TRANSVERSAL STABILITY AND VARIABILITY OF URBAN ROAD PROFILES

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ABSTRACT

The survey of the longitudinal profile of road pavements is a crucial operation when evaluating the superstructure conservation state. For a correct and accurate verification of evenness, it is necessary that the alignment chosen for the acquisition of profilometric data is as representative as possible of the real road surface, which doesn't always prove to be the case, especially in urban areas. This emerges more clearly in profilometric surveys conducted with the ARRB Walking Profiler (characterised by a preset data acquisition step of 24 cm, in correspondence to the mega-texture wavebands), the sensitivity of which requires detailed attention.

The study reported in this paper investigated the effects of randomness or stability of the profilometric surveys of road surfaces along parallel longitudinal alignments in different urban road contexts. The acquisition, and successive numerical processing of the profilometric data also allowed the variability and stability to be verified of the evenness indexes currently used in a transverse direction with respect to the platform (IRI, RN, MRI, RMS, PSD).

The profilometer used was the Walking Profiler, an instrument produced by ARRB Transport Research following the World Bank specifications for Class I profilometers. The profilometric data acquired using the ARRB Walking Profiler were then downloaded and analysed using the software ProVAL (Profile Viewing and AnaLysis), an application sponsored by the US Department of Transportation, as well as the Federal Highway Administration (FHWA) and the Long Term Pavement Performance Program (LTPP), and specifically built to allow the users to make a diversified analysis of the longitudinal profiles of pavements.

Keywords: profiler, unevenness, IRI, transverse profile, data processing

1. INTRODUCTION

The survey of the longitudinal profile of road pavements is a crucial operation in the evaluation of the conservation state of the superstructures. It is well known that the evenness of the road surface is one of the indexes of pavement functionality, and that this index is closely correlated with the other surface and depth characteristics of the superstructures.

For a correct and accurate verification of evenness, it is necessary that the alignment chosen for the acquisition of the profilometric data is as representative as possible of the real road surface, which doesn't always prove to be the case, especially in urban areas.

The problem is therefore in the choice of the longitudinal section (or sections) to monitor, as well as the definition of specific analysis and aggregation methods of the data acquired, using relatively simplified, but representative indicators. It is clear that, in the case of single-track surveys of evenness, the main difficulty is in choosing the alignment most indicative of the surface being investigated. In the case of multi-track surveys, the real problem consists in the definition of the methods of aggregation and interpretation of the data obtained, especially where these denote obvious and reciprocal discrepancies.

With the aim of verifying the stability of the profilometric data and related evenness indexes, it was decided to conduct instrumental tests in different urban contexts representative of typical situations found along city roads. The choice of contexts was dictated by the presumed greater transversal unevenness of the roadway surfaces, and for operational reasons correlated with the defined survey methods (transversal geometry).

2. DATA COLLECTION

The data acquisition campaign was defined on the basis of the need to obtain a significantly valid sample of profilometric data referring to a number of case-studies sufficiently representative of the normal conditions found on urban roads.

Five types of road were identified corresponding to roads geometrically catalogued as “urban district roads” according to the classification of D.M. 5 November 2001 and the Italian Highway Code. For each of these, a rectilinear stretch was identified, never less than 200 metres long, with homogeneous characteristics for type of pavement, maintenance state and presence/absence of discontinuities in the roadway, such as manhole covers or drain wells. The minimum length of 200 m was defined on the basis of the need to obtain an adequate and appropriate description of the surface, as well as of the representativeness of the texture indexes being studied. Four parallel longitudinal profilometric surveys were conducted on each site, according to the geometry reported in figure 1, referred to the axis-lane. Assuming that the wheel tracks are on average 0.75 m from the reference axis (to the right and left respectively), the evenness characteristics were measured of 4 parallel alignments – T1, T2, T3 and T4 – defined in such a way that the average of tracks 1 and 2 would be representative of the right wheel track and that of tracks 3 and 4 would be representative of the alignment of the left-hand wheels. The distance between profiles T1, T2, T3 and T4 was set at 0.25 m with respect to the wheel tracks (table 1).

Table 1 List of studied roads

Name	Survey number	Length (m)
Type A (Via Bainsizza…)	4	200
Type B (Via Colombo…)	4	200
Type C (Via Forcellini…)	4	200
Type D (Via Pelosa…)	4	200
Type E (Via Svizzera…)	4	200

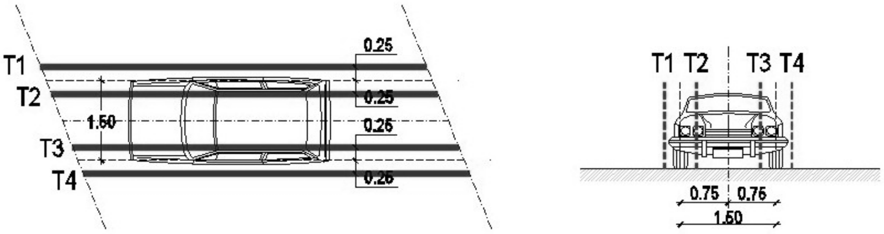

Figure 1 Schematisation of the survey geometry

The evenness surveys of the pavements were conducted using the Walking Profiler, an inertial profilometer produced by ARRB Transport Research following the World Bank specifications for Class I profilometers. This allows the acquisition of the profilometric trend of road surfaces using a foot of a set length of 241.3 mm (sampling interval 9.5 inches). The precision guaranteed by the manufacturer is ± 0.01 mm a step. The accuracy of the data is specified as ± 1.0 mm every 50 m of smooth surface. The waveband range covered by this profilometer, for which the accuracy of the values registered is guaranteed, is generally identified by the half-space with $\lambda > 0.5$ m, characteristic of the dominions of the mega-texture and irregularity. The instrument is better adapted for rectilinear surveys, but can also be used on curves with a radius of more than 15 m. The limit of the longitudinal slope, for a correct functioning of the acquisition system, was set by the manufacturer at 9.5 degrees, corresponding to a slope of 16.7%. For reasons of instrument sensitivity, the recommended temperature range is 0-45 °C, preferably in the absence of humidity. A precision inclinometer is placed at the centre of the foot, which can instantly establish the angle between the gravity vector and normal at the bar. The disparity between the heights of the ends of the foot is automatically calculated by the on-board computer (Controller) as a trigonometric product of the measured angle and the fixed length of the bar (241.3 mm).

The profilometric data acquired using the ARRB Walking Profiler were downloaded and analysed using the ProVAL (Profile Viewing and AnaLysis) software, an application sponsored by the US Department of Transportation, as well as the Federal Highway Administration (FHWA) and the Long Term Pavement Performance Program (LTPP), and specifically built to allow users to make a diversified analysis of the longitudinal profiles of pavements. A fact that cannot be ignored is that the ProVal operates on a binary basis (Pavement Profile Standard File format), generating files that can be easily managed and modified, entirely in agreement with the "Draft ASTM Profile Data File Specifications".

The ProVal functions mainly used in this study regarded the processing of the statistical parameters describing the evenness, at both set intervals and continuous, with particular reference to the International Roughness Index (IRI), Half-car Roughness Index (HRI), Mean Roughness Index (MRI), Pre-Transformed Ride Number (PTRN) and Ride Number (RN). For the frequency analysis of the profiles acquired using the ARRB Walking Profiler, the filtering functions of Butterworth Filtering and Power Spectral Density (PSD) were used, in accordance with pr-EN 13036-5 "Surface characteristics of road and airfield pavements – Test methods – Part 5: Determination of longitudinal *evenness indices*". In the same way, the test and analysis protocol defined by the Working Group of Austroads was taken into account, which is specifically structured on the analysis of longitudinal profiles obtained with the ARRB Walking Profiler.

3. DATA ANALYSIS

When the instrumental data of all the alignments had been acquired, they were processed according to the methods given in pr-EN 13036-5. The first operation was the pre-filtering of the whole measured spectrum, setting the 0.781 m and 50 m wavebands as lower and upper "cut-off" limits, in order to eliminate as far as possible unwanted profile distortions and the phenomenon of aliasing. The choice of the lower limit of calculation wavebands (0.781 m) is coherent with that given by Karamihas et al. (Nyquist Sampling Theorem) relative to the ratio between sample interval and lower waveband indifferent to the phenomenon of aliasing. Consequently, in the case of the ARRB Walking Profiler, with a fixed sample interval set at 24 cm, the lowest waveband of interest corresponds to 0.48 m. The limit of 0.781 m provides a further margin of safety for the significance of the analysed data.

After the wavebands outside the range of interest had been filtered from every profile, the International Roughness Index was calculated referring to a base-length of 100 m, as specified in the pre-European regulation. The calculation was done for each of the 4 parallel profiles, with the aim of verifying the stability and variability in a transverse direction. In agreement with the "Commentary to AG:PT/T450: Determination of the International Roughness Index (IRI) using ARRB TR Walking Profiler", edited by the Working Group of Austroads in June 2006, starting from the values of IRI of the single alignments, the average arithmetical values of the 2 wheel tracks were calculated first and then the entire lane. The initial, intermediate and final values are reported in table 2.

Table 2 Values of IRI on a 100 m base-length

	IRI (mm/m)						
	Track 1	Track 2	Track 3	Track 4	R.Wheel Track	L.Wheel Track	MRI
Type A Road	4.39	4.44	3.95	3.56	4.41	3.76	4.08
Type B Road	4.99	4.41	7.28	7.13	4.70	7.21	5.95
Type C Road	3.95	4.08	4.26	4.84	4.01	4.55	4.37
Type D Road	3.17	3.44	2.44	2.38	2.91	3.30	2.41
Type E Road	1.33	1.48	1.41	1.08	1.41	1.24	1.32

The standardised reference for the calculation of the IRI index, in "AASHTO Designation PP37-99 – Standard Practise for Determining Roughness of Pavements", does not specify the criteria of choice and tracking of the longitudinal alignment along which to do the profile and calculate the roughness parameters, and nor does it specify how to aggregate or average the evenness indexes measured on the same surface, with successive or transverse surveys. It is therefore possible to adapt the choice of the base-length of the IRI roughness index to the characteristics of the surface that it is intended to investigate, especially depending on the traffic levels it has to carry.

The freedom allowed by the AASHTO standard justifies the legitimacy of questioning how much more or less information does a continuous trend of the IRI parameter along the alignment provide, compared to a single value referred to a longer base-length (100 m according to prEN 13036-5 or 320 m according to the indications of the World Bank). An example of this is given in figures 2 and 3: the first figure describes the trend of the IRI index with a base-length of 5 m for the four tracks surveyed in Type D Road (IRI_{lane} = 5.95 mm/m). The second describes the trend of the IRI index of the same four tracks with a base-length of 100 m, according to prEN.

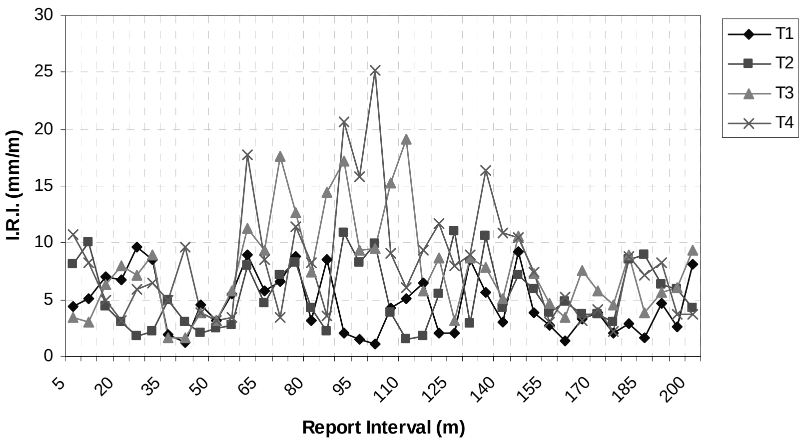

Figure 2 Trend of the IRI index with base-length of 5 m (Type D Road)

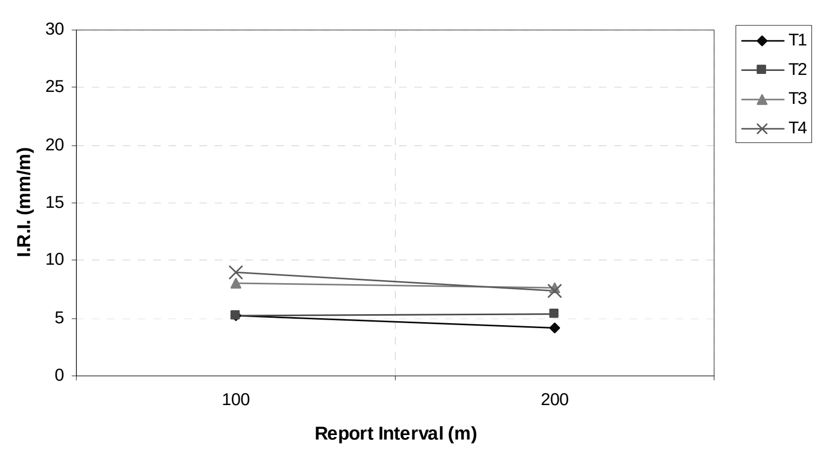

Figure 3 Trend of the IRI index with base-length of 100 m (Type D Road)

Naturally the main potential of the trend shown in figure 3 consists of the possibility of recognising the most critical points along the single tracks, information that is obviously toned down in the representation of averaged values on longer stretches. At the same time, the representation at 5 m base-length also allows the different trend of the IRI index along the four tracks to be established, with the same longitudinal coordinates. In this specific case, figure 2 describes a good affinity between profiles T1 and T2 and between profiles T3 and T4, although denoting a marked variability (longitudinal displacement) of the index. The same type of agreement in absolute value is referred to by the diagram reported in figure 3, where, however, information is lost about the exact location of the critical points surveyed. However, it should be specified that the significance of the diagram reported in figure 2 is expressed more from the qualitative point of view – i.e. as a comparison between trends of parallel tracks - than quantitative, given the impossibility of tracing reference values for the specific case in point of the IRI_5.

A second reason for discussion regards the analysis of the transverse variability of the IRI index average on the four surveyed tracks. In particular, the validation of the test protocol of the Working Group of Austroads relative to the survey of roughness using an ARRB Walking Profiler has been studied. This protocol takes into account that for double-track surveys – at a distance of 0.75 m from the lane axis – the IRI value of the surface derives from the pure arithmetical average of the values calculated along the two single original tracks. This is an effective rule that can be utilised in the majority of cases, but it does not consider the transverse variability of the indexes in particular situations, nor report the error made when averaging the data. An eloquent example of this is reported in figure 4, which represents the average values of the 4 profiles on five of the surveyed surfaces referred to a spatial axis in a transverse direction to the centre-line of the lane.

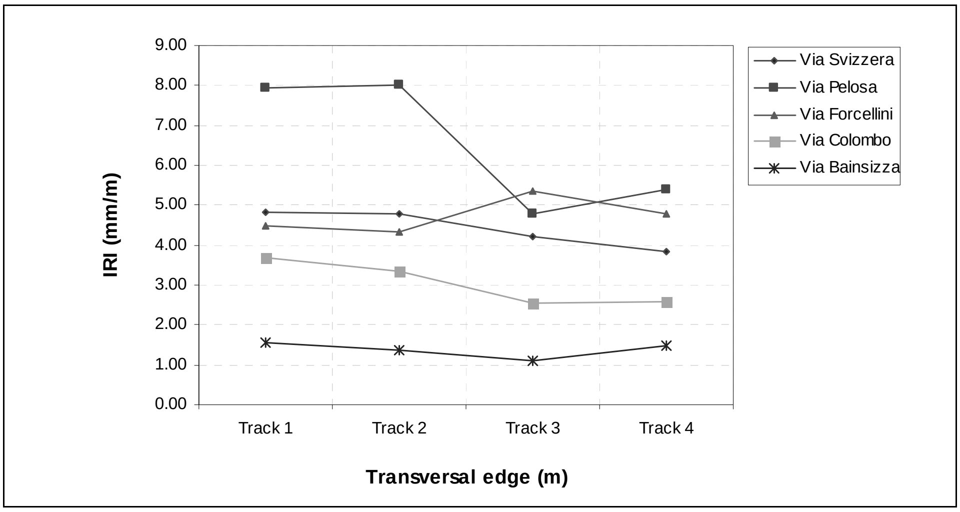

Figure 4 Transverse trend of the IRI index

Given the wide variety of the values of IRI calculated, it was decided to calculate the standard deviations resulting from the operation of arithmetical averaging, as well as their incidence on the average values obtained, with the aim of verifying the representativeness and stability of the aggregate indexes obtained. The average value of the IRI on the four alignments was calculated simply as the arithmetical average of the four values corresponding to the four tracks (Table 3 can be examined for the details).

Table 3 – Estimate of the error made in averaging the values of IRI

	IRI (mm/m)						
	Track 1	**Track 2**	**Track 3**	**Track 4**	**MRI**	**St. Dev.**	**Error (%)**
Type A Road	4.83	4.77	4.23	3.84	4.42	0.41	9%
Type B Road	7.94	8.02	4.78	5.41	6.54	1.46	22%
Type C Road	4.48	4.34	5.36	4.78	4.74	0.39	8%
Type D Road	3.68	3.36	2.56	2.59	3.05	0.49	16%
Type E Road	1.54	1.37	1.10	1.49	1.38	0.17	12%

It clearly emerges from the results obtained that in some cases (for example, Type D Road) the operation of arithmetical averaging of the single values can entail glaring errors, in both absolute value (± 1.5 mm/m) and percentage value (22%). Also in the remaining cases the error made ranges on percentage values in the order of 10-15% with respect to the calculated average value, only occasionally corresponding to 8% (Type C Road). Clearly, the consistence of the roughness indexes obtained and the error made in their processing depends strongly on the alignment chosen, the number of tracks considered and methods of data aggregation, as well as inevitably on the variability of the surface characteristics of the roadway.

Starting from the profilometric data and through an analysis of the characteristics of each of the profiles and – more specifically – through the derivation of the Profile Index, computed directly from the surveyed data, it was possible to calculate (“Ride statistics” implemented in the software ProVal) the parameter Ride Number, analytically correlated to the profile characteristics by the equation (eq. 1):

$$RN = 5 \cdot e^{-160 \cdot PI} \qquad \text{(Eq. 1)}$$

It follows that higher values of RN correspond to more regular surfaces and lower values of RN to more irregular surfaces. The range of values of RN, experimentally validated by the FHWA, comprises magnitudes of between 1 and 4.5. The values calculated for the single profiles of the five studied roads are summarised in table 4:

Table 4 – Expression of RN in the single and averaged alignments

	RIDE NUMBER						
	Track 1	**Track 2**	**Track 3**	**Track 4**	**Right W.Tr.**	**Left W.Tr.**	**MRI**
Type A Road	2.22	2.21	2.37	2.30	2.22	2.33	2.27
Type B Road	1.84	2.14	1.10	1.22	1.99	1.16	1.57
Type C Road	2.72	2.76	2.44	2.04	2.74	2.24	2.49
Type D Road	3.49	3.31	3.74	3.77	3.40	3.30	3.75
Type E Road	3.85	3.98	3.44	4.30	3.91	3.87	3.89

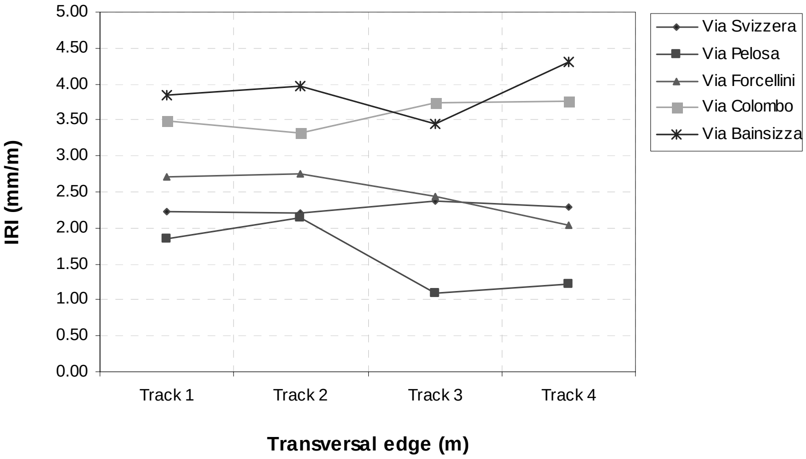

Figure 5 Transverse trend of RN

One of the priorities of this research was to study the transverse variability of the roughness indexes deriving from the acquisition of profilometric data on arbitrarily assumed alignments, in order to verify the reliability of the final parameters with respect to the possible variety of conditions found on urban roads. As described for the IRI index, a trend was also reconstructed for RN of the transverse variability of the parameter with respect to the four tracks surveyed, as reported in figure 5.

Also in the case of RN the aggregation methods were verified of the values obtained in a transverse direction for the four tracks of the studied surfaces, then determining the errors (absolute and percentage) made during the data processing.

The numerical values obtained are reported in detail in table 5.

Table 5 – Estimate of the error committed in averaging the values of RN

	RIDE NUMBER						
	Track 1	**Track 2**	**Track 3**	**Track 4**	**MRN**	**Dev.St.**	**D.S./MRN**
Type A Road	2.22	2.21	2.37	2.30	2.28	0.06	3%
Type B Road	1.84	2.14	1.10	1.22	1.58	0.43	27%
Type C Road	2.72	2.76	2.44	2.04	2.49	0.29	12%
Type D Road	3.49	3.31	3.74	3.77	3.58	0.19	5%
Type E Road	3.85	3.98	3.44	4.30	3.89	0.31	8%

The protocol for the determination of the evenness indexes in longitudinal direction contained in the draft of European regulation Pr-EN 13036:5 also includes the determination of the RMS parameter referring to three waveband ranges, termed “Short Waveband” (0.781 m < λ < 3.125 m), “Medium Waveband” (3.125 m < λ < 12.5 m) and “Long Waveband” (12.5 m < λ < 50 m). The Software ProVal – used in the processing presented in this context – cannot make a continuous calculation of the parameter RMS along the alignment, just determine its average value along each of the tracks. Nonetheless, this aspect does not limit the possibility of a transverse comparison of the average values of the parameter, determined along each of the alignments of the individual roads examined, after filtering of the spectrum of texture measured according to Pr-EN 13036:5.

The values of the RMS parameter calculated and divided by road and by waveband and for each of the surveyed tracks are reported in table 6.

Table 6 – Values of RMS of the single alignments per waveband

	ROOT MEAN SQUARE VALUE (10^{-4} cm/m^2)											
	SHORT WAVEBAND				MEDIUM WAVEBAND				LONG WAVEBAND			
	T1	**T2**	**T3**	**T4**	**T1**	**T2**	**T3**	**T4**	**T1**	**T2**	**T3**	**T4**
Type A Road	21.60	22.40	16.50	17.40	17.30	17.10	13.90	14.20	4.34	4.30	3.61	3.59
Type B Road	41.40	39.40	23.40	25.70	17.00	15.10	15.10	17.00	6.08	7.26	4.48	5.57
Type C Road	13.30	13.80	17.70	22.90	14.20	14.20	13.10	16.20	5.17	4.71	4.27	4.99
Type D Road	3.24	4.84	4.46	3.36	7.67	11.20	9.94	8.13	7.46	1.10	9.67	7.48
Type E Road	5.51	6.30	10.20	3.39	5.51	5.26	6.34	3.46	1.97	2.38	2.36	2.20

One of the most useful parameters for the spectrum analysis of road profiles is certainly the PSD, the determination of which is also included in the draft of European regulation pr-EN 13036:5. In this particular case, determination of the PSD is clearly not so important in itself, but rather the possibility of comparing the PSD of different profiles and of understanding what information to gather from the possible variety of information deriving from the survey of parallel tracks of the same surface. Thus, as provided for in Pr-EN 13036:5, the best prospects in terms of comparability of the PSD are offered by the functional classification of the surfaces given in ISO 8608, using the eight classes laid down by the regulation in correspondence to an assigned reference value of the *n* abscissa (Wave Number) (table 7). It was thus possible to assign a functional class to each of the surveyed tracks according to ISO 8608, allowing a more immediate interpretation of the transverse unevenness of the PSD for each of the investigated surfaces. When the summary table had been drawn up of the determined functional classes, it was possible to evaluate to what level the variability of the data acquired in a transverse direction reflects on the functional class of the surface, in other words if and to what extent the ISO 8608 classification – fully adopted in Pr-EN 13036:5 – is sensitive to the transverse unevenness of the alignments assumed.

Table 7 Functional classification of the road surfaces according to ISO 8608

UNEVENNESS INDEX (ISO 8608)		
Road class	**Gd (n_0) [10^{-6} m^3]**	
	Lower bound	**Upper bound**
A	-	32
B	32	128
C	128	512
D	512	2048
E	2048	8192
F	8192	32768
G	32768	131072
H	131072	-
n_0 = 0.1 cycle/m		

Table 8 Functional evaluation of the single alignments according to ISO 8608

	UNEVENNESS INDICES (ISO 8608)							
	G (0.1 cycle/m) [10^{-6} m^3]				**Class road**			
	T1	**T2**	**T3**	**T4**	**T1**	**T2**	**T3**	**T4**
Type A Road	77.3	93.7	49.4	37.7	B	B	B	B
Type B Road	77.1	12.4	145.0	427.0	B	A	C	C
Type C Road	340.0	341.0	258.0	512.0	C	C	C	D
Type D Road	33.1	66.2	37.1	48.8	B	B	B	B
Type E Road	46.5	39.0	36.8	2.58	B	B	B	A

4. CONCLUSIONS

The main aim of the study was to verify the transverse variability of the road profiles and corresponding roughness indexes, determined according to the indications in the draft of European regulation Pr-EN 13036:5.

The interest deriving from the acquisition of the profilometric data also translated into an evaluation of the methods of representation and reproduction of the results obtained, as part of a wider discussion related to the significance of the single datum. It was therefore decided to adopt a simplified analytical approach, based on the criterion of the arithmetical average of the partial results, already verified by the Working Group of Austroads (Determination of the International Roughness Index (IRI) using the ARRB TR Walking Profiler). Consequently, starting from the profilometric data acquired along four parallel alignments separated according to a predefined fixed geometry and coherent with that established by the Australian test protocol, the roughness indexes given in Pr-EN 13036:5 were calculated, after filtering the raw data according to the specifications in the draft standard. The single indexes, calculated for each of the four tracks, in the five studied contexts, were then analysed and represented in a transverse direction, as well as evaluated with respect to the calculated average arithmetical value, as further guarantee of the reliability of the final data.

Determination of the percentage error committed, calculated as the percentage incidence of the standard deviation with respect to the average arithmetical value of each of the four indexes, demonstrated that, in the calculation of the IRI index, there was a percentage of uncertainty of 10% on average, with respect to the average value calculated, only occasionally higher (22%) where the studied surface (Type D Road) was intentionally irregular, in both longitudinal and transverse direction. In the calculation of RN, the picture is even more varied, passing from a statistical uncertainty of 5% to one of 27% in the case of Type D Road. The same considerations can be made about the high variability (in absolute value) of the parameters in the case of RMS, in all three spectrum bands considered.

The functional classification of the surfaces on the basis of the value $G(n_0)$ deriving from the PSD of the single profiles is particularly interesting. Table 8 shows that only in two cases out of 5 there is coherence between the four tracks examined, confirming the high sensitivity of the descriptive parameters of the evenness to the choice of alignment. Evidently, the convergence of the roughness indexes – i.e. the maximum reduction of the connected statistical uncertainty – depends, strongly and proportionally, on the chosen number of alignments, contributing to increasing the level of information on the characteristics of the studied surface. Nevertheless, the conducting of numerous surveys on the same surface being unlikely for practical reasons, it is considered indispensable to compensate for the higher level of uncertainty in the representation of roughness indexes with absolute and percentage ranges of error that also guarantee the significance in the transverse direction.

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