontinuities at the edges of each measured sample area, the amplitude of the signal at the outer

225 edges was attenuated using a cosine taper Tukey window that extended for 10% from the extreme edges

226 of the sample line [57].   The resulting 2D wavenumber spectra enabled the wavenumber content of the

227 data to be determined, which facilitated the selection of an appropriate 2D wavenumber filter to

228 attenuate high wavenumber noise from the macrotexture signal.

229 Examining the spectra for each non-contact technique the 3D Smart Laser Profile Sensor was the lowest

230 resolution technique, containing wavenumbers not greater than 0.1 mm^{-1}. Consequently, to achieve

231 conformity of the wavelengths for areal parameter analysis across techniques a wavenumber filter of 0.1

232 mm $^{-1}$ was applied to the SfM and TLS data. A low pass zero phase Butterworth wavenumber filter [57]

233 was then designed to remove high wavenumber noise components from the data, up to the Nyquist

234 wavenumber [58]. The filter was applied in a two-pass process, firstly for every trace in the x-direction

235 and then the y-direction, thus creating a 2D filtered data set. Normalised 2D autocorrelations and cross-

236 correlation plots of the filtered surface data were then prepared as a means of measuring image spatial

237 similarity (as the macro-texture scale pushes the limit of conventional differencing techniques adopted

238 for identifying similarity and change in point cloud analysis [56]).

239 **3. Results and discussion**

240 Nyquist values are given in Table 2. The 3D Smart Laser Profile Sensor minimum Nyquist wavelengths

241 mean that the technique is unable to measure a small part of the lower range of macrotexture

242 wavelengths between 0.5 and 1 mm. The SfM and TLS Nyquist wavelengths mean the techniques can

243 measure the full range of macrotexture wavelengths and have the potential to also measure some part

244 of microtexture below 0.5 mm, this capability should be explored as part of a further research study. The

245 Nyquist wavelengths vary between samples, possibly because the techniques are sensitive to pavement

246 surface albedo, environmental conditions, and edge effects. Given technique sensitivity, oversampling to

247 ensure a sufficiently fine Nyquist wavelength is beneficial and in this regard adopting a higher resolution

248 technique such as TLS is advantageous. The Nyquist wavelength for a TLS, will increase with distance from

249 the laser source, because of the elongation of the beam, as the angle of incidence with a surface increases.

250 Therefore, the optimal location to acquire TLS data with an 'off-the-shelf scanner', is within a narrow cone

251 of incidence directly in line with the laser source, with data captured using an inverted head tripod set-

252 up.

253 Surface height plots for each surface scanning technique are illustrated in Figure 5. For the DBM greater

254 similarity is evident between Figure 5(a) and Figure 5(b) as the 3D Smart Laser Profile Sensor and SfM

255 techniques have similar resolution. The higher resolution of the TLS is evident in the finer granularity of

256 plot Figure 5(c). All the techniques are able to capture the voids between aggregates (e.g. i) and aggregate

257 features (e.g. ii) on the DBM surface at the same locations. Equally, for the HRA surface there is greater

258 similarity between Figure 5(e) and Figure 5(f), the data captured with the 3D Smart Laser Profile Sensor

259 and SfM techniques. The higher resolution of the TLS is evident again in the finer granularity of the edges

260 of the red chipping aggregate (Figure 5g). Finally, although the SD aggregate chippings are the smallest

261 for the three surfaces, all the techniques have still collectively identified areas of void between aggregates

262 in blue Figure 5(J) to (l)(e.g. vi) and areas of elevated macrotexture in orange located to the right and left

263 edge of each plot. Again there is greater similarity between Figure 5(j) and Figure 5(k), the data capture

264 with the 3D Smart Laser Profile Sensor and SfM technique. The higher resolution of the TLS is evident in

265   the finer granularity of plot (l). The degree of similarity between the techniques has been characterised

266   using areal parameters and 2D correlation analysis discussed in Section 3.1 and 3.2 respectively.

267   INSERT FIGURE 5 AND TABLE 2 HERE

268   *3.1 Unfiltered areal parameters*

269   The areal parameters derived for each technique are given in Table 2. Sq is spatially equivalent to the

270   mean profile depth that is used at present to evaluate macrotexture. Table 2 shows that $Sq,$ for the 3D

271   Smart Laser Profile Sensor and SfM are within 0.002 mm agreement for the DBM, 0.013 mm for the SD

272   and 0.09 mm for the HRA. This presents the 3D Smart Laser Profile Sensor and SfM, as an alternative

273   method to capture texture depth. The TLS obtained results for Sq are very different, with differences in

274   comparison with the 3D Smart Laser Profile Sensor value ranging from 0.139 mm to 0.394 mm; the largest

275   value being obtained for the SD surface. The value for Sp and $Sv,$ the maximum peak and pit heights,

276   demonstrate greater agreement between the SfM and 3D Smart Laser Profile Sensor results, than the TLS

277   technique. The variance in TLS derived parameters is because of the higher resolution nature of the data.

278   Values for Spd and Spc, which have previously been shown to have positive correlations with skid

279   resistance [34], are typically different by an order of magnitude for all the techniques and surfaces

280   considered. The variability of Spd and Spc suggests the parameters are also sensitive to resolution and

281   limits the potential to adopt unfiltered data in 'universal' across technique parametric comparison studies

282   with friction. For Ssk, the parameter defining skewness (thus indicating whether texture is positive or

283   negative), all three unfiltered techniques were able to identify the positive texture of the surfaces. The

284   skewness is sensitive to the spatial sampling resolution of the technique, with closer agreement

285   demonstrated between the SfM and 3D Smart Sensor technique.

286   *3.2 2D Correlation analysis*

287   Areal parameters only characterise discrete functions of surface roughness. Therefore, 2D cross-

288   correlation analysis to measure x-y and z plane similarity between images was completed. Perfect

289   correlation is characterised by a strong central peak with a value of 1. The normalised 2D cross-correlation

290   plots are shown in Figure 6. For the DBM surface a central peak is evident of 0.4492 and 0.3515 for

291   similarity between the 3D Smart Laser Profile Sensor and SfM, and 3D Smart Laser Profile Sensor and TLS

292   respectively (Figure 6 (a) and Figure 6 (d)); defining positive correlation and symmetry (or lack of shift)

293   between the wavelength frequencies. To the left of the central peak there is a dominating positive feature

294   on both plots, depicted as the yellow to red zone (e.g. Figure 6 (a)(i)), representing an area of higher

295   macrotexture departure from the surface. For the SD surface, no central peak is evident with elongated

296   bands of positive and negative agreement being visible (Figure 6 cii and ciii) for similarity between both

297   the 3D Smart Laser Profile Sensor and SfM, and 3D Smart Laser Profile Sensor and TLS. The bands arise as

298   the macrotexture of the SD surface is dominated by a repeating texture feature.

299

300   Overall, the best correlation is achieved between the 3D Smart Laser Profile Sensor and SfM measurement

301   technique for the HRA surface Figure 6(b). The plot has a clear strong centralised peak of 0.729,

302   demonstrating an alignment or lack of lateral shift between the wavelength frequencies of the two

303   techniques. The rest of the plot is generally blue indicating a general lack of secondary dominating

304   features on the surface. This can be attributed to the parity of resolution between two techniques and

305   the larger wavelength features of the HRA surface. The 2D cross-correlations affirm the areal parameter

306   results with greater agreement between the unfiltered 3D Smart Laser Profile Sensor and SfM surface

307   measurements. The 2D cross-correlation plots comparing similarity between the 3D Smart Laser Profile

308   Sensor and TLS demonstrate less agreement. The normalised cross-correlation peaks are either not

309   present or where present are lower being 0.3515 for the DBM (Figure 6(d)). This confirms the influence

310   of the higher resolution shorter wavelengths within the unfiltered data, which cause the reduction in the

311   normalised peak, and reduced agreement. After the application of a 0.1 wavenumber filter the heights of

312   the normalised 2D cross- correlation peaks increase by 16.6 to 25% demonstrating stronger agreement

313   between the 3D Smart Laser Profile Sensor and the other two techniques.

314   INSERT FIGURE 6 HERE

315   *3.3 Filtered areal parameters*

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

317   INSERT Figure 7 Here

318   surfaces after the application of a 0.1 mm^{-1} wavenumber filter there is greater visual similarity between

319   all three techniques. The filter has reduced the resolution of the TLS data, removing the finer granularity,

320   to reveal the macrotexture more clearly. Furthermore, post-filtering increased agreement was achieved

321   for areal parameters *Spd* and *Spc,* previously shown to have a positive correlation with skid resistance*.*

322   The filtered areal parameters are shown in Table 2. The filtered *Spc* (arithmetic mean peak curvature)

323   values, related to the shape of the road aggregates, measured using the 3D Smart Laser Sensor and SfM

324   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

325   not demonstrate agreement. The filtered Spd (peak density) values, related to the distribution of road

326   aggregates upon a pavement surface, measured using the 3D Smart Laser Sensor and SfM are within

327   0.00087mm^{-2} for the DBM, 0.01417 mm^{-2} for the HRA, and 0.00044 mm^{-2} respectively for the SD. The

328   filtered Spd (peak density) values measured using the 3D Smart Laser Sensor and TLS are within 0.00059

329   mm^{-2} for the DBM, 0.01747 mm^{-2} for the HRA, and 0.00054 mm^{-2} for the SD. The filtered Spd values

330   measured using the SfM and TLS are within 0.00028 mm^{-2} for the DBM, 0.0033 mm^{-2} for the HRA, and

331   0.0001 mm^{-2} for the SD. Although an increased agreement has been achieved for Spd and Spc, importantly

332   for practical pavement characterisation of surface height departures, for the 3D Smart Laser Profile Sensor

333   and SfM techniques this is at the expense of the accuracy of $Sq,$ which experiences magnification at a

334   range of four to ten times. Therefore, filtering improves spatial agreement, but at the cost of vertical

335   measurement, a factor that should be considered by researchers seeking correlations between non-

336   contact texture measurements and skid resistance. Moreover, the filtered values of Sq obtained from the

337   TLS whilst closer to the original unfiltered 3D Smart Laser Profile Sensor, demonstrate at best ten percent

338   accuracy; being in 0.213 mm agreement for the DBM, 1.928 mm agreement for the HRA and 0.063 mm

339   agreement for the SD. The TLS technique does offer the best balance between the vertical and spatial

340   areal functions post-filtering, fundamentally because it enables oversampling of the surfaces, with

341   correspondingly the shortest Nyquist wavelength. However, the improved resolution of the technique still

342   does not lead to sufficiently accurate measurement of Sq, the vertical departure heights from a pavement

343   surface. Greater technique resolution does not necessarily equate to sufficiently improved accuracy for

344   some measurements.

345   *3.4 Spectral analysis*

346   The spectra in Figure 8 illustrate the areal wavenumber characteristics of the three surface materials in

347   the 'x' and 'y' plane [55]. As wavenumber is the reciprocal of wavelength, the plots serve to demonstrate

348   differences in macrotexture characteristic between the surfaces. The spectra are sensitive both to the

349   scale of the macrotexture and the technique of measurement. The TLS has the largest spectral cloud of

350   the three techniques for all surfaces, illustrating that it is consistently the highest resolution technique.

351   Considering the SfM spectral plots, it is clear that the HRA surface has the largest wavelength features

352 represented by the brightest spectral cloud centre; whilst the DBM contains the smallest wavelength

353 features represented by the largest cloud. As a high pass filter was not applied to the cloud data, the larger

354 wavelengths in the centre of the spectral plots represent the unevenness of the surfaces. The spectra

355 reveal for the SfM technique that for the HRA the wavelengths features are typically 4 mm or larger; the

356 SD 3.5 mm or larger and DBM 2.6 mm or larger. Finally, greater similarity is generally evident between

357 the unfiltered spectra for the SfM and 3D Smart Laser Profile Sensor, as the techniques have similar

358 resolution and accuracy.

359 <p align="center">INSERT FIGURE 8 Here</p>

360 *3.5 Spatial variability*

361

362 The spatial variability of *Sq, Ssk, Sp, Sv, Spd* and S*pc* for seventy-two 150 mm x 150mm samples and

363 eighteen 300 mm x 300 mm samples captured using SfM were considered for a 1.8 m x 0.9 m area of HRA

364 in Figure 9 and 10.

365 <p align="center">INSERT FIGURE 9 and 10 Here</p>

366 The computed parameters (*Sq, Ssk, Sp, Sv, Spd* and S*pc*) for each individual sample, were divided into a

367 percentage of the overall maximum for each considered areal parameter, with the discrete colour

368 contrasts representing 20% . Thereby each colour represents a 20th percentile in the overall maximum

369 parameter value, and thus illustrates the variability of the parameters across the 1.8 m x 0.9 m HRA surface

370 . The 150 mm x 150 mm sample size for *Sp,* maximum peak height, reflects the distribution of red

371 aggregate chippings across the HRA surface. Lower peaks are encountered near the top edge of the

372 sample, where the surface is predominantly bituminous binder. Some discrete squares of increased peak

373 height are shown in dark green, representing the higher texture height of isolated red chippings.

374 Principally, the peak height values *Sp* are within the percentile range of 1.85 mm to 3.65 mm. The 150 mm

375 x 150 mm sample size for *Sv*, maximum pit height, demonstrated limited variability between separate

376 sample areas, with 87.5% of the HRA surface being within 4.4 mm to 7.4 mm. This consistency most likely

377 reflects the method of laying HRA, with the precoated red aggregate chippings being scattered across the

378 surface of the previously laid asphalt binder and rolled into the surface at a constant pressure, resulting

379 in more consistent pit heights. For vertical macrotexture characterisation parameters, such as *Sv* , *Sp* and

380 *Sq* spatially equivalent to the mean profile depth used at present to evaluate macrotexture, there is some

381 similarity between the location of darker colour contrast for both the 150 mm x 150 mm and 300 mm x

382 300 mm sample sizes.

383

384 There is a lack of parity between the surface characterised using the 150 mm x 150 mm sample and the

385 300 mm x 300 mm sample for *Spd*; with an increase in sample size appearing to 'smooth' the density of

386 peaks removing altogether the highest percentile range 3.42×10^{-3} mm^{-2} to 4.06×10^{-3} mm^{-2} from the 300

387 mm x 300 mm plot. The 150 mm x 150 mm samples reflect the distribution of red chippings across the

388 surface, with the lower peak densities recorded near the top and edge of the HRA surface where there is

389 predominantly bituminous binder present. The *Spd* parameter also demonstrates the greatest variability

390 between different 150 mm x 150 mm samples. *Spd* has previously been shown as being important to skid

391 resistance, with positive correlation achieved with friction measurements. However, the variability of *Spd*

392 values, means picking a representative 150 mm x 150 mm sample to characterise the whole surface to

393 correlate with friction is difficult. *Spd* represents the number of peaks in a unit area and is sensitive to

394 sample size. Figure 11 considered the influence of upscaling the sample size for areal parameters (*Sq, Ssk,*

395   INSERT FIGURE 11 Here

396   *Sp, Sv, Spd* and S*pc*) on the HRA surfacing capture using SfM with the point cloud extended to 1.05 m x

397 1.95m. For *Spd* the optimum sample size for the HRA surface was found to be 1050 mm x 1050mm. For

398 the vertical macrotexture parameters, the optimum sample size was found to be 750 mm x 750 mm for

399 *Sv* , 1050 mm x 1200 mm for *Sp,* and 1050 mm x 1650 mm for *Sq*.

400 For S*pc* mean curvature of peaks, the optimum sample size was discovered to be 450 mm x 450 mm for

401 the HRA surface. S*pc* was found to have the smallest sample size of all the parameters considered perhaps

402 reflecting its general lack of heterogeneity. The 150 mm x 150 mm sample size demonstrating the least

403 variability across the HRA surface of any of the areal parameters considered by the study; with 80% of the

404 samples falling within the 20% range 0.58 mm^{-1} to 0.88 mm^{-1}.

405

406 Whilst *Sq*, *Sp, and Sv* just capture the overall height and depth of peak and pit surface departures, *Ssk*

407 gives the location (or skewness) above and below the mean plane; consequently, providing an indication

408 of the distribution of texture available to contribute to skid resistance. For *Ssk*, both the 150mm x 150

409 mm and 300mm x 300 mm sized samples confirm that the HRA has positive texture. The split of the

410   contrasting light and dark blue squares for *Ssk*, is similar for each sample size, with the predominant

411   number of darker squares below the white diagonal line bisecting the 1.8 m x 0.9 m area (refer to Fig 10).

412   However, the location of the mean plane was determined to be sensitive to sample size, with the value of

413   *Ssk* varying. A sample size of 1050 mm x 1200 mm of smaller was found in the upscaling analysis to have

414   a negative texture confirming a positive texture, but above this size *Ssk* was shown to have a positive value

415   indicating a skew to negative texture. The change in *Ssk* can be attributed to the influence of the variability

416   of peak height with changing sample area, on the location of the mean plane. Overall reviewing individual

417   areal parameters typically used to characterise friction (*Sp, Sv, Spd* and S*pc*) optimal sample size, suggests

418   that a suitable sample size of 1050 mm x 1200mm is appropriate to characterise HRA; this being

419   established from the maximum size of the individual parameters

420

421   Further research should be conducted to explore the efficiency of sample sizes for areal parameters for

422   different pavement textures. As contact friction devices are known to be susceptible to seasonal variation

423   and machine operating conditions such as load, speed slip ratio and the composition of rubber, using

424   reliable non-contact areal parameter data to be able to analytically model a relationship with friction is

425   desirable. Moreover, higher resolution does not always equate to greater accuracy. It was found that

426   whilst SfM photogrammetry successfully provides an alternative method to the 3D Smart Laser Profile

427   Sensor to capture vertical pavement measurement *Sv, Sp and Sq* for mean profile depth estimation and

428   correlation with friction, the higher resolution TLS data contained significant inaccuracies. Furthermore,

429   the values of *Spd* and S*pc*, which together define the shape and distribution of pavement aggregates and

430   have previously been proven to have positive correlation with friction [34], are sensitive to resolution,

431   incurring order of magnitude differences. A 2D low pass wavenumber filter achieved improved agreement

432   with the 3D smart profiler for *Spd* and S*pc* parameters. Optimising such filters consistently across a range

433   of non-contact techniques is needed to achieve a 'universal' correlation between these parameters and

434   to model relationships with skid resistance. Further, as the application of such a filter has the potential

435   to impact on vertical accuracy of measurement (*Sq, Sp,* and *Sv*) for some high resolution techniques,

436   findings of this study indicate the filter should be applied only to the *Spd* and S*pc* spatial parameters.

437

438

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 Spd, 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.

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