Asphalt production, paving and compaction techniques

Evaluation of innovative automated systems for monitoring asphalt pavement surface conditions in England. Part 1: Surface Regularity and Texture

Giacomo D'Angelo[1], Yi Xu[2], Iswandaru Widyatmoko[2], Robin Hudson-Griffiths[1], Arash Khojinian[1], Malcolm Simms[3], David Giles[4]
[1]Highways England, [2]AECOM, [3]Mineral Products Association, [4]Eurobitume UK

Abstract

Methods for measurements of asphalt pavement properties play an important role in assessing compliance to work specifications. At the same time, the continuous monitoring of pavement conditions can facilitate improvement in planning or trigger early sign for maintenance. Currently, the conventional methods used to measure and monitor pavement conditions typically require manual handling and operations during various phases of construction works or surveys. These methods inherently carry safety risks for site technicians and operators. These risks could be removed or mitigated if relevant automated technologies currently available for the construction industry would be employed. This paper presents findings from a recent collaborative research commissioned by Highways England, Mineral Products Association, and Eurobitume UK, carried out by AECOM on automated assessment of pavement surface conditions. The scope of this study was to review and explore the possibility of employing systems available for quality control/quality assurance (QC/QA) purposes. This paper focuses on pavement surface regularity and macrotexture detection methods. Two innovative laser scanning technologies (laser systems 1 and 2) have been assessed and compared with conventional methods, i.e. Volumetric Patch and Rolling Straight Edge (RSE). Several survey trials have been conducted in England on motorways, trunk roads and local roads; comparison was made between the innovative and the conventional methods. Results from site surveys indicated that laser system 1 has a strong correlation with the Volumetric Patch results (94%) and a good repeatability. Laser system 2 matched the RSE outcome in the majority of sections surveyed (80%), presenting a fair repeatability. The few discrepancies between systems appear not to affect the outcome on pavement compliance to specifications. Overall, the analysed laser scanning technologies approximated to the conventional methods. Additional work (e.g. reproducibility trials) is expected to improve the confidence on findings from this study for consideration of adopting them for QC/QA purposes.

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1. INTRODUCTION

1.1. Background

Studies have shown that road workers carry among the highest risk of fatality amongst construction workers [1]. Improving safety for both employees and road users in relation to work zone areas on, and adjacent to, roads was the primary concern of the study. Similarly, conventional methods used to assess the compliance of new pavements typically involve manual handling and operations during various phases of construction works or surveys. These site technicians and operators are exposed to significant risk as a direct result of this. These risks could be minimised or mitigated if the manual works can be substituted by automated technologies which have become increasingly available for the construction industry.

1.2. Scope

The scope of this study is to review the most relevant systems, and explore the possibility of employing systems readily available in England for quality control/quality assurance (QC/QA) purposes. According to ISO 9000:2015 [2] definitions: QC is the part of quality management focused on fulfilling quality requirement; QA is the part of quality management focused on providing confidence that quality requirement will be fulfilled.
This paper focuses on pavement surface regularity and macrotexture detection methods. Two innovative laser scanning technologies have been assessed and compared with conventional methods, i.e. Rolling Straight Edge (RSE) and Volumetric Patch. Several survey trials have been conducted on English motorways, trunk roads and local roads, and comparison was made between the innovative and conventional methods.

2. LITERATURE REVIEW AND TECHNOLOGY SELECTION

2.1. Review of Existing and Innovative Technologies for measuring Asphalt Surface Regularity

Pavement roughness is one of the most important characteristic of pavement surfacing, as an indicator of functional performance and structural condition. BS EN 13036-6 defines the unevenness as the "deviation of a pavement surface from a filtered true planar surface in wavelength range of 0.5 m to 50 m" [3]. According to this standard, any device able to obtain a real profile is valid for profiling as long as it satisfies the objective of the measurements. A profilometer system can be mechanical, acoustical, electro-optical or a video camera [4].

In England, the Manual of Contract Documents for Highway Works (MCHW) specifies the maximum permitted number of surface irregularities (Table 7/2) in sections of 75 m or 300 m long for the specified road categories [5]. Conventional methods used in England are the rolling straight-edge test for longitudinal regularity and 3 m straight-edge for transverse regularity in accordance with BS EN 13036-7 [6].

MERLIN (Machine for Evaluating Roughness using Low cost Instrumentation) provides discrete readings and reports the roughness in MERLIN scale which can be converted to International Roughness Index (IRI) through empirical calibration equations. This equipment was purposely designed for use in developing countries for its benefits of easy to use, low cost, low maintenance and reasonable accuracy.

Higher levels of precision (Class 1 ASTM E950) is offered by stationary (e.g. ROMDAS z-250 or DipstickTM) or walking profilometers (e.g. ARRB G3). However, as per the MERLIN, the main limitation of these systems is that an operator is needed to 'walk' them along the road.

Accelerometers can measure the relative movement in 3D, being able to detect pavement irregularities at higher speed. In this regard, two smartphone applications (RoadBump Pro and Roadroid Pro V2) were developed to make use of modern smartphones capabilities and real-time processes. Nevertheless, these systems are considered to have a relatively poor level of accuracy [7].

More accurate systems making use of accelerometers are used by Dynatest, ARRB, ROMDAS and ARAN, among others, typically for calculating the IRI. However, these systems are generally employed as a support for validation and verification of other data collection systems (e.g. laser profilers).

To obtain a profile with a high level of accuracy (Class 1 ASTM E950), laser profilers are the most common techniques. In this regard, P3-AT (autonomous robot) and ALPS2 (Automated Laser Profile System 2) are two relevant research projects making use of laser technology to automatically measure regularity of pavement. Their measurement of IRI is comparable to that of the ARRB Walking Profiler, their main advantages being the use of a joystick (for P3-AT) and the full carriageway cover (for the ALPS2), respectively. Laser systems are amongst others used by Dynatest, ARAN, ROMDAS, Pathway Services Inc., International Cybernetics, LIMAB RoadRun, PaveTesting, AID, ERI, Pavision, PaveVision3D Ultra, HSP and SSI [7]. MATtest Laser Straight Edge (LSE) system uses a software which calculates a running 3 m straight line. Therefore, results can be correlated to the Rolling Straight Edge (RSE), which is the conventional method used for QA in UK. In this regard, this system can be of particular interest for the UK network.

A summary of reviewed technologies to measure surface regularity and their main characteristics to measure surface regularity is presented in Table 1.

2.2. Review of Existing and Innovative Technologies for measuring Asphalt Surface Macro-Texture

Macro-texture is an important factor that contributes to the pavement skid resistance. It also provides drainage channels for water expulsion between the tyre and the pavement.

The conventional testing method for measuring texture depth is the volumetric patch technique, as described in BS EN 13036-1 [8]. In England, the MCHW clause 921 specifies the spacing, the location and the upper and lower limit of the average texture depths for materials other than thin surface course systems, which are instead specified in clause 942 [9].

Close Range Photogrammetry is an innovative 3D modelling method developed by Ulster University to investigate surface texture. The data collection is based on camera images. Different volumetric properties can be extracted once the 3D dense point cloud is generated. However, this procedure needs image post processing with specific software/skills requirements, bringing down the level of automation.

The RoboTex and the Circular Texture Meter (CTM) are examples of equipment that use computer vision techniques. These research technologies make use of laser line scanning which can provide a 3D texture map. In this way, macro-texture measurements can be directly compared with measurements obtained using volumetric methods. The CTM is a stationary apparatus while RoboTex is a robotic apparatus. Both are not completely autonomous in detecting surface texture, however, these technologies allow a rapid, dense and precise data sets acquisition.

The WDM Texture Meter (TM2) and the Transit NZ Stationary Laser Profiler (SLP) are examples of measuring instruments using single point laser for a high-precision measurement of the road surface. These technologies present a good correlation with Volumetric Patch. However, they still require an operator on site.

The above-mentioned technologies have in common relatively slow speed and low automation level. These issues are overcome by vehicle-mounted systems which typically measure surface texture at traffic speed without the need for traffic disruption.

These technologies use a laser line scanning and camera for creating 3D surface reconstructions. Such an approach is amongst others used by ARAN, ARRB Hawkeye, Dynatest, ROMDAS, ERI, Pavision, PaveVision3D Ultra, and SSI. A UK application of this system is given by MATtest 3D-TD. A common disadvantage is the high cost of the equipment, but the results generally correlate very well with field direct measurements. An additional advantage of using laser-based technologies is that apart from macro-texture, cracks (and other pavement distress) can be detected and categorised, when a sufficiently high projection frequency is used. This principle is used in the Laser Crack Measurement System (LCMS).

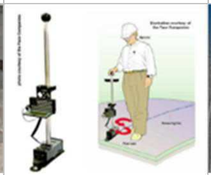
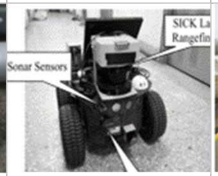
The review of conventional and innovative technologies and their main characteristics to measure surface texture are summarised in Table 2.

2.3. Selection of Innovative Technologies for further assessment

A wide range of technologies and products have been included in the review, ranging from early-stage research to fully-developed and trialled devices; from semi-automatic equipment to fully-automated, vehicle-mounted equipment. An objective of this study is to compare and validate the automated testing with the traditional methods. Thus, the technologies with high automation level, fast measurement speed, experience at the strategic highways network and availability in the UK were considered the most suitable for this purpose. Hence, the preferred options for further compliance assessment were chosen to be:

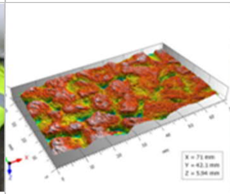
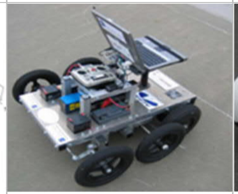
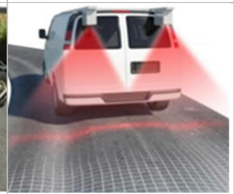
- Laser Straight Edge (LSE) for surface regularity measurements
- 3D-TD for surface texture measurements

Table 1. Asphalt Surface Regularity Measurement Technologies

Methods	Straightedge and Rolling Straight Edge	MERLIN (Machine for Evaluating Roughness using Low cost Instrumentation)	Stationary Inclinometer DipStick™; ROMDAS z-250	ARRB Walking Profilometer G3	Smartphone apps (RoadBump Pro and Roadroid Pro V2)	Inertial Profilers - Dynatest 5051 Mk II and IV Road Surface Profiler; or in ARAN	Autonomous Robot (P3-AT)	Automated Laser Profile System (ALPS2)	MATtest Laser Straight Edge
Visual appearance									
Data collection technique	Manual reading	Manual reading	Inclinometer	Rolling inclinometer	Accelerometer	Accelerometer plus laser	Laser	Laser	Laser
Automation	✕	✕	✕	Semi-automatic	✓	✓	✓	✓	✓
Precision and accuracy	Accuracy ± 0.25 mm (Rolling Straight Edge)	Class 2*or 3*	Precision of ± 0.127 mm (DipStick); R^2 = 0.95 (with IRI measurement); Resolution ± 0.05 mm (ROMDAS)	Precision of ± 0.01 mm; Longitudinal precision of ± 0.045%	Class 3* or 4*	Accelerometer resolution: 9.81 x 10^{-6} m/s^2; Accuracy: ± 5% of the measurements by manual profiling	Resolution of ± 0.0005 mm	Class 1*	Class 1*; r = 11% (for 4 mm irregularities)
Travelling Speed	1-2 km/h	Walking speed	Approx. 3.2 km/h	4.8 km/h	Best results at 50 – 60 mph.; Data collection at 30 – 60 mph.	Up to 70 km/h	Up to 3 km/h	8-20 km/h	Up to 80 km/h
Sample Interval		Variable	Every 250 mm (ROMDAS)	Every 241.3 mm	20 m - Roadroid	Every 25 mm	Every 150 mm	Every 6 mm	Every 1 m
Compatibility/ Correlation	Not correlated with other methods; IRI estimates	IRI and BI (fifth wheel bump integrator)	IRI	IRI	Poor correlation with IRI calculated from Class 1 devices	IRI; RN (Ride Number); Boeing Bump Index	IRI and RN	IRI	TRL device (RSE) by constantly calculating a running 3 m straight line; IRI
Research or QC/QA Tools	QC/QA	QC	QC/QA	QC/QA	Research / QC	QC/QA	Research / QC	Research / QC	
References	[10] [11]	[12][13][14]	[10][14][15][12][13][16][17]	[12][13][16][18][19][14][20]	[21]	[22][23][15]	[24]	[10][25][14]	[26][27][28]

*ASTM E950: Class 1 less than or equal to 0.1 mm; Class 2 greater than 0.1 mm to 0.2 mm; Class 3 greater than 0.2 mm to 0.5 mm; Class 4 greater than 0.5 mm

Table 2. Asphalt Surface Macro-Texture Measurement Technologies

Method	**Volumetric patch technique**	**Close Range Photogrammetry 3D model (UUTex3D);**	**Computer vision techniques: RoboTex; Circular texture meter (CTM) (stationary)**	**WDM Ltd Laser Texture Meter TM2**	**Transit NZ Stationary Laser Profiler (SLP)**	**LCMS (Laser Crack Measurement System) - 3D road scanning and texture**	**Dynatest 5051 Mk IV**	**MATtest 3D-TD Laser scanning**
Visual appearance								
Data collection technique	Manual	Camera (wide range of cameras can be used)	RoboTex: 1 kHz Laser line approx. 100 mm wide	Single 16 kHz Laser line	Single 32 kHz Laser along the 1.7m beam	3D Profiler: Laser line plus camera	3D Profiler: Laser line plus camera	3D Profiler: Laser line plus camera
Automation	✕	Semi-automatic	Semi-automatic	Semi-automatic	Semi-automatic	✓	✓	✓
Precision and accuracy	BS EN 13036-1: r = 0.166 mm R = 0.321 mm (Validity range: 0.5 mm – 1.2 mm)		RoboTex: Lateral resolution of 0.5-1.0 mm; Vertical resolution of ±0.01 mm; CTM: r = 3.2% R = 5.9%	Vertical resolution of <±0.05 mm; Longitudinal resolution of ±0.5 mm; Transversal resolution of ±1.0 mm;	Vertical resolution of ±0.0008 mm; Horizontal resolution of ±0.3 mm; r < 1%	Vertical resolution of 0.1-0.25 mm; Longitudinal resolution ±1 mm; Lateral resolution ±1 mm; r < 0.5%	Complies with ASTM E1845-01 and ISO 13473-1 Macrotexture; Longitudinal resolution ±1 mm;	r = 4% (see Section **Error! Reference source not found.**)
Travelling Speed			RoboTex:1.8 km/h CTM: N/A	3-5 km/h (walking speed)	N/A	100 km/h	Traffic speed (70 km/h)	Up to 80 km/h
Sample Interval	Every 5 m		RoboTex: (width: 100 mm) CTM: 0.9 mm	Every 2-5 mm (width: 100 mm)	Every 0.3 mm (width: 1.67 m)	5.600/28.000 profiles; Adjustable profile spacing		Every 1 m
Compatibility/ Correlation between different systems	MTD and MPD	Volumetrics	CTM: Correlation with Sand Patch: MTD= 1.03*MPD+0.15	MPD and RMSTD.	MPD Correlation with Sand Patch and LCMS (R^2 > 0.9)	MTD Correlation with SLP (R^2 > 0.9)	Correlation of macrotexture to friction and skid resistance	MTD Correlation with Sand Patch (R^2 > 0.94)
Research or QC/QA Tools	QC/QA	Research	Research	QC/QA	QC/QA	QC/QA	QC/QA	
References	[29][30]	[31]	[32][33][29][34]	[35][36]	[37][38][19][39][18][40]	[39][38]	[22][23][41]	[26][42][28]

3. ASSESSMENT OF SELECTED AUTOMATED TECHNOLOGIES IN CONTROLLING SURFACE REGULARITY AND MACRO-TEXTURE

3.1. Surface Regularity

Results obtained from the new technology, called Laser Straight Edge (LSE), selected in this study, were compared against those of the Rolling Straight Edge (RSE). Table 3 presents sites on the Strategic Road Network (SRN) in England where trials with the new technology were carried out, and the respective outcome on the compliance test results. The two methods appear to give comparable compliance results with the exceptions of M1 J5, A76 North of Garleffanand and A269 Ninfield Road. The A269 runs through small towns/villages including several junctions and has numerous iron works. In this regard, the discrepancies could be due to the different paths along the LSE and RSE surveys. RSE surveys would typically avoid white lining, iron works and other road features; whilst LSE is more likely to drive over these features in a straight run. Overall, LSE appears to have identified more surface irregularities than RSE. It is arguable that the travel paths explain the discrepancy in full. However, this may be an indication that LSE is a more rigorous measurement system than RSE. Following the analysis, the overview of initial findings is summarised in Figure 1. Overall, based on the data analysed, the automated LSE seems to approximate to RSE, matching the RSE outcome in the majority (80%) of the sections surveyed. Nonetheless further work is recommended to build up the evidence base for any future change to the contractual base line of the RSE.

Table 3. Technology Trial Sites and Compliance Test Results

Site	Compliance to MCHW1 Table 7/2 based on:	
	LSE	RSE
M1 J5	Pass	Fail (7 mm)NOTE 1
M25 J25	Pass	Pass
M25 J28	Pass	Pass
M25 J23	Pass	Pass
M4 J4	Pass	Pass
M4 J4 Heathrow Spur Road	Pass	Pass
A76 North of Garleffan	PassNOTE 2	Fail (10 mm)NOTE 2
A82 Garshake Road	Pass	Pass
M8 Arkleston	Pass	Pass
M1 J16-J19	Pass	Pass
A269 Ninfield Road	Fail (7 mm and 10 mm)	Pass
A46 Hobby Horse to Widmerpool	Pass	Pass

NOTE 1: The section was approximated to 75 m for the criterion for a compliance assessment.
NOTE 2: The two 10 mm irregularities detected by RSE were on joints. These joints were not included within the LSE survey.

LSE shows promising results when benchmarked on site trials versus RSE

Based on the limited number of trials the LSE generally appears to detect a higher number of irregularities than RSE

This could be due to the different path along the LSE and RSE, which would normally avoid white lining and road features

- ✓ H&S risk reduced (technician)
- ✓ BIM and PMS system incorporated
- ✓ Survey at Traffic Speed
- ✓ International Roughness Index (IRI) available
- ✓ Continuous Measurement & Road profile plots
- ✓ GPS location, time stamp & live feedback

Figure 1: Initial Findings from Automation in Surface Regularity

3.2. Surface Macro-Texture

The new technology being assessed called 3D-TD, developed by MATtest Southern Ltd [42], utilised a laser line scanning and camera for creating 3D surface reconstructions. Table 4 presents sites within the SRN where trials with the new technology were carried out. It reports also the average difference between the 3D-TD and Volumetric Patch (conventional method) for each site together with the variations of Volumetric Patch within the same site.

The absolute difference between the two methods for each site ranges from 3% to 13%, with a total average of 8%. This is comparable with the measured average variation of volumetric patch measurements for the analysed sites (7%). Therefore, 3D-TD outcomes are likely to reach the same conclusion in terms of compliance with specifications (Table 9/3 (08/08) of MCHW1) [9].

Further to this, results analysed show a correlation with Volumetric Patch of approximately 94% and a good repeatability. The relative difference between the two methods was lower than the volumetric patch variation from randomly selected locations within a nominally homogeneous pavement section reported in BS EN 13036-1 [8] (27%). Therefore, based on this work it is considered that 3D-TD approximates to the volumetric patch. Figure 2 presents an overview of the initial findings.

Table 4: % Difference between 3D-TD and Volumetric Patch, together with variations of Volumetric Patch

Site	Absolute Measured difference 3D-TD *v.* Volumetric Patch (%) Site average	Volumetric Patch Variations = SD/Mean
M1 J5	7%	7%
M25 J25	7%	8%
M25 J28	11%	13%
M25 J23	4%	11%
M4 J4	10%	8%
M4 J4 Heathrow Spur Road	8%	3%
A76 North of Garleffan	11%	9%
A82 Garshake Road	11%	10%
M8 Arkleston	7%	6%
M1 J16-J19	6%	4%
A269 Ninfield Road	7%	0%
A46 Hobby Horse to Widmerpool – 14 mm	13%	10%
A46 Hobby Horse to Widmerpool – 10 mm	3%	5%
Total average	**8%**	**7%**

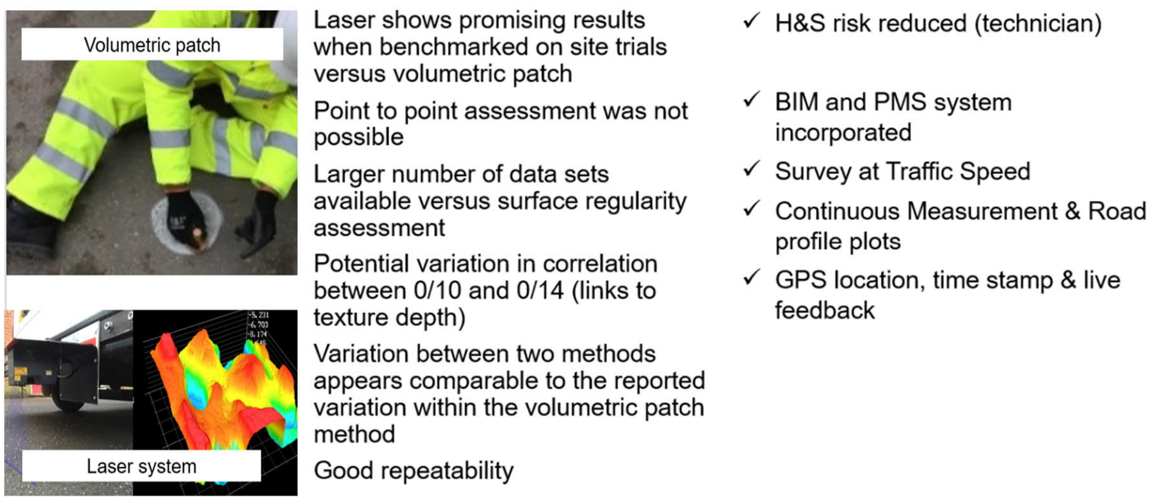


Figure 2: Initial Findings from Automation in Surface Macro-texture

4. CONCLUSIONS

Overall, the study has yielded further understanding of how innovative technologies can assist in increasing the automation level of conventional QC/QA test methods. The research has provided a foundation for further development of the assessed technologies and future revision of specification requirements.

Data sets of surface regularity and surface macro-texture from several schemes in the UK conducted on motorways, trunk roads and local roads have been analysed for both conventional and innovative systems.

For the measurement of surface regularity, the Rolling Straight Edge (RSE) is the industry standard method. The use of laser surveys to measure pavement regularity can output the total number of irregularities above 4 mm, 7 mm and 10 mm for a given section (75 m or 300 m), as specified in current MCHW. Based on the data analysed, the automated LSE approximates to RSE at 80% match. Nonetheless further work is recommended to build the evidence base for any future change to the compliance level of the RSE.

Volumetric patch is a standard method to measure surface texture depth, which is currently referenced in the MCHW. The laser surveys (3D-TD) can provide the average MTD for a 50 m section every 250 m, as specified in current MCHW Series 900 albeit on a linear direction (as opposed to diagonally within lane). Results analysed show a good correlation with volumetric patch (higher than 94%). Therefore, on the basis of this work, it is considered that 3D-TD approximates to the volumetric patch.

Overall, both LSE and 3D-TD systems present clear advantages in relation with conventional methods: the risk for a technician is reduced because the surveys are conducted under traffic speed without the need for road closure; measurements are carried out continuously and stored digitally with additional information for incorporation into management systems.

In this regard, these systems are useful supplementary methods to the contractual requirements for Highways England works. Further validation works should be carried out required before fully implementing these new technologies as direct replacement to the current specification. In this context, it is recommended to consider LSE and 3D-TD as screening tests whilst the RSE and Volumetric Patch remain use and the reference methods in cases of dispute.

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REFERENCES

[1] ETSC, Road safety at work zones, Prev. Road Accid. Inj. Saf. Employees Road Saf. Work Zo. (2011) 1–42.
[2] BS EN ISO 9000, Quality management systems Fundamentals and vocabulary, 2015.
[3] BS EN 13036-6, Road and airfield surface characteristics — Test methods — Part 6: Measurement of transverse and longitudinal profiles in the evenness and megatexture wavelength ranges, 2008.
[4] BSI BS EN ISO 13473-1, Characterization of pavement texture by use of surface profiles - Part 1: Determination of Mean Profile Depth, 2004.
[5] MCHW, Volume 1 Series 700 Road Pavements - General, 2016.
[6] BS EN 13036-7, Road and airfield surface characteristics — Test methods — Part 7: Irregularity measurement of pavement courses — The straightedge test, 2003.
[7] T.B.J. Coenen, A. Golroo, A review on automated pavement distress detection methods, Cogent Eng. 4 (2017) 1–23. doi:10.1080/23311916.2017.1374822.
[8] BS EN 13036-1, Road and airfield surface characteristics - Test methods - Part 1 : Measurement of pavement surface macrotexture depth using a volumetric patch technique, 2010.
[9] MCHW, Volume 1 Series 900 Road Pavements - Bituminous Bound Materials, 2009.
[10] M.W. Sayers, S.M. Karamihas, The little book of profiling - Basic Information about Measuring and Interpreting Road Profiles, 1998.
[11] UKAS, Measurement of Surface Regularity of Road Pavement Surfaces using the Rolling Straight Edge – Requirements for Calibration and Performance Checks, 2008.
[12] G. Morrow, A. Francis, S.B. Costello, R.C.M. Dunn, Comparison of Roughness Calibration Equipment - with a View to Increased Confidence in Network Level Data, (2004).
[13] G. Morrow, Comparison of Roughness Measuring Instruments, University of Auckland, 2006.
[14] H. Ceylan, R.F. Steffes, K. Gopalakrishnan, S. Kim, S. Yang, Development and Evaluation of a Portable

Device for Measuring Curling and Warping in Concrete Pavements, 2016.
[15] A. Marradi, Harmonization in pavement smoothness rating of new and old pavements, Copenhagen, Denmark, 2013.
[16] H. Wang, Road Profiler Performance Evaluation and Accuracy Criteria Analysis, Virginia Polytechnic Institute and State University, 2006.
[17] DCL, Z-250 Reference Profiler User's Guide, New Zeland, 2004.
[18] T.F. Henning, S.B. Costello, R.C. Dunn, C.C. Parkman, G. Hart, The Establishment of a Long-Term Pavement Performance Study on the New Zealand State Highway Network, Road Transp. Res. 13 (2004) 17–32.
[19] D.N. Brown, Measuring Pavement Condition Data for the Establishment of a Long-Term Pavement Performance Study on New Zealand Roads, (n.d.) 1–23.
[20] ARRB Group, Walking Profiler G3, (2015). https://www.arrb.com.au/Equipment-services/Walking-Profiler-G3.aspx?ForeignLanguage=3.
[21] A. Shah, J. Zhong, J. Ly, Adopting smartphone technology to supplement road asset performance monitoring, in: 17th AAPA Int. Flex. Pavement Conf., 2017.
[22] Dynatest, Dynatest 5051 Mark III/IV RSP Road Surface Profiler, (2013).
[23] Dynatest, Dynatest Model 5051 Mk IV – Portable Road Surface Profiler (RSP) - Quotation, (2017).
[24] J. Chang, Y. Su, T. Huang, S. Kang, S. Hsieh, Measurement of the International Roughness Index (IRI) Using an Autonomous Robot (P3-AT), in: 26th Int. Symp. Autom. Robot. Constr., 2009: pp. 325–331.
[25] B. Worel, B. Chadbourn, R. Strommen, MnROAD Automated Laser Profile System " ALPS ," 2003.
[26] MATtest Southern Ltd, Surface regularity, (2018) 1–3. http://mattestsouth.co.uk.
[27] MATtest Southern Ltd, Report to determine and compare Surface Regularity using the Laser Straight Edge and Rolling Straight Edge in accordance with SHW 702.5, 2017.
[28] MATtest Southern Ltd, Report to determine and compare traditional testing methods and new automated systems proposed by Mattest/HDS and Aggregate Industries, 2017.
[29] D.I. Hanson, B.D. Prowell, Evaluation of Circular Texture Meter for Measuring Surface Texture of Pavements, 2004. doi:10.3141/1929-11.
[30] Highway Department UK, Guidance Notes on Road Testing, 1989.
[31] P. Millar, D. Woodward, Ulster University Photogrammetric Method of Highway Surface Recovery and 3D Modelling (UUTex3D), 2017.
[32] E.T. Cackler, Evaluation of U. S. and European Concrete Pavement Noise Reduction Methods, 2006.
[33] R.Y. Kim, E. Jones, Development of a Testing System for Asphalt Surface Treatments, North Carolina State University, 2015.
[34] J.J. Henry, Determination of the international Friction Index Using the Circular Track Meter and the Dynamic Friction Tester, in: SURF World Road Assoc., 2000.
[35] W.D.M. Limited, TM2 Surface Texture Measurement, (2018). https://www.wdm.co.uk/equipment/equipment-tm2.
[36] D. Holloway, Calibration of laser devices used for the measurement of pavement surface texture: accuracy of pavement texture measurement, in: 3rd Int. Surf. Frict. Conf. Safer Road Surfaces, Saving Lives, Gold Coast, Australia, 2011: pp. 1–9.
[37] MAIN ROADS Western Australia, Surface Texture Depth Stationary Laser Profilometer method, 2012.
[38] J. Laurent, J.F. Hébert, M. Talbot, Using full lane 3d road texture data for the automated detection of sealed cracks , bleeding and raveling, in: World Conf. Pavement Asset Manag. WCPAM, Milan, Italy, 2017.
[39] Pavimetrics Systems Inc, LCMS - 3D road scanning and texture, 2017.
[40] P. Cenek, N.J. Jamieson, Sensitivity of In-Service Skid Resistance Performance of Chipseal Surfaces to Aggregate and Texture Characteristics, in: 1st Int. Conf. Surf. Frict., 2005: pp. 1–4.
[41] https://www.dynatest.com/rsp-mk-iv, Road Surface Profiler (RSP) MK_IV, (2017) 1–2. https://www.dynatest.com/rsp-mk-iv.
[42] MATtest Southern Ltd, Report to determine and compare the difference of the Mean Texture Depth using the 3DTD Laser device and sand patch method reported in accordance with SHW921 table 9/3, 2017.