Theoretical Development and Validation of a New 3D Macrotexture Index Evaluated from Laser Based Profile Measurements

Mauro D'Apuzzo[1], Azzurra Evangelisti[1], Daniela Santilli[1(✉)], and Vittorio Nicolosi[2]

[1] University of Cassino and Southern Lazio, Via G. Di Biasio 43, 03043 Cassino, Italy
{dapuzzo, daniela.santilli}@unicas.it, aevangelisti.ing@gmail.com
[2] University of Rome "Tor Vergata", via del Politecnico 1, 00133 Rome, Italy
nicolosi@uniroma2.it

Abstract. The Mean Profile Depth (MPD) is the synthetic index worldwide used to describe the macrotexture of road pavement surfaces. MPD is evaluated from two dimensional profiles captured by macrotexture laser-based devices, by means of ISO (International Organization for Standardization) or ASTM (American Society for Testing and Materials International) algorithms.

Several macrotexture laser-based measuring devices are present in the world market and, usually each one provides different MPD values also for the same road pavement. Furthermore the Standard Algorithm application produces MPD values affected by a wide variability. For these reasons the comparison of MPD values deriving from different laser-based macrotexture measuring devices is unsatisfying and it can produces deep misunderstanding on road macrotexture characterization.

In order to reduce the MPD variability and to improve the MPD values comparison a new algorithm to evaluate a more stable macrotexture synthetic index (Estimated Texture Depth) ETD, has been proposed. It has been developed with more than two hundred profiles belonging to virtual pavements and it has been validated on fifteen real road profiles.

The results seems to be promising: the Square Weight Estimated Texture Depth (ETDsw) provides more stable and reliable MPD values and in the same time, it improves the agreement between macrotexture values provided by different laser-based devices.

Keywords: Macrotexture · Profile analysis · Variability · Harmonization issue · Virtual pavement · Square Weight Estimated Texture Depth (ETD_{SW})

1 Introduction

It is worldwide recognized that road pavement macrotexture can deeply influence the safety and environmental performances nowadays required to the road surface. Indeed the macrotexture is directly involved into tire-pavement interaction phenomenon, as it affects the frictional resistance, the water and contaminant drainage, the vehicle riding comfort and the rolling noise and resistance [1].

© Springer Nature Switzerland AG 2020
O. Gervasi et al. (Eds.): ICCSA 2020, LNCS 12251, pp. 367–382, 2020.
https://doi.org/10.1007/978-3-030-58808-3_27

Based on this premise, it is reasonable to believe that, between the road pavement performance requirement classes, the macrotexture is one of the most significant, together with the evaluation of road performance in terms of skid resistance along the lines of the approach adopted in evaluating tire grip class [2]. At the moment, in the international overview, several macrotexture measuring devices and different evaluation algorithms exist.

The volumetric technique is the traditional method to measure the macrotexture of road pavements and provides the Mean Texture Depth (MTD) index, which is a 3-dimensional (3D) measurement of the macrotexture [3]. Lately the use of the macrotexture laser-based devices was becoming predominant and consequently, different algorithms for the profiles analysis and empirical relations for volumetric conversions, have been developed.

According to the ISO 13473 [4] and the ASTM E1845 [5], from the 2D profiles analysis, the Mean Profile Depth (MPD) index can be evaluated and the indirect macrotexture estimation, expressed by means of the Estimated Texture Depth (ETD) index, can be provided by means of the Eq. (1) [5] and (2) [6] if the High Speed Laser (HSL) or Static (Circular Texture Meter, CTM) Devices, have been used, respectively:

$$\mathrm{ETD} = 0.8\,\mathrm{MPD} + 0.2 \tag{1}$$

$$\mathrm{ETD} = 0.947\,\mathrm{MPD} + 0.069 \tag{2}$$

Regrettably, the macrotexture values, evaluated on the 2D profiles, are characterized by a wide variability which can be caused by two orders of factors: 1) pavement physically related (as the heterogeneity of used pavement materials [7] and laying techniques) and 2) measurement related (as the devices' technology and operating conditions and the profile analysis algorithms).

This variability can affect the reliability measure of the macrotexture and, in turn, the agreement between ETD estimated on the same pavements, by different devices.

With the aim to investigate the macrotexture variability due to the measurements related factors, a theoretical approach, based on the analysis of more than 200 virtual pavements has been performed. The virtual pavements have simple and repetitive geometric layouts (of which all the features are completely known) and can be considered an extreme simplification of the real pavements but allow to exclude the macrotexture variability caused to pavement physical factors.

Based on this theoretical approach, a new macrotexture descriptor, namely the "square weighted estimated texture depth", ETDsw [8], has been proposed, evaluated and validated on a set of 15 real road pavements belonging to the Virginia Smart Road test track.

2 Theoretical Approach

In order to characterize the macrotexture's variability due to theoretical and technical related factors, as the pavement laying finishing, the laser sampling technology and the algorithms for profiles analysis, and to improve agreement between road macrotexture measurements with different laser-based devices, a theoretical investigation has been performed on virtual pavements. It consists 1) in the generation of a set of virtual

pavements, designed on an heterogeneous set of real pavements; 2) in the profiles extraction by simulating different device technology sampling and 3) in the profile analysis, comparing different algorithms for macrotexture evaluation.

2.1 Design and Generation of Virtual Pavements

The outline of the virtual pavements has been inspired by the geometry of the concrete pavements finishing and some examples are reported in the Fig. 1a.

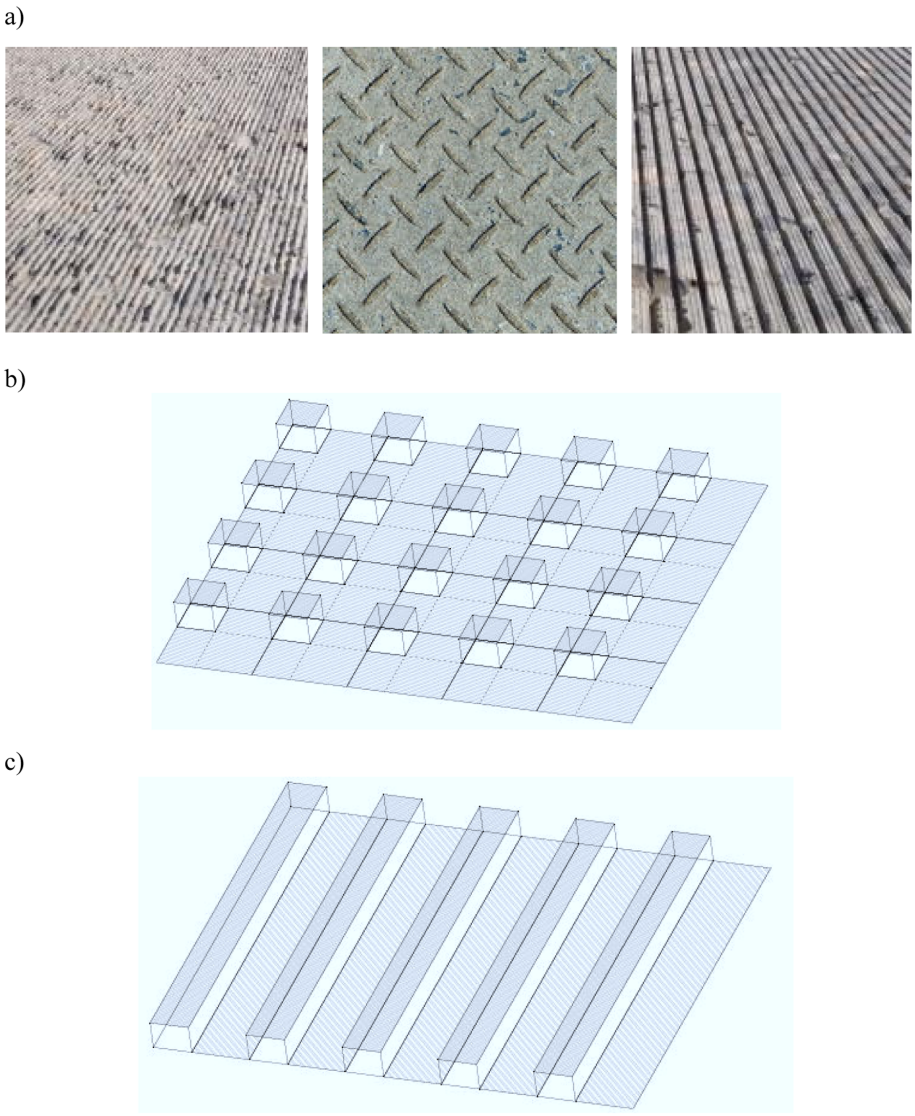

Fig. 1. a) Real concrete pavement finishing geometries; b) isotropic virtual pavement and c) orthotropic virtual pavement.

The generic layouts of virtual pavements have been reported in the Fig. 1b and Fig. 1c. As it is possible to see, they can be described as simple and repetitive geometric entities. If on an hand the layouts can represent a strong simplification, on the other, the most common and used texture synthetic indices, can be totally compute without approximation or uncertainty, as occurs for real road pavements.

According to the standards [4; 5; 6; 9] and to the layout reported in the Fig. 2, the definitions, summarized in the Table 1, can be expressed for both real and virtual pavements, respectively.

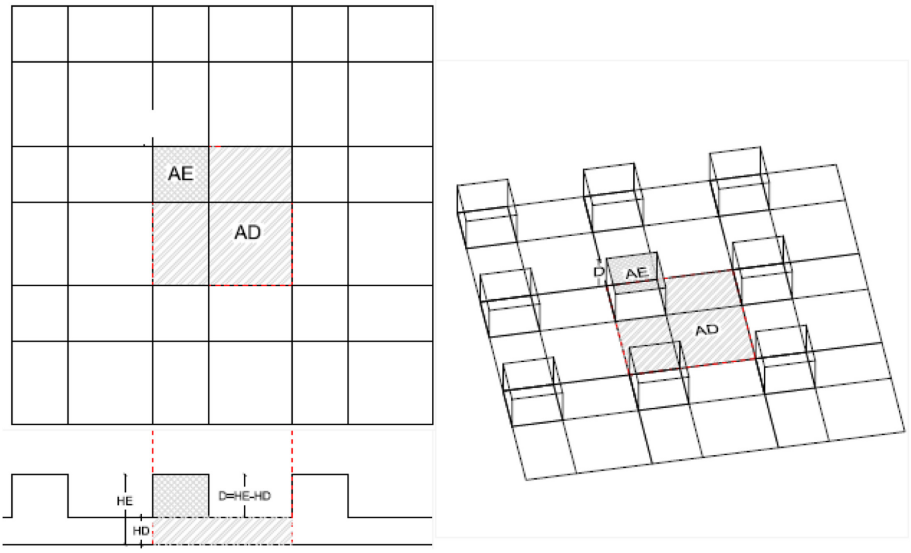

Fig. 2. Generic virtual pavement and nomenclature.

Table 1. Synthetic indices definitions for both real and virtual pavements.

Definition	Real pavement		Virtual pavement	
D = Depth between Peak height (HE) and Valley height (HD)			*HE – HD*	*(3)*
R = Ratio between Peak area (AE) and Valley area (AD)			*AE/AD*	*(4)*
MTD = Mean texture depth [4]	Equation (1) or Eq. (2)	*	$\frac{D}{R+1}$	**(5)
$\mathbf{R_q}$ = Root mean square [9]	$\sqrt{\frac{1}{l}\int_0^l z(x)^2 dx}$	*(6)	$\sqrt{\frac{R}{(R+1)^2}\cdot D^2}$	**(7)
$\mathbf{R_{SK}}$= Skewness [9]	$\frac{1}{l \cdot Rq^3}\int_0^l \lvert z(x)\rvert dx$	*(8)	$\frac{1-R}{\sqrt{R}}$	**(9)

* evaluated on 2D profiles; ** evaluated on 3D surface.
Where:
$z(x)$ = ordinate values of the pavement profile;
l = sampling length.

In order to obtain road pavements macrotexture values, as realistic as possible, a domain modelled on real road pavements has been conceived and used as pattern for the virtual pavement generation. Twelve real heterogeneous pavement mixes, belonging to the Virginia Smart Road track, have been selected: for each single pavement, a moving window, MS (Maximum Aggregate Size of the mixture) wide, has been advanced along the profile and the values of Depth (D) and Skewness (Rsk) [9], for each step, have been evaluated. Then, within a baseline, 100 mm long, the maximum, minimum and mean values, for both D and Rsk, have been computed. Their systematic combination allows to produce a more numerous and significant dataset, that has been used as foundation of the Rsk-D domain (see Fig. 3a).

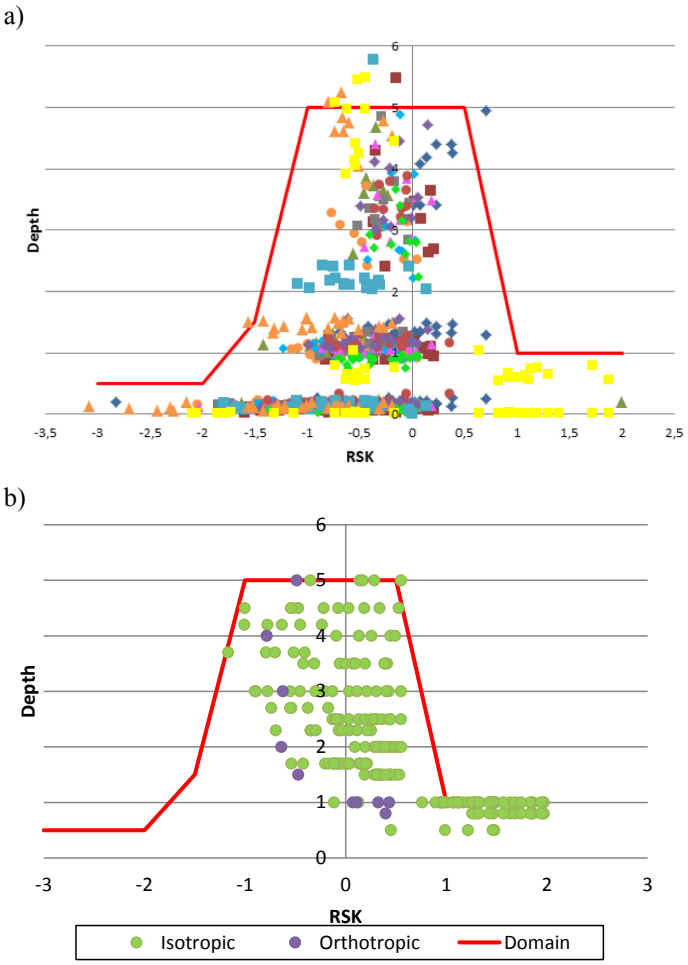

Fig. 3. R_{SK}-D domain from a) real pavements and b) virtual pavements.

Then, based on the domain (red line in the Fig. 3a), more than 200 virtual pavements have been generated (Fig. 3b). According to the real pavement types incidence, the 5% of the generated dataset follows the orthotropic layout (Fig. 1c) and the remaining part the isotropic layout (Fig. 1b).

As it is possible to see in the Fig. 3b, the generated dataset doesn't cover entirely the domain. It is due to the virtual pavements simplified geometry, which in the right-lower part of the domain corresponds to unrealistic layouts (too deep D or too wide AE or AD).

2.2 Extrapolation of Virtual Profiles

In order to simulate the virtual pavement profiles sampled by means of both Static and HSL measuring devices, two different algorithms has been implemented. Their features have been summarized in the Table 2.

Table 2. Features of both static and high speed laser-based measuring devices

Macrotexture laser-based measuring device	Static	High-speed
Length	892.2 mm along a circ.	Along the road pavement
Sample spacing	0.87 mm (approx.)	0.50 mm
Baseline length	111.525 mm	100 mm

In addition, the virtual profiles sampled by the HSL device, are characterized by a straight line, which follows the vehicle path. To better described the variability due to the sampling process, for each virtual pavement, virtual profiles every 5°, from 0° to 90°, have been extracted, as reported in the framework of Fig. 4.

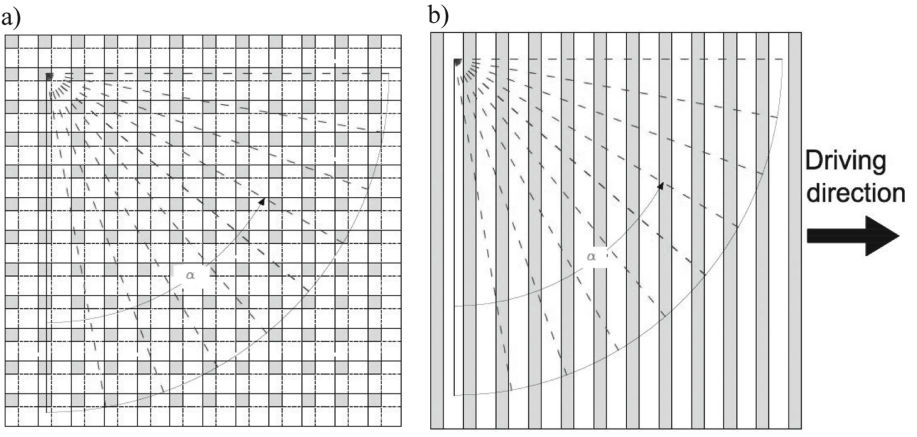

Fig. 4. High-speed laser sampling angles on both a) isotropic and b) orthotropic pavements.

Quite the opposite, the virtual profiles sampled by the Static device, are characterized by a circular line (see Fig. 5), for this reason, the analysis with different angles is not required.

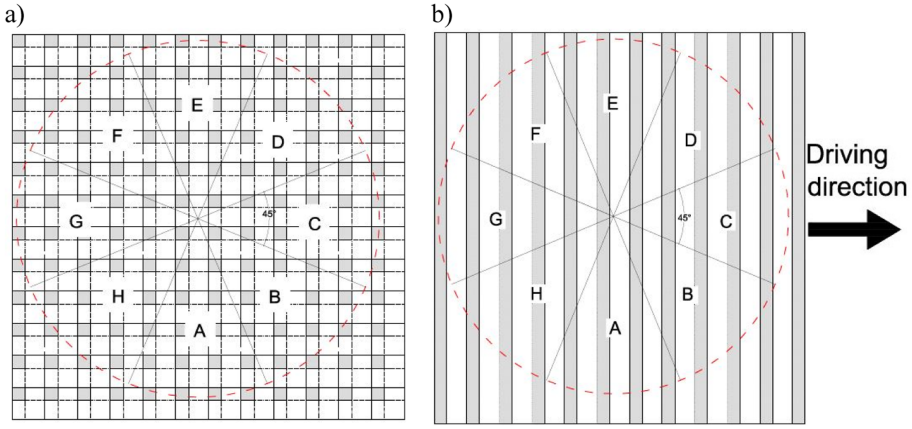

Fig. 5. Static laser sampling line on both a) isotropic and b) orthotropic pavements.

As an example, for a given isotropic pavement, virtual profiles, simulating both HSL and Static devices sampling technique, have been reported in the Fig. 6 and in the Fig. 7, respectively.

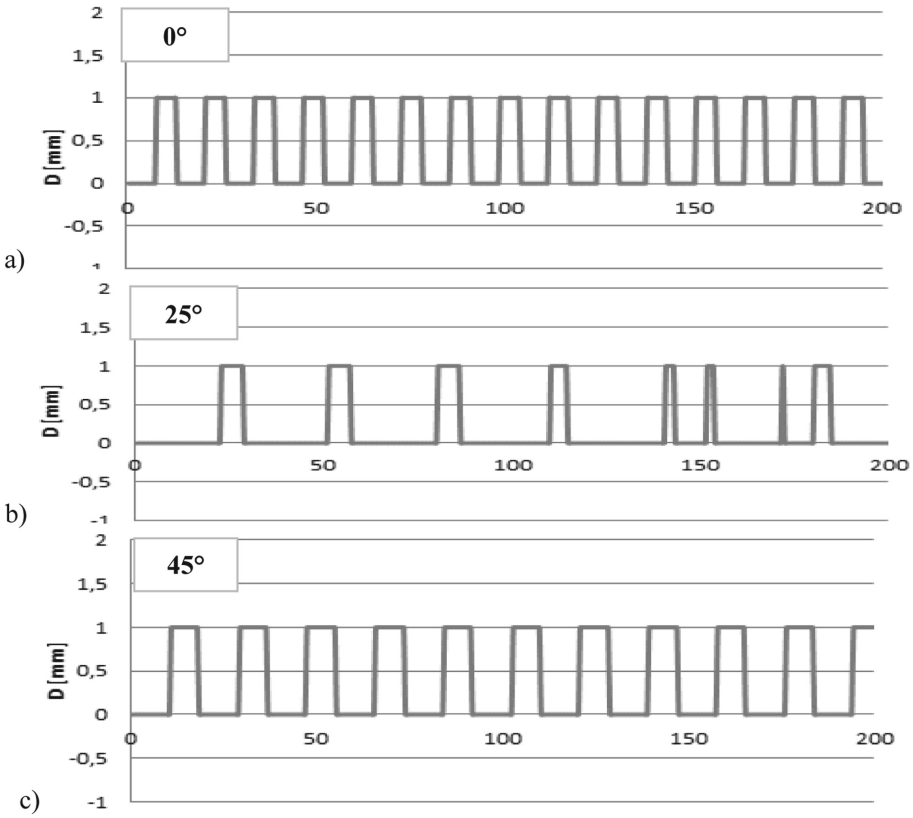

Fig. 6. Example of virtual profiles sampled by high speed laser device with a) 0°; b) 25° and c) 45° incident angle.

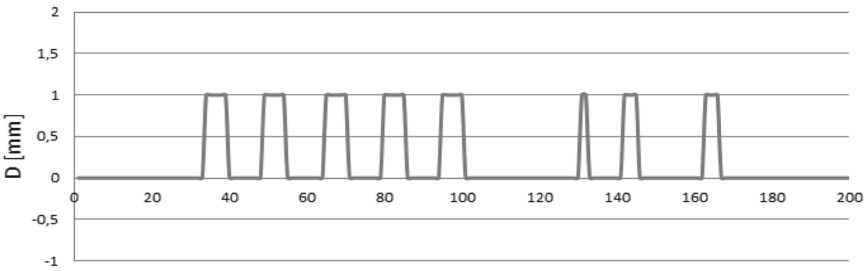

Fig. 7. Example of virtual profile sampled by static device.

2.3 Algorithms for Virtual Profiles Analysis

As far as macrotexture evaluation on 2D profiles has been concerned, according to the standards [4; 5; 6] and to the more widespread custom software, different algorithms have been proposed and their features have been summarized in the following Table 3:

Table 3. Algorithm features

Device	Static	HSL
Algorithm A: standard	A1 [6]	A2 [5]
Sample spacing	0.87 mm	0.5 mm
Baseline (BL) length	111 mm (approx.)	100 mm
Evaluation length for linear regression	55.5 mm	100 mm
Index evaluation frequency	1/111 mm	1/100 mm
ETD evaluation	Equation (2)	Equation (1)
Algorithm B: windowing – half BL	B1	B2
Sample spacing	0.87 mm	0.5 mm
BL length	111 mm (approx.)	100 mm
Evaluation length for linear regression	55.5 mm	50 mm
Index evaluation frequency	1/0.87 mm	1/0.5 mm
ETD evaluation	Equation (2)	Equation (1)
Algorithm C: windowing – whole BL	C1	C2
Sample spacing	0.87 mm	0.5 mm
BL length	111 mm (approx.)	100 mm
Evaluation length for linear regression	111 mm	100 mm
Index evaluation frequency	1/0.87 mm	1/0.5 mm
ETD evaluation	Equation (2)	Equation (1)

For each virtual pavement, by means of the algorithms (Table 3) and the Eq. 5, the macrotexture values have been computed and in the Fig. 8, the comparison of the macrotexture values, evaluated for both Static and HSL devices, has been shown.

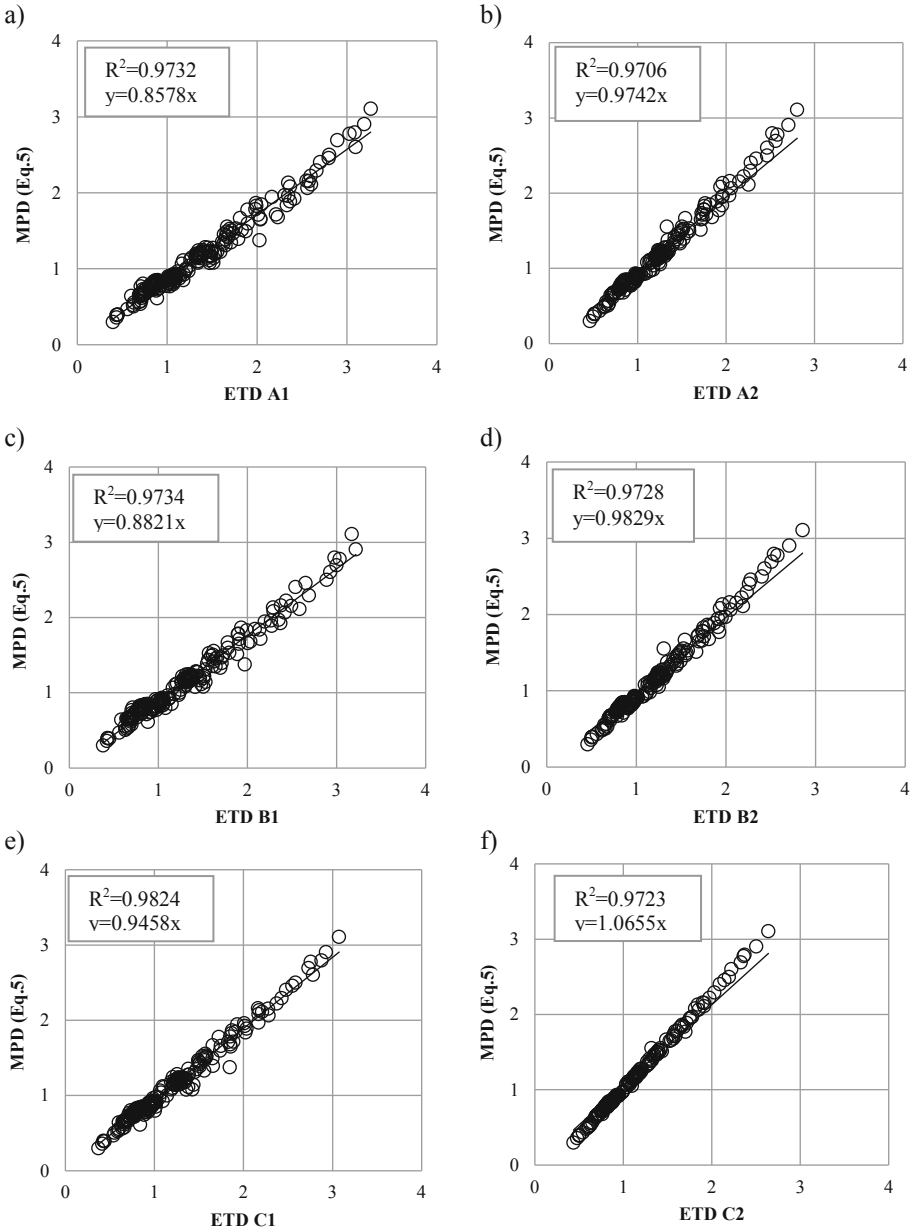

Fig. 8. Comparison of 3D macrotexture values (Eq. 5) VS a) ETD algorithm A1; b) ETD algorithm A2; c) ETD algorithm B1; d) ETD algorithm B2; e) ETD algorithm C1; f) ETD algorithm C2.

In addition, the comparison in terms of Concordance Correlation Coefficient (ρc) [10], Pearson's Coefficient (P), Mean Error and Coefficient of determination (R^2) and angular coefficient of the linear regression (a, b = 0), has been expressed and summarized in the following Table 4:

Table 4. Agreement descriptive coefficient for the Algorithms comparison

Comparison	ρc	Pearson	MeanError	R^2	a
Figure 8a	0,923	0,982	0,148	0,973	0,858
Figure 8b	0,967	0,994	0,063	0,971	0,974
Figure 8c	0,942	0,982	0,120	0,973	0,882
Figure 8d	0,979	0,989	0,074	0,973	0,983
Figure 8e	0,978	0,986	0,066	0,982	0,946
Figure 8f	0,966	0,994	0,062	0,972	1,065

Although the agreement descriptive coefficients seem rather satisfactory (Table 4 and Fig. 8), due to the simple and regular layout of the virtual pavement and to the absence of laser reading errors, it looks evident the necessity to investigate the effectiveness of non-conventional macrotexture synthetic index, to improve the agreement.

3 Proposed 3D Macrotexture Index from 2D Profile Data

Previous efforts have been spent, to evaluate a more stable and effective macrotexture index: the square weighted ETD is based on a sectioning process to identify homogeneous sections in terms of macrotexture and on attributing an only weighted index able to better describe the macrotexture's variability [8]. The theoretical concept of the square weight ETD, expresses by means of the Eq. (10), has been summarized in the Fig. 9:

$$ETD_{SW} = \frac{\sum_{i=1}^{n} MPD_i \cdot L_i^2}{\sum_{i=1}^{n} L_i^2} \tag{10}$$

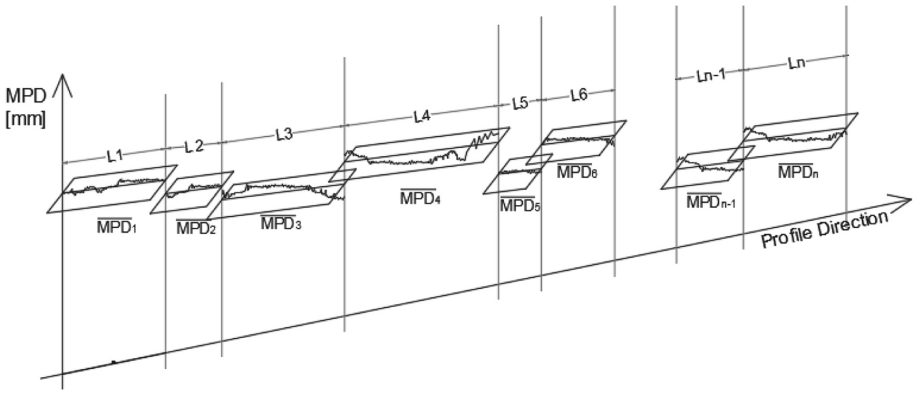

Fig. 9. Graphical representation of square weight ETD evaluation process.

Observing the Fig. 9, it is possible to deduce that, due to the fact that the ETD_{SW} converts MPD values, evaluated on 2D profiles, into areal volumetric macrotexture estimate, the linear transformations (Eq. (1) and Eq. (2)) suggested to transform MPD into ETD are unnecessary.

The algorithm used to evaluate the ETDsw index is summarized in the Table 5:

Table 5. ETDsw algorithm features

Device	Static	HSL
Algorithm D	D1	D2
Sample spacing	0.87 mm	0.5 mm
Baseline length	111 mm (approx.)	100 mm
Evaluation length for linear regression	111 mm	100 mm
Index evaluation frequency	1/0.87 mm	1/0.5 mm
ETD evaluation	Equation (10)	Equation (10)

Then, in the Fig. 10a) and in the Fig. 10b), the comparisons between the effective macrotexture (evaluated by Eq. 5) and the synthetic macrotexture index ETD_{SW}, have been reported, respectively.

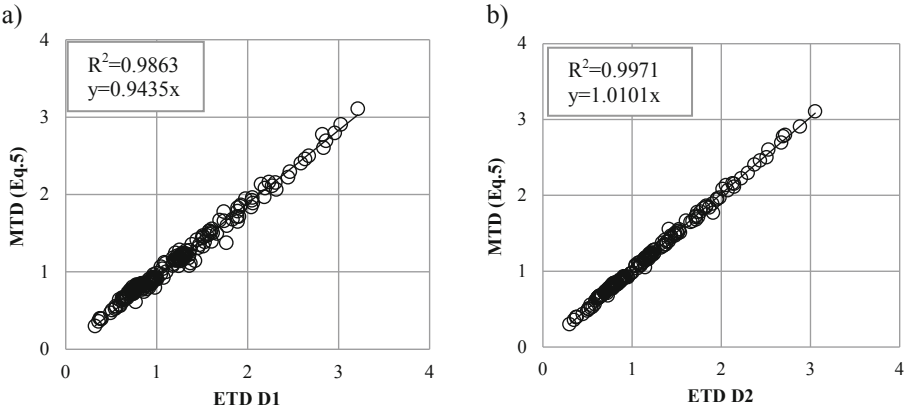

Fig. 10. Comparison of 3D macrotexture values (Eq. 5) VS a) ETD algorithm D1and b) ETD algorithm D2.

Also in this case the agreement descriptive coefficients in terms of Concordance Correlation Coefficient (ρc), Pearson's Coefficient (P), Mean Error and Coefficient of determination (R^2) and angular coefficient of the linear regression (a, b = 0), have been evaluated and summarized in the following Table 6.

Table 6. Agreement descriptive coefficient for the ETD_{SW} algorithms comparison.

Comparison	ρc	Pearson	MeanError	R^2	a
Figure 10a	0,979	0,989	0,058	0,986	0,943
Figure 10b	0,993	0,994	0,024	0,997	1,01

As far as the harmonization issue is concerned, the comparison between the Static and HSL Devices, for both A and D algorithms, has been performed and the results have been summarized in the following Table 7 and Fig. 11:

Table 7. Descriptive coefficient for the devices comparison

Comparison	ρc	Pearson	MeanError	R^2	a
Figure 11a	0,919	0,986	0,106	0,969	1,131
Figure 11b	0,976	0,988	0,064	0,985	1,067

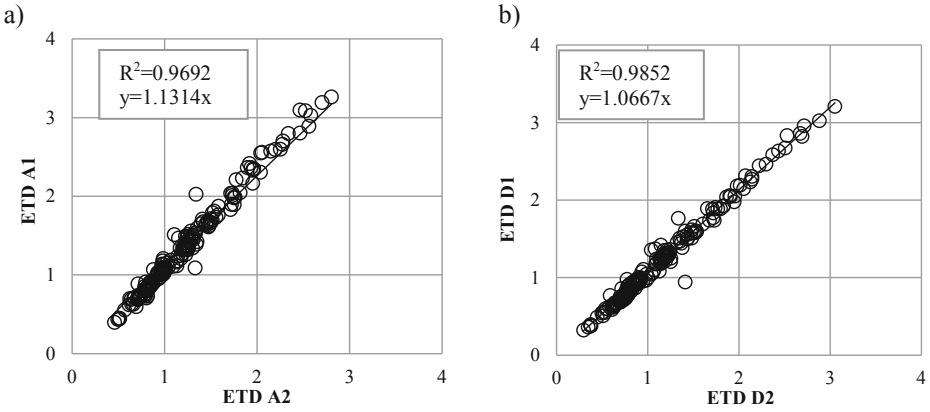

Fig. 11. Comparison between ETD values obtained by a) algorithm A1 VS algorithm A2 and b) algorithm D1 VS algorithm D2.

As it is possible to see, in terms of both, macrotexture evaluation and harmonization issues, the ETD_{SW} provides better results than all the other tested indices and algorithms.

Finally, in order to validate the approach, previously presented, the application of the method to a set of real pavements, has been performed.

4 Validation on Real Pavement

The validation has been performed on a set of 15 real pavements, belonging to the test-track owned by the Virginia Tech Transportation Institute. The entire set has been selected to guarantee a satisfactory heterogeneity in terms of pavement types (asphalt and concrete), used materials and finishing lays.

Both Static and HSL devices, previously introduced (see Table 2 for their main features) have been used to collect 2D profiles.

Two example of real pavement profiles, collected with both Static and HSL devices, have been reported in the Fig. 12a and Fig. 12b, respectively.

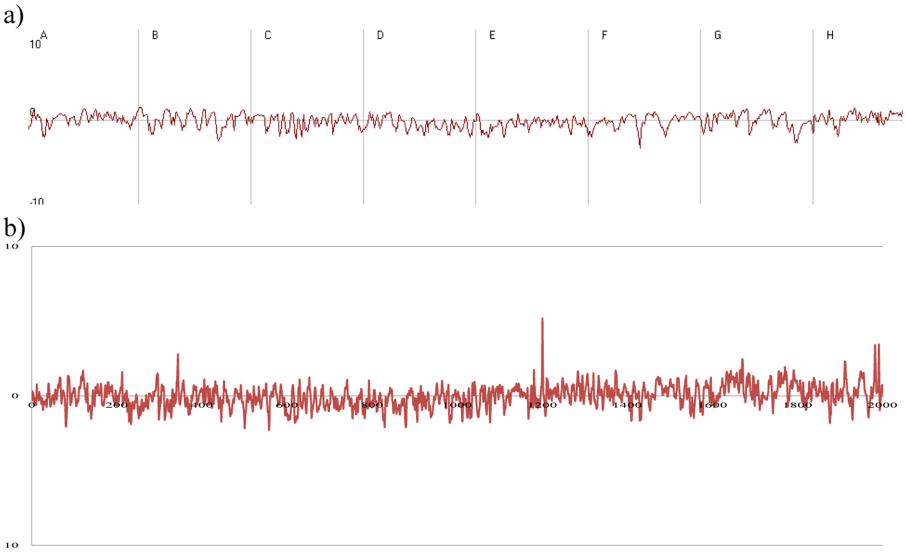

Fig. 12. a) Profile of a generic mix asphalt pavement sampled by a) Static and b) HSL devices.

At this stage, it is important to remember that, as far as real profiles have been concerned, issues related to the invalid laser sensor reading, cannot be neglect and it is highlighted in the Fig. 12b where spikes and drop-outs are present. For this reason, a preliminary filtering process, aim to detect and remove invalid sensor readings is requested [8, 11, 12].

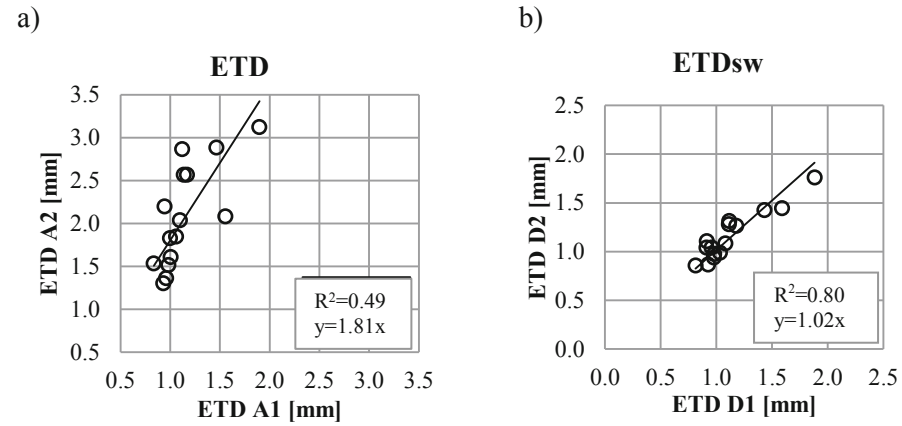

Fig. 13. Comparison between ETD values obtained by a) algorithm A1 VS algorithm A2 and b) algorithm D1 VS algorithm D2.

Table 8. Descriptive coefficient for the devices comparison on real pavements

	ρc	Pearson	MeanError	R^2	a
Figure 13a	0,17	0,67	0,83	0,49	1,81
Figure 13b	0,85	0,865	0,078	0,80	1,02

In the Fig. 13 and in the Table 8 the results of the comparison between the macrotexture values obtained by Static and HSL devices, have been summarized. In particular it is possible to see that the application of the ETD_{SW} (Fig. 13b) improve significantly the agreement respect to the conventional approach (Fig. 13a).

5 Conclusion

In this paper an investigation aimed at improving the reliability of macrotexture measurements has been performed. In order to address the study on the characterization of the macrotexture source of uncertainty only induced by both different operating conditions of measuring devices and different evaluation procedures to compute synthetic indices (pavement physical factors such as mix grading and volumetric properties, energy compaction, finishing laying techniques, have been intentionally excluded), a set of more than 200 virtual pavements have been generated. Two commercial laser-based macrotexture measuring "devices have been selected and used for the analysis of the profiles". Several algorithms have been compared and the ETDsw index has been finally validated on a set of 15 real road pavements, belonging to the Virginia Smart Road facility.

Although further investigation are needed, preliminary results seem to highlight that the ETDsw index reduces the macrotexture variability and provides macrotexture

estimate closer to the volumetric macrotexture value of real pavements. In addition, an improvement in term of agreement between different devices, has been demonstrated.

Acknowledgement. The authors wish to acknowledge the Virginia Polytechnic Institute and State University, Professor Gerardo Flintsch, director of the Center for Sustainable Transportation Infrastructure, and the staff of the Virginia Tech Transportation Institute for allowing us to use the data collected on the Virginia Smart Road.

References

1. Mahone, D.C., Sherwood, W.C.: The Effect of Aggregate Type and Mix Design on the Wet Skid Resistance of Bituminous Pavement: Recommendations for Virginia's Wet Accident Reduction Program. Report n°FHWNVA-96-RIO (1995)
2. D'Apuzzo, M., Evangelisti, A., Nicolosi, V.: An exploratory step for a general unified approach to labelling of road surface and tire wet friction. Elsevier Acc. Anal. Prevent. **138**, 105462 (2020). https://doi.org/10.1016/j.aap.2020.105462
3. ASTM E965. Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique. American Society for Testing and Materials (2006)
4. ISO 13473-1. Characterization of pavement texture by use of surface profiles - Part 1: Determination of mean profile depth. International Organization for Standardization (2019)
5. ASTM E1845. Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth. American Society for Testing and Materials (2015)
6. ASTM E2157. Standard Test Method for Measuring Pavement Macrotexture Properties Using the Circular Track Meter. American Society for Testing and Materials (2019)
7. D'Apuzzo, M., Evangelisti, A., Nicolosi, V.: Preliminary findings for a prediction model of road surface macrotexture. Procedia Soc. Behav. Sci. **53**, 1110–1119 (2012). https://doi.org/10.1016/j.sbspro.2012.09.960. ISSN: 1877–0428
8. D'Apuzzo, M., et al.: Evaluation of variability of macrotexture measurement with different laser-based devices. In: Airfield and Highway Pavements 2015: Innovative and Cost-Effective Pavements for a Sustainable Future, pp. 294–305 (2014). https://doi.org/10.1061/9780784479216.027. ISBN (PDF): 9780784479216
9. ISO 4287, Geometrical Product Specifications (GPS) – Surface texture: Profile method – Terms, definitions and surface texture parameters. International Organization for Standardization (ISO) (1997)
10. Lawrence, L.: A concordance correlation coefficient to evaluate reproducibility. Biometrics (International Biometric Society) **45**(1), 255–268 (1989). https://doi.org/10.2307/2532051. JSTOR 2532051. PMID 2720055
11. Katicha, S., Mogrovejo, D., Flintsch, G., de León Izeppi, E.: Latest development in the processing of pavement macrotexture measurements of high speed laser devices. In: 9th International Conference on Managing Pavement Assets (2014)
12. Losa, M., Leandri, P.: The reliability of tests and data processing procedures for pavement macrotexture evaluation. Int. J. Pavement Eng. **12**(1), 59–73 (2011). Taylor and Francis