Evaluation of Variability of Macrotexture Measurement with Different Laser-Based Devices

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Abstract

The comparison of macrotexture values estimated from different measuring techniques, usually provides poor agreement and unsatisfactory confidence on the real macrotexture estimates by means of the Mean Texture Depth (MTD) Index. For this reason a new algorithm, to evaluate a more reliable 3D macrotexture index evaluated directly from 2D profile, has been proposed. This algorithm includes a profile data cleaning process, developed to detect and remove invalid laser readings present on pavement profile data recorded by means of a high speed laser device (HSLD). Preliminary results obtained on pavements of Virginia Smart Road seem promising.

INTRODUCTION

There is an increasing interest in the Highways and Airfields' surfaces characterization due to the awareness that texture of pavements surface affects directly the tyre-road interaction. In particular, all the safety and environmental aspects like the skid resistance, the splash and spray phenomenon, the hydroplaning, the tire-pavement noise, and the rolling resistance, are affected by the surface macrotexture

As established in 1987 by the Permanent International Association of Road Congresses (PIARC) the pavement surface texture is defined as the deviations of the pavement surface from a true planar surface and the macrotexture scale is defined by the wavelength values from 0.5 to 50 mm and peak-to-peak amplitude values from 0.1 to 20 mm [PIARC 1987]. The simplest and most widespread method used to measure the macrotexture is the Sand Patch Method, which is a volumetric technique and it provides the average pavement macrotexture depth, known as Mean Texture Depth (MTD) [ASTM E965, 2006]. In the last years, the use of laser-based macrotexture measuring devices, is becoming more attractive within pavement quality control procedures. If these devices are used, the estimation of the macrotexture volumetric value (namely the *Estimated Texture Depth, ETD*) can be derived from the macrotexture descriptor based on 2D profiles (namely the *Mean Profile Depth, MPD*) provided by laser-based devices (such as the Circular Texture Meter, CTM according to [ASTM E2157, 2009] and High Speed Laser Device, HSLD, according to [ASTM E1845, 2009]) by means of the following empirical relationships:

$$ETD = 0.8 \cdot MPD + 0.2 \quad \text{[ASTM E1845]} \tag{1}$$

$$ETD = 0.947 \cdot MPD + 0.069 \quad \text{[ASTM E2157]} \tag{2}$$

Unfortunately the MPD values, obtained applying the standard algorithms (ISO 13473 and/or ASTM E1845) on the 2D profiles, are affected by a wide variability which can be ascribed to several factors: the profile analysis algorithms, the devices’ technology and operating conditions (i.e. sample spacing), the heterogeneity of pavement materials (as grading curve or volumetric properties of the mixes [D’Apuzzo et al. 2012] and laying techniques (compaction level or methods of finishing as dragging, tinning, grooving and depth, width, spacing and orientation of grooves used on a concrete paved surfaces). This variability can yield a poor agreement between ETD estimated from different devices’ profiles, measured on the same pavements and this, on turn, may cause possible misinterpretation as far as the fulfillment of the macrotexture threshold specifications is concerned.

OBJECTIVE

The aim of this paper is to present preliminary results obtained by the application of the new theoretical algorithms aimed at evaluating a more stable synthetic index for the macrotexture derived from pavements laser 2D profiles and at improving the agreement between macrotexture values provided by different laser-based devices. To validate it, fifteen different pavements (among which: Dense, Stone Mastic Asphalt (SMA), Open Graded Friction Course (OGFC) and Rigid Pavements), with two different laser-based macrotexture measuring devices, have been measured and all the macrotexture parameters are evaluated and compared.

BACKGROUND

Static and dynamic methods are today available for collection and analysis of pavement macrotexture, but the profiles collected with both static and dynamic laser-based devices, are characterized by noise and invalid readings in form of spikes or drop-outs. To avoid inconsistent macrotexture values, a process of profile data cleaning should be applied and different methods are available, as the Discrete Wavelet Transform technique [Katicha et al. 2014] or filtering process [Losa & Leandri, 2011].

Previous studies have been performed to compare the macrotexture measurements obtained from different measuring techniques: Flintsch et al. (2003), Flintsch et al.(2005) and Meegoda (2005) compared different laser-based methods, to sand patch test. A more recent work analized the comparison between sand patch tests and digital surface roughness meter laser technique [China et al. 2012], but none of them proposed a different macrotexture synthetic index evaluation process for avoiding the use of linear equations (e.g. 1 end 2) to transform 2D index (MPD) into 3d index (ETD) and for improving the comparison between different macrotexture laser-based measurements. According to ISO 13473, the algorithm to analyze the profiles and to compute the MTD values is summarized as:

1. Data Cleaning:
    - Handling of invalid readings;
    - Highpass filtering (to eliminate data trend);
    - Lowpass filtering (to eliminate noise);
2. Baseline limiting: at least 100 mm ± 10 mm long;
3. Slope suppression (instead of Highpass filtering in 1.);
4. Peak determination;
5. MPD determination;
6. ETD determination (by (1) or (2)).

Following this layout, all the procedure steps have been implemented and analyzed and new data analysis algorithms have been proposed

EXPERIMENTAL CAMPAIGN

All the data used in this study have been collected on the Virginia Smart Road, which is a controlled-access test track, located at the Virginia Tech Transportation Institute. This track is around 3,5 km long and asphalt and rigid sections are present. In particular, the Smart Road have 15 different sections: ten ordinary asphalt, one SMA, one OGFC, three concrete sections, (further information about The Smart Road are available on the VTTI Web page (VTTI)). Table 1 shows detailed information for each section.

Table 1: Sections and measurements' information

Section name	Mix types	Asphalt binder	Length (approx.) [m]	CTM measurements	HSLD runs
A	SM – 12D	PG 70-22	106	10	10
B	SM – 9.5D	PG 70-22	88	10	10
C	SM – 9.5E	PG 76-22	89	10	10
D	SM – 9.5A	PG 64-22	124	10	10
E	SM – 9.5D	PG 70-22	82	10	10
F	SM – 9.5D	PG 70-22	92	10	10
G	SM – 9.5D	PG 70-22	93	10	10
H	SM – 9.5D	PG 70-22	89	10	10
I	SM – 9.5A	PG 64-22	103	10	10
J	SM – 9.5D	PG 70-22	85	10	10
K	OGFC	PG 76-22	92	10	10
L	SMA	PG 70-22	99	10	10
VDOT ModifiedEP-5*	Epoxi-(Silica, Basalt) concrete overlay	epoxy	30	10	10
CRCP	CRCP	Tined	70	10	10
SafeLane ™ *	3/8-in-think polymer-Limestone concrete overlay	epoxy	30	10	10

*Further information about these special surfaces are available on (Sprinkel et al.).

Each section was measured by means of two different laser-based devices: a Circular Track Meter (CTM, Figure 1.a) which performs static measurements on a circular alignment and a high speed laser device (HSLD Figure 1.b) which performs dynamic measurements on a straight alignment.

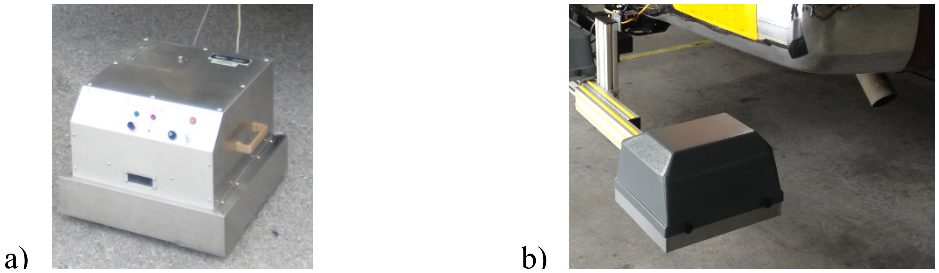

a) b)

Figure 1: a) Circular Track Meter. b) High Speed Laser Device

The CTM has a laser-displacement sensor, mounted on an arm 142 mm long that rotates such that the sensor follows a circular track of approximate 892 mm. It has a laser spot with diameter of 0.07 mm and a sample spacing of 0.87 mm (approx.). The HSLD has a laser spot of 0.2 mm and a sampling frequency of 64 kHz.

Ten measurements with the CTM for every section along the left wheel path, following the ASTM E2157, and ten runs at 50 mph (sample spacing of 0.5 mm. approx.) along the same locations, with the HSLD have been performed. For the following analysis all the CTM measurements and the first run of HSLD are used.

DATA ANALYSIS

Comparison between MPD values provided by CTM and HSLD according to "conventional" computation procedures.

The following observations take origin from a direct comparison of the MPD values computed by algorithms, worldwide implemented in commercial software, usually provided by the laser devices themselves.

Comparing MPD values, different applications of the standard algorithm are emerged and in particular, the software provided by CTM, after identifying and removing dropouts from the profile, divides the circumference into eight arc sectors and eight baseline of around 111 mm are identified. The slope suppression is applied by means of the subtraction of a regression line, evaluated on half arc sector, from the profile. It means that, for each baseline, there are two regression line, one evaluated on the first half baseline and one on the second half baseline. This approach is not in agreement with ISO 13473 which suggests that the slope of the profile should be evaluated along the whole baseline. On the other hand, the commercial software provided by HSLD, should evaluate the slope in agreement with ISO 13473, identifying baseline of 100 mm, but in advance, it doesn't remove dropouts or spikes from the profile.

In the Table 2, the MPD average values computed by both static and dynamic laser-based devices' software, are reported: for CTM software, the MPDs computed for each arc sector separately are considered (80 MPDs for each pavement) and averaged; for HSLD software, 1 MPD every 100 mm along whole sections are evaluated and averaged. The ETD comparison in terms of Mean Error (ME), Pearson's Coefficient (P), Coefficient of determination (R^2) and Concordance Correlation Coefficient (ρ_c) (Lin, 1989) is expressed.

As it can be easily observed, there is a very poor agreement between MPD values provided by CTM and HSLD. In addition, MPD based on HSLD measurement are characterized by a high variability. This can be mainly due to the presence of invalid readings (or spikes) in the digitalized longitudinal profile.

Corresponding macrotexture volumetric values, derived from the equations (1) and (2) have been evaluated.

The comparison is summarized in Figure 2 and the agreement between ETD values, obtained by CTM and HSLD profiles, on the same pavements, is again fairly poor.

Table 2: MPD values computed by software' devices

Devices	MPD [mm] - Traditional computation									
	CTM				HSLD					
Section name	Average	CV	Max	Min	Average	CV	Max	Min		
A	1,11	0,24	1,98	0,61	3,33	0,89	22,65	0,88		
B	1,47	0,24	2,32	0,92	3,35	0,96	30,52	1,01		
C	0,98	0,24	2,29	0,67	2,03	0,99	21,52	0,72		
D	0,81	0,20	1,29	0,51	1,67	0,98	22,08	0,74		
E	0,96	0,23	1,75	0,57	1,64	0,89	19,82	0,69		
F	0,94	0,23	1,82	0,56	1,45	0,80	21,53	0,74		
G	0,99	0,24	1,81	0,6	1,76	0,78	18,92	0,67		
H	1,09	0,25	1,97	0,66	2,29	0,90	21,74	0,75		
I	0,92	0,18	1,42	0,51	2,50	0,81	19,43	0,84		
J	1,13	0,27	1,96	0,61	2,96	0,73	20,34	0,89		
K	1,93	0,21	2,99	1,09	3,65	0,80	35,80	1,17		
L	1,16	0,22	2	0,78	2,96	0,74	19,47	0,75	ME	1,09
VDOT Mod EP-5 *	1,05	0,18	1,81	0,75	2,06	0,81	20,45	0,91	R^2	0,5
CRCP Tined	0,91	0,34	2,29	0,42	1,38	0,55	15,63	0,57	P	0,67
SafeLane ™ *	1,57	0,19	2,44	1,09	2,35	0,70	19,32	1,15	ρ_c	0,14

In order to reduce the MPD variability, especially for HSLD evaluations, and to improve the agreement of the ETD values, further analysis have been necessary and new approach to detect and remove invalid sensor readings and to improve the estimate macrotexture volumetric values, is proposed.

ETD [mm] Traditional computation method

Sections/Devices	CTM by (2)	HSLD by (1)	
A	1,12	2,87	
B	1,46	2,88	
C	1,00	1,83	
D	0,83	1,53	
E	0,98	1,51	
F	0,96	1,36	
G	1,01	1,61	
H	1,10	2,03	
I	0,94	2,20	
J	1,14	2,56	
K	1,90	3,12	
L	1,17	2,57	ME=0,83
VDOT Mod EP-5 *	1,06	1,85	P=0,67
CRCP Tined	0,93	1,30	R^2=0,49
SafeLane ™ *	1,56	2,08	ρ_c=0,17

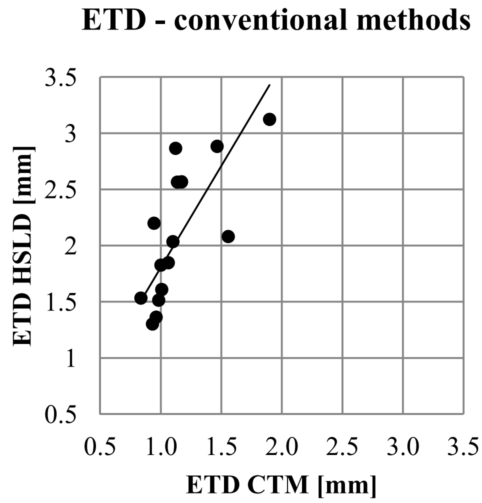


Figure 2: Comparison between ETD values estimated from CTM and HSLD conventional computation methods.

PROPOSED APPROACH FOR MACROTEXTURE EVALUATION FROM PROFILE DATA

Detecting and removing of invalid sensor readings and filtering process

There isn't a recommended way to identify and to remove invalid readings produced by the sensor devices; several methods are available [Katicha et al. 2014; Losa & Leandri, 2011] and the chosen methodology can strongly affect MPD values. The profiles captured by CTM, are characterized by the presence of drop-outs (one or more missed points of the profiles), especially for pavements with a high macrotexture value, where the number of single or consecutive missed points increases (anyway the maximum length of consecutive number of invalid missed points, usually, doesn't not exceed 20 mm). The software provided by the device, allocates to them a default value of -30 mm and replaces them by a linear interpolation of neighboring values. The presence of spikes (one or more local missed readings of the laser, positive or negative) is typical of profiles captured by HSLD, and their shapes can be widely different. They can be characterized by a length of few points (few mm) and a height difference of more than ±50 mm or by a consistent length (several mm) and a height difference of several mm (positive or negative). To detect and to remove all the spikes' shapes, a filtering algorithm was proposed. It consist of a sequence of moving windows, applied along the profiles, within all the profiles' points exceeding a fixed "Δ" are replaced by a linear interpolation of neighboring values. The windows move on each point of the measured profile. Δ is defined as:

$$\Delta = ave \pm \delta$$

Where : δ is defined in Table 3 ,

ave is the mean of the profile in the moving window.

Observing the profiles recorded by the HSLD on the Smart Road, and analyzing all the present spikes' shape, three different moving windows were defined and subsequently applied on the profiles. The Table 3 shows the features of the moving windows.

Table 3: Moving windows features

Features	Moving windows		
	1	2	3
Length	30000 points	3000points	200points
δ	40 mm	20 mm	3 mm

The moving window method involves the orderly application of the windows: from the wider to the narrower one. In this way the window 1, because of its length, guarantees the identification of a possible set of close spikes, which raises the mean value within the window and with a narrower one, could be omitted. The window 2 removes spikes with a sizeable length (comparable with baseline length) and window 3, completes the cleaning of the profile. The proposed cleaning profile method has the limit to be an empirical approach, but on the other hand, its comprehension and application are extremely simple and the results can be satisfactory. Finally, as suggested by ISO 13473, after the profile cleaning process, to eliminate the noise on the profiles captured by HSLD, a 2.5 mm moving average lowpass filter is applied. In the Figure 2 the results of the application of each moving window separately are reported.

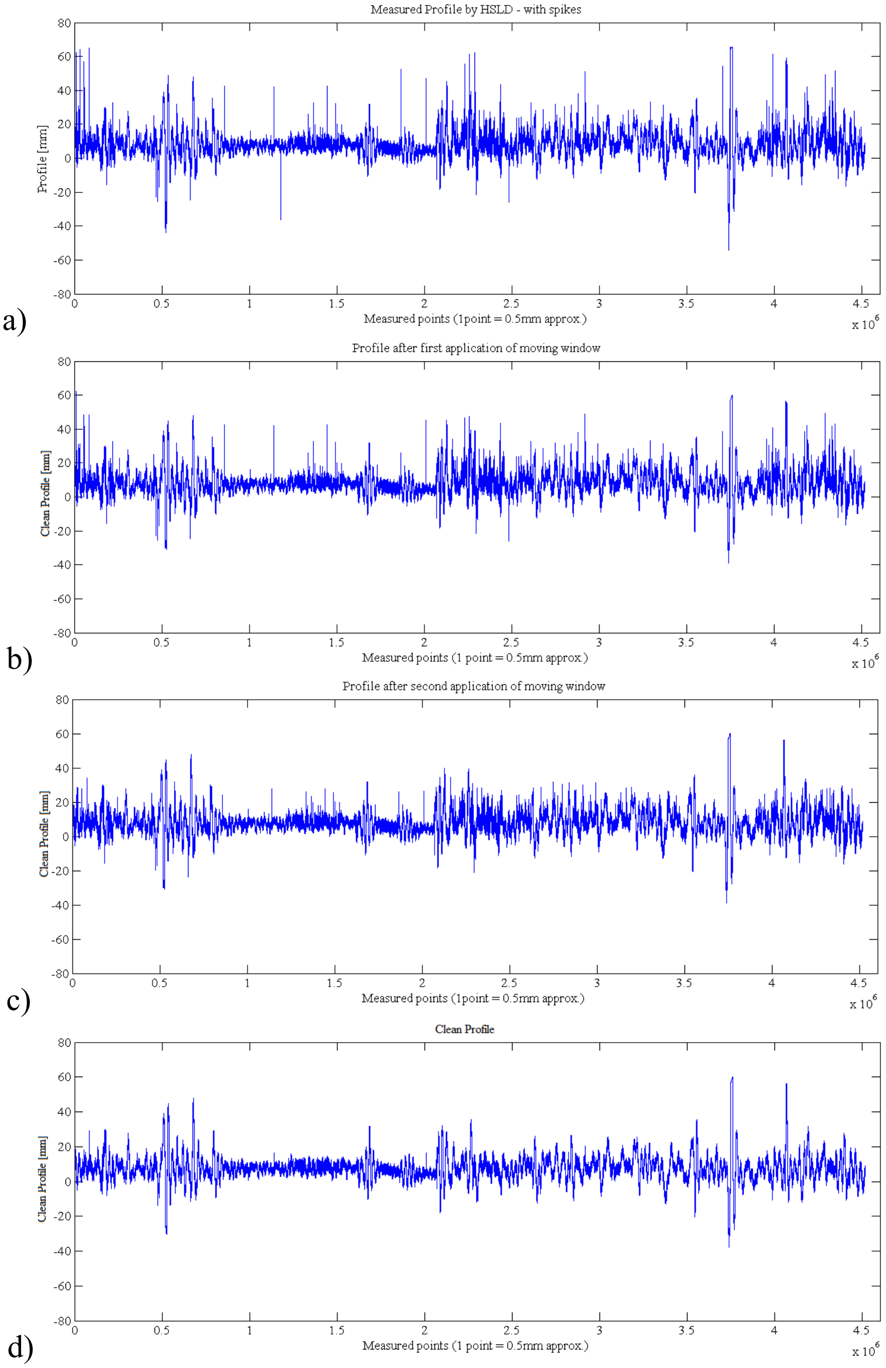


Figure 3: Moving windows process. a) Profile measured by HSLD- with spikes. b) Profile

after the application of Moving window 1. c) Profile after the application of Moving windows 1 and 2. d) Profile after the application of all Moving windows.

According to ISO 13473, "the maximum proportion of invalid readings in a profile shall not exceed 20%, if it exceeds 10%, caution should be used in interpretation of data". The proposed cleaning process produced the detecting and removing of less than 1.8 % of the data, that is comparable with CTM percentages and it proves the validity of the recorded data. On the clean and filtered HSLD profile the MPD values are computed (1 MPD every 100 mm along all profiles' sections) and through the equation (1) the ETDs are estimated. The comparison between these latter and the ETD estimated from CTM profiles (previously presented in Figure 1) has been carried out and the results are summarized in the Figure 5.

Sections / Devices	ETD [mm] CTM by (2)	 HSLD by (1)	
A	1,12	1,27	
B	1,46	1,38	
C	1,00	1,05	
D	0,83	0,90	
E	0,98	0,96	
F	0,96	0,90	
G	1,01	0,99	
H	1,10	1,08	
I	0,94	1,11	
J	1,14	1,25	
K	1,90	1,61	
L	1,17	1,21	ME=0,08
VDOT ModEP-5*	1,06	1,02	P=0,87
CRCP Tined	0,93	1,02	R^2=0,67
SafeLane TM *	1,56	1,39	ρ_c=0,82

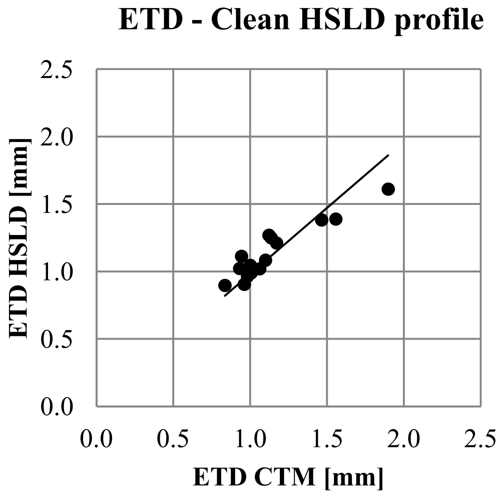
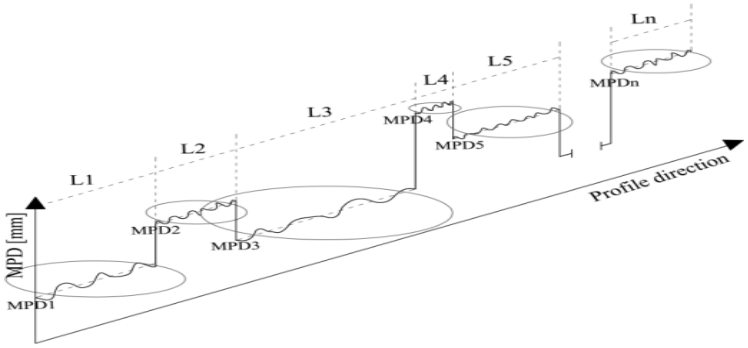


Figure 5: Comparison between ETD values estimated from CTM traditional computation and HSLD clean and filtered profile.

As it is possible to observe, the statistic descriptors highlight an improved agreement between estimated macrotexture values obtained from 2D clean profiles and the Mean Error reduced of 90%. In order to propose a new procedure to evaluate 3D macrotexture estimate from 2D profiles, a new algorithm was developed.

A new approach for the ETD computation from 2D profile data

The new approach to estimate macrotexture value directly from 2D pavements profile, consists of two main steps: the *MPD windowing computation* and the *square weight ETD evaluation (ETD$_{SW}$)*. Both steps will be described below. On the clean and filtered profiles, the baselines are identified: 111mm (approx.) long for the profiles recorded by CTM and 100 mm (approx.) long for the profiles provided by HSLD. To suppress the possible slope of the profiles, the regression line method has been used on both whole and half baseline. The *MPD windowing computation* suggests moving the baseline along the profile and computing the MPD value for each step. This step depends on the devices' sample spacing: for the CTM the step is 0.87 mm and for HSLD is 0.5 mm. In this way the number of MPD values is almost the same of measured points for each profile. To all the recorded profiles, these processes are applied; and the intermediate results highlight that for the CTM profiles, the slope suppression by means of half baseline regression, produces higher MPDs' variability, than the whole baseline regression, but it is not for HSLD profiles. In the second step, a sectioning process on MPDs results is performed. It consists of defining, comparing and, in case, aggregating homogeneous sections in terms of MPD's mean and standard deviation. For each comparison the T Student test and the Fisher test are performed. The sectioning process allows to identify several subsequent sections with different mean (MPD_1, MPD_2, …, MPD_n) and length (L_1, L_2, …, L_n, which are related to the corresponding frequencies of the mean values) and the *ETD_{SW} evaluation* confers to each section, a square weight depending on its length that reflects the areal statistical significance of the specific MPD value pertaining to each section. The procedure and the equation are represented in the Figure 6.



$$ETD_{SW} = \frac{\sum_{i=1}^{n} MPDi \cdot Li^2}{\sum_{i=1}^{n} Li^2}$$

Figure 6: Graphical representation of square weight ETD evaluation process and equation.

The ETD_{SW} provides a direct macrotexture estimate, because it converts MPD values, related to 2D evaluations, into areal volumetric macrotexture estimate. In this way the linear transformations (equations (1) and (2)) suggested to convert MPD to ETD are not needed. Observing the results, summarized in the Figure 7, a satisfactory agreement, between ETD values, evaluated on 2D profiles captured by CTM and HSLD, is obtained. Comparing ETD_{SW} and conventional ETD (Figure 2) the new proposed approach improves the agreement in terms of ρc of 80%.

ETD$_{SW}$ [mm] - Square Weight

Devices	CTM	HSLD	
Section name	Mean	Mean	
A	1,11	1,31	
B	1,43	1,42	
C	0,96	1,04	
D	0,81	0,86	
E	0,98	0,94	
F	0,93	0,87	
G	0,98	0,97	
H	1,08	1,08	
I	0,91	1,11	
J	1,11	1,28	
K	1,88	1,76	
L	1,18	1,26	ME=0,08
VDOT Mod.EP-5*	1,03	0,99	P=0,87
CRCP Tined	0,91	1,04	R^2=0,80
SafeLane ™ *	1,59	1,44	ρ_c=0,85

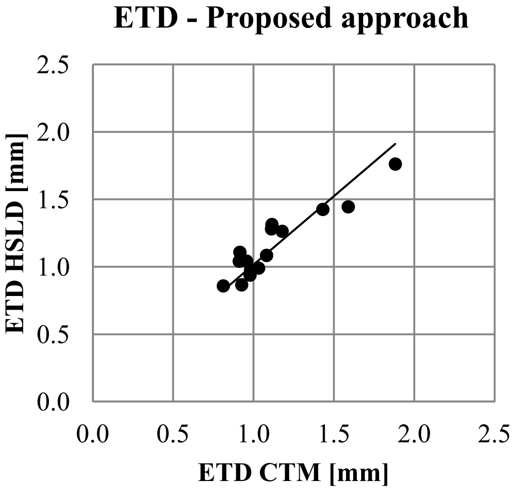


Figure 7: Comparison between ETD values estimated with proposed approach from CTM and HSLD profiles.

SUMMARY AND CONCLUSION

The MPD value, used to estimate the macrotexture of road pavements, is generally characterized by a wide variability thus may affect the estimation of volumetric macrotexture values by means of different laser-based devices. In this paper the variability related to profile analysis procedures has been investigated. Observing the original profiles, collected by CTM and HSLD on a wide range of pavements, a very poor correlation among the corresponding MPD and ETD values, has emerged (Figure 1). In order to improve the agreement between ETD values, a new data analysis methodology comprising two main step is proposed: a filtering process based in *moving windows*, to clean profiles up from unwanted noise and invalid sensor readings, and the *ETD$_{SW}$ evaluation based on sectioning procedure,* to directly estimate a volumetric macrotexture values from 2D profiles.

It has to be highlighted that the proposed filtering process mainly affects the analysis of HSLD data, however it has to be acknowledged that HSLD devices are going to replace Sand Patch Methods and CTM in the future and therefore this paper wants to shed some light on reliability issues related to HSLD devices.

In addition, an original texture volumetric (3D) estimation method based on 2D measurements has been proposed. The algorithm does not rely on empirical relationships (1) and (2) proposed in ASTM and therefore it is irrespective of the specific device used. Although further investigation are needed, preliminary results (Figure 7) seem to show a satisfactory agreement between ETD values obtained from CTM and HSLD's profiles by means of this new approach (improved of 80%).

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