Figure 7). This dash line is only a reference line to the circular marks in order to observe the variations of the calculated IRI values. The IRI value of the dash line was measured only at one speed. The average IRI value of this road measured using DTPS and the axle accelerometer at different speeds was 6.9 m/km, which is more than double of the IRI value measured in 2012.

The reason why the DTPS-based IRI values are so consistent but different from the IRI value measured in 2012 is that the road has many potholes and patches due to the deterioration over the two years. Two sample images of this road taken with the camera are shown in Figure 8. About one third to a half of the road was in this condition depicted in these images. This proves that the road deteriorated severely from 2012 to 2014. The weather record showed that there was heavy snow and large precipitation events over the two years in this area (National Climatic Data Center, 2012). The weather condition accelerates the road deterioration. Moreover, the riders felt strong undulations and sharp movement over the road defects while driving. The actual road condition from images and riders' feedback matches the description of ASTM standard (E1926-08, Standard Practice for Computing International Roughness Index of Roads from Longitudinal Profile Measurements, 2008). Therefore, based on the current condition of this road, the IRI value should be much larger than 3.11 m/km. The current condition should be much worse than that it was in 2012. Therefore, the IRI value of 6.9 m/km is reasonable to represent the current condition of this road.

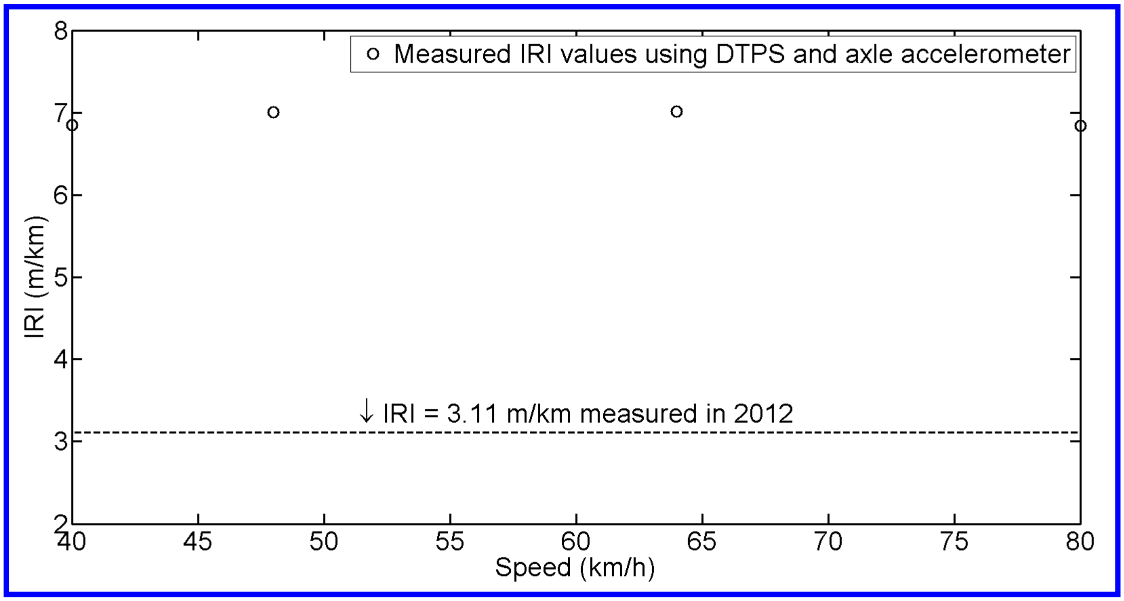

Figure 7 IRI results comparison at different speeds for the same urban road, MA

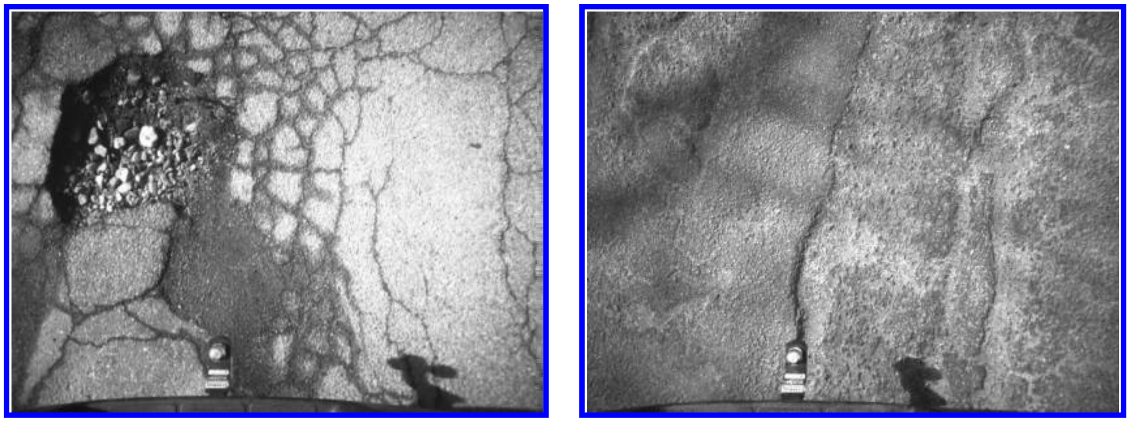

Figure 8 Typical images of the urban road from the camera

Certification test

A certification test, administered by MassDOT, was conducted on an airport runway. Contractors who want to survey IRI for government have to pass this test. Multiple contractors using laser profilometers with accelerometers participated in this test along with our DTPS-based system. The official running speed is 72 km/h (45 mph). In order to validate the speed effect, 48 km/h and 72 km/h (30 mph and 45 mph) were used in this certification test using DTPS and axle accelerometer. Due to the logistics administered by MassDOT, no other speeds were applied. The IRI values were 1.55 m/km and 1.52 m/km at 48 km/h and 72 km/h (30 mph and 45 mph) using DTPS with an axle accelerometer, respectively. The IRI value of this airport runway was 1.50 m/km. The error was 1.3 % to 3.3 % using the new method. Other contractors got the similar result from 1.48 m/km to 1.55 m/km at one speed of 72 km/h (45 mph) using laser profilometers with accelerometers. The difference and variation is small to the actual IRI value in average.

CONCLUSION

This paper presented an approach to estimating IRI using a dynamic tire pressure sensor (DTPS) with an axle accelerometer attached to a moving vehicle. In general, speed affects the IRI measurement. The magnitude of profile increases with speed. This causes the IRI value to change with speed. This paper develops a 2-D dynamic tire model to eliminate speed effect for IRI measurements based on DTPS sensor system. This model was applied to field tests on both highway I-95 and an urban road in Boston area, MA. Results had shown that this 2-D dynamic tire model worked effectively to measure road profile and to calculate IRI value with speed effect considered in the derivation. Additionally, results of IRI values measured with DTPS with an axle accelerometer indicate that the data are dependent on road roughness. This method works at speeds between 15 mph and 60 mph. The measured IRI values match the IRI values measured with laser profilometers with accelerometers on highway, urban road, and airport runways. It is confirmed through riders' feedback and pictures taken while driving. The images taken from camera match the descriptions of ASTM standard.

However, the limitations are that a) This method does not measure the exact profile but an average profile over the tire footprint due to the tire/road interaction; b) Traffic conditions such as sudden accelerations or decelerations due to stop signs, traffic lights, and emergency brakes are not considered.

In general, the method of IRI measurement using DTPS with an axle accelerometer is applicable to both highways and urban roads without speed effect. This two-sensor system has the potential to be integrated into a vehicle during manufacturing in order to form a network-wide continuous monitoring system of roadways under normal driving conditions. The method works under wet and raining condition since the measurement is carried out inside the tire.

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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 TM *	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

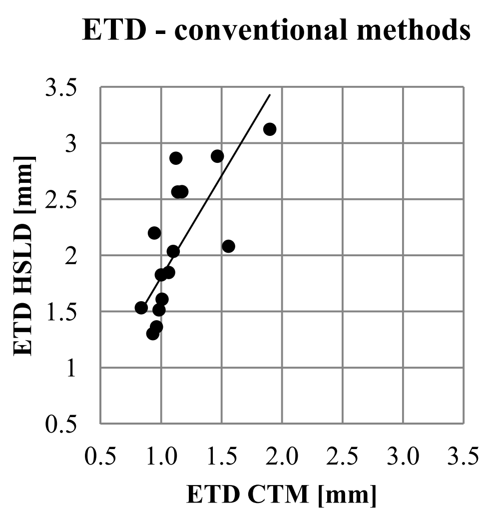

Figure 2: Comparison between ETD values estimated from CTM and HSLD conventional computation methods.

PROPOSED APPROACH FOR MACROTEXTURE EVALUATION FROM PROFILE DATA