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Characterization of pavement texture by use of surface profiles —

Part 1:
Determination of mean profile depth

Caractérisation de la texture d'un revêtement de chaussée à partir de relevés de profils de la surface —

Partie 1: Détermination de la profondeur moyenne du profil

Reference number
ISO 13473-1:2019(E)

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 43, *Acoustics*, Subcommittee SC 1, *Noise*.

This second edition cancels and replaces the first edition (ISO 13473-1:1997), which has been technically revised. The main changes compared to the previous edition are as follows:

— Some alternative calculation options such as the slope suppression for continuous data have been removed.

— A more precise definition of high-pass and low-pass filtering has been provided.

— Removal of spikes has been introduced in the profile.

— The MPD now refers only to the overall value obtained after averaging all *MSD*s where *MSD* means Mean Segment Depth (earlier, MPD was used as the term both for the mean segment depth and for mean profile depth, which might have been confusing).

A list of all parts in the ISO 13473 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

This corrected version of ISO 13473-1:2019 incorporates the following corrections:

— The segment length was corrected to 100 mm throughout the document;

— in 7.3, at the end of the fourth paragraph, the following sentence was added: "If there are more invalid samples than 5 mm in the beginning or the end of a sampled profile the effected MSD value(s) should be discarded." and in the last paragraph, "Profiles" was replaced by "Segments" and "readings" replaced by "samples";

— in 7.6, the third paragraph was replaced by the following one: "If there are no data available before and after the section to be computed, one should extend the signal by mirroring the first and the last segments before filtering.";

— in 7.10, the first list element was rephrased;

— in Clause 10, the following text was deleted: "whether or not spike removal procedure was applied;", "type and order of filters used;" and "and type of interpolation used";

— in D.3.7, replace "7.10" by "7.9";

— in E.1, fifth paragraph, a third sentence was added as follows: "The spikes are first identified in forward and reverse direction before replacing them with the interpolated value.".

— Figure E.3 was corrected.

Introduction

Road surface texture determines factors such as noise emission from the tyre/pavement interface, acoustic comfort inside vehicles, friction between the tyre and road, rolling resistance and tyre wear. The main concept and the basic terms are illustrated for information in Annex A. Valid methods for measuring surface texture are therefore highly desirable.

The so-called “sand patch” method, or the more general “volumetric patch” method (see Clause 3), has been used worldwide for many years to give a single and very simple measurement describing surface texture. It relies on a given volume of sand or glass beads which is spread out on a surface. The material is distributed to form a circular patch, the diameter of which is measured. By dividing the volume of material spread out by the area covered, a value is obtained which represents the average depth of the sand or glass bead layer, known as “mean texture depth” (MTD). The method was originally standardized in ISO 10844:1994[1)], Annex A[5] in order to put limits concerning surface texture for a reference surface used for vehicle noise testing but was later adopted by CEN as EN 13036-1[13].

The volumetric patch method is operator-dependent and can be used only on surfaces which are partly or fully closed to traffic. Therefore, it is not practical for use in network surveys of roads, for example. Along with developments in contactless surface profiling techniques, it has become possible to replace the volumetric patch measurements with those derived from profile recordings, which are possible to make by mobile equipment in flowing traffic. However, several very different techniques have been used to calculate a “predicted mean texture depth”, many of them quite successfully. The values they give are not always comparable, although individually they generally offer good correlation coefficients with texture depth measured with the volumetric patch method.

It is, therefore, important to have a standardized method for measuring and evaluating the texture depth by a more modern, safe and economical technique than the traditional volumetric patch method, resulting in values which are directly compatible both with the patch-measured values and between different equipment.

1) Withdrawn and replaced by ISO 10844:2014.

Characterization of pavement texture by use of surface profiles —

Part 1:
Determination of mean profile depth

1 Scope

This document describes a test method to determine the average depth of pavement surface macrotexture (see Clause 3) by measuring the profile of a surface and calculating the texture depth from this profile. The technique is designed to provide an average depth value of only the pavement macrotexture and is considered insensitive to pavement microtexture and unevenness characteristics.

The objective of this document is to make available an internationally accepted procedure for determination of pavement surface texture depth which is an alternative to the traditionally used volumetric patch technique (generally using sand or glass beads), giving comparable texture depth values. To this end, this document describes filtering procedures that are designed to give the best possible representation of texture depths determined with the volumetric patch method[13].

Modern profilometers in use are almost entirely of the contactless type (e.g. laser, light slit or light sheet, to mention a few) and this document is primarily intended for this type. However, this does not exclude application of parts of it for other types of profilometers.

This ISO 13473 series has been prepared as a result of a need identified when specifying a test surface for vehicle noise measurement (see ISO 10844:2014[6]). Macrotexture depth measurements according to this document are not generally adequate for specifying test conditions of vehicle or traffic noise measurements, but have limited applications as a supplement in conjunction with other ways of specifying a surfacing.

This test method is suitable for determining the mean profile depth (MPD) of a pavement surface. This MPD can be transformed to a quantity which estimates the macrotexture depth according to the volumetric patch method. It is applicable to field tests as well as laboratory tests on pavement samples. When used in conjunction with other physical tests, the macrotexture depth values derived from this test method are applicable to estimation of pavement skid resistance characteristics (see e.g. Reference [15]), estimation of noise characteristics and assessment of the suitability of paving materials or pavement finishing techniques.

The method, together with other measurements (where applicable), such as porosity or microtexture, can be used to assess the quality of pavements.

This document is adapted for pavement texture measurement and is not intended for other applications. Pavement aggregate particle shape, size and distribution are surface texture features not addressed in this procedure. The method is not meant to provide a complete assessment of pavement surface texture characteristics. In particular, it is known that there are problems in interpreting the result if the method is applied to porous surfaces or to grooved surfaces (see Annex B).

NOTE Other International Standards dealing with surface profiling methods include, for example, References [1], [2] and [3]. Although it is not clearly stated in these, they are mainly used for measuring surface finish (microtexture) of metal surfaces and are not intended to be applied to pavements.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/IEC Guide 98-3, *Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
texture wavelength
λ
quantity describing the horizontal dimension of the irregularities of a *texture profile* (3.3)

Note 1 to entry: Texture wavelength is normally expressed in metres (m) or millimetres (mm).

Note 2 to entry: Texture wavelength is a descriptor of the wavelength components of the profile and is related to the concept of the Fourier Transform of a series regularly sampled measurement points along a spatial axis. Vertical displacement (height) has an arbitrary reference.

3.2
texture
pavement texture
deviation of a pavement surface from a true planar surface, with a *texture wavelength* (3.1) less than 0,5 m

3.3
surface profile
texture profile
upper contour of a vertical cross-section through a pavement

Note 1 to entry: Texture profile is similar to surface profile but limited to the texture range.

Note 2 to entry: The profile of the surface is described by two coordinates: one in the surface plane, called **distance** (the abscissa), and the other in a direction normal to the surface plane, called **vertical displacement** (the ordinate). An example is given in Figure A.1. The distance may be in the longitudinal or lateral (transverse) directions in relation to the travel direction on a pavement, or in a circle or any other direction between these extremes.

3.4
macrotexture
pavement macrotexture
deviation of a pavement surface from a true planar surface with the characteristic dimensions along the surface of 0,5 mm to 50 mm, corresponding to *texture wavelengths* (3.1) with one-third-octave bands including the range 0,63 mm to 50 mm of centre wavelengths

Note 1 to entry: Peak-to-peak amplitudes may normally vary in the range 0,1 mm to 20 mm. This type of texture is the texture which has wavelengths of the same order of size as tyre tread elements in the tyre/road interface. Surfaces are normally designed with a sufficient macrotexture to obtain suitable water drainage in the tyre/road interface. The macrotexture is obtained by suitable proportioning of the aggregate and mortar of the mix or by surface finishing techniques.

Note 2 to entry: Based on physical relations between texture and friction, noise, etc., the World Road Association (PIARC) originally defined the ranges of micro-, macro- and megatexture[16]. Figure A.2, which is a modified version of the original PIARC figure, illustrates how these definitions cover certain ranges of surface texture wavelength and spatial frequency. In this figure, "discomfort for travellers" includes effects experienced in and on motorized road vehicles and bicycles, as well as wheelchairs and other vehicles used by disabled people.

3.5 Texture depth measurements

3.5.1
texture depth
TD
in the three-dimensional case, the distance between the surface and a plane through the top of the three highest peaks within a surface area in the same order of a size as that of a car tyre/pavement interface

Note 1 to entry: See Figure A.3.

3.5.2
mean texture depth
MTD
texture depth (3.5.1) obtained from the volumetric patch method

Note 1 to entry: In the application of the "volumetric patch method" (see below), the "plane" is in practice determined by the contact between a rubber pad and the surface when the pad is rubbed over the area. Therefore, the texture depth obtained in this case is not based on exactly a "plane", but rather an approximation which is a somewhat curved surface that is hard to define.

3.5.3
profile depth
PD
in the two-dimensional case, i.e. when studying a profile, the difference, within a certain longitudinal/lateral distance in the same order of length as that of a car tyre/pavement contact interface, between the profile and a horizontal line through the top of the highest peak within this profile

3.5.4
evaluation length
l
length of a portion of one or more profiles for which *MPD* (3.5.2) is to be calculated

3.5.5
segment
portion of the profile over a length of 100 mm

Note 1 to entry: See Figure A.4.

3.5.6
mean segment depth
MSD
average value of the *profile depth* (3.5.3) of a *segment* (3.5.5)

Note 1 to entry: See Figure A.4.

3.5.7
mean profile depth
d_{MPD}
MPD
average of the values of the *MSD* (3.5.6) of the tested section

3.5.8
estimated texture depth
d_{ETD}
ETD
term used when the *MPD* (3.5.7) is used to estimate the *MTD* (3.5.2) by means of a transformation formula

3.6
volumetric patch method
method relying on the spreading of a material, usually sand or graded glass beads, in a patch

Note 1 to entry: The material is distributed with a rubber pad to form an approximately circular patch, the average diameter of which is measured. By dividing the volume of material by the area covered, a value is obtained which represents the average depth of the layer, i.e. MTD. The volumetric patch method is described in EN 13036-1.

Note 2 to entry: The volumetric patch method is used not only with sand or glass beads as the patch material, but in some cases with putty or grease. However, such materials have certain disadvantages, and for international standardization, only glass beads have been recommended. The ETD measure is based on glass beads as the patch material.

3.7
drop-out
data in the measured profile indicated by the sensor as invalid

3.8
spike
unusually high and sharply defined peak in the measured profile, which is not part of the true profile and is not automatically detected as invalid by the system

Note 1 to entry: See Annex E for a quantitative definition of a spike.

4 Test surfaces

4.1 Condition of the surface

Measurements shall not be made during rain or snow fall. Unless it has been demonstrated that the equipment provides valid measurements on wet or damp surfaces, the surface shall be dry during the measurements. It shall also be clean and reasonably free of debris and foreign objects.

It is possible that optical-based measuring systems do not perform properly on newly laid asphalt surfaces which are glossy and dark. If the test is performed during the paving process, optical distortions due to temperature gradients in the air above the tested surface can produce invalid data.

For roads which have been in service, the texture can vary across the pavement. In this case, the transverse location of the measurement is normally determined by the intended use of the data.

4.2 Amount of data to be collected per field test section

4.2.1 Continuous measurements

Continuous measurements are made when a certain length of a road is measured with possible interruptions of a maximum of 10 % of the length. The minimum evaluation length over which MPD is calculated shall be 1,0 m. It is not meaningful to report MPD over shorter lengths.

It is recommended that measurements and calculations be made continuously along the entire test section.

4.2.2 Spot measurements

If a continuous measurement is not possible, as is the case for stationary devices, measurements may be made at certain spots which are appropriately distributed. The following minimum provisions apply:

- Each evaluation length shall include at least eight single measured segments of at least 100 mm length. This would normally be along a straight line, but may also be in a circular path or in parallel lines (in connection with 3D measurements). Each segment shall be measured continuously. The exception is when analysing round laboratory samples; see 4.3.
- The procedure in Annex C is recommended to select measurement positions and evaluation lengths in an unbiased manner.
- The minimum evaluation length shall be 1,0 m.

For surfaces with periodic textures (e.g. grooved or tined surfaces), the total profile length shall include at least 10 periods of the dominant texture frequency.

4.3 Amount of data to be collected on laboratory samples

Laboratory samples are generally either circular cores or rectangular slabs. They may be directly taken from a road or airfield, produced in a laboratory or replicated based on mouldings from an actual road or airfield site.

When measuring laboratory samples, care should be taken that edge effects of the samples do not affect the measurement.

In order for the measurements to give values reasonably representative of an actual field site, the following three requirements shall be met:

- Cores, slabs or mouldings intended for profile measurement shall be taken from at least four different places, evenly distributed longitudinally along the site.
- The measurements shall include at least 4 segments (per core), evenly distributed on the laboratory samples (see below), each profile measured over at least 100 mm length and not being part of another profile, except that one profile may cross another profile.
- The minimum evaluation length shall be 1,0 m.

It is recommended that cores have a minimum 150 mm diameter, although 100 mm diameter cores are acceptable. If the core diameter does not allow measurements to follow a straight line of the required length across the core, it is recommended to rotate the core underneath the sensor (or vice versa) and make the measurement along a circle around the core centre. Such circles should have a minimum circumference of 200 mm (corresponding to a diameter of 64 mm).

Rectangular samples often have dimensions which exceed typical core dimensions. On such samples, individual profile measurements should be distributed uniformly.

Measurements on laboratory samples can have many different purposes. This means that it is difficult to specify general minimum requirements. The specification here assumes that the purpose is to obtain values which are reasonably representative of pavements.

5 Measurement instruments

5.1 Instruments in general

A profilometer system shall be used which produces a signal output that is proportional to the distance between a sensor reference plane and the surface spot in question. Examples of sensors include acoustical, electro-optical type or a video camera. The final output shall be linearly related to the texture profile and this may be obtained either in hardware or software, as necessary. The profilometer system shall also provide means of moving the sensor along or across the surface at an elevation (vertically) which is essentially constant over at least one profile length. This does not apply when the profile is produced by some techniques such as light sectioning.

5.2 Vertical resolution

The vertical resolution shall be 0,05 mm or better. The measuring range of the sensor should be a minimum of 20 mm. When measuring smoother surfaces, a smaller range is permissible. For a sensor mounted on a moving vehicle, a higher range is usually required to allow for vehicle motion.

NOTE 1 A laser sensor system having a measuring range of 200 mm and a 12-bit digital resolution has a vertical resolution of a little less than 0,05 mm.

NOTE 2 It has appeared that many of the laser profilometers have a noise floor which corresponds to 0,13 mm to 0,17 mm of MPD. A vertical resolution of 0,05 mm means that the vertical resolution does not contribute to the noise floor.

5.3 Horizontal resolution

In the case of a device utilizing a laser, other electro-optical sensor, or a sensor based on sound transmission, the spot of the radiation should be such that its average diameter on the road surface shall in no case be greater than 1 mm over the used vertical range. In this case, the effective spot is taken as that contained within an area limited by a contour line where the intensity of the spot is 1/e (approximately 37 %) of the maximum intensity within the spot.

In the case where a light-sectioning device is used, the projected light band or line shall be sufficiently sharp to give a light/dark transition within 1 mm. In this case, the effective line width is taken as that where the intensity of the line has reduced from 100 % to 1/e (approximately 37 %) of the maximum intensity within the line.

In the case where a contact device is used (e.g. utilizing a stylus sensor), the widest dimension of the contacting part (tip) shall have a diameter of no more than 1 mm up to 1 mm in height from the tip. Contact forces on the surface shall not be so high as to cause penetration or destruction of the surface texture. Such destruction is usually detectable as a clearly visible trace where contact was made.

The sampling interval shall not be more than 1,0 mm, and samples shall be taken at a fixed interval in the horizontal direction.

It shall be noted that the movement by the laser or light spot during the time of collecting each sample means that the spot is extended somewhat in the direction of measurement. This “stretching” of the spot due to the measurement speed can be calculated by dividing the measurement speed by the time for each sample collection and it should never result in a spot longer than 1 mm. It can mean a limitation of the measurement speed.

5.4 Measurement speed

The measurement speed is the speed with which the profile is traced by the profilometer, and shall be such that the requirements on sampling interval are met. This applies to stationary as well as mobile profilometers. The relation is:

$$v \leq f_s \cdot s / 1\,000 \tag{1}$$

where

v is the profilometer speed (m/s);

f_s is the sampling frequency of the sensor (Hz);

s is the sampling interval (mm).

In some devices, the speed influences the effect of the background noise, since the latter can be higher at higher frequencies. Depending on how sampling takes place and the low-pass filtering, the speed can influence the electronic frequency corresponding to the lower texture wavelength limit. See 5.2 regarding possible effect of sampling variations.

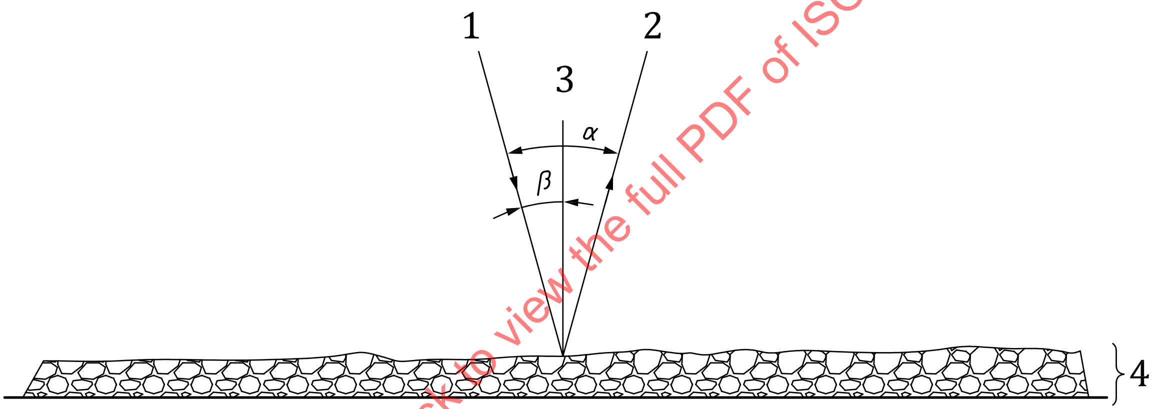
NOTE Low-pass refers to a filtering of the signal with the intention to attenuate the higher frequencies (either temporal or spatial).

5.5 Alignment of sensor

In case of reflected radiation, the angle between the optical or acoustical axis of the radiation toward the surface and the optical or acoustical axis of the detector (α) should not exceed 30°. See Figure 1. Larger angles underestimate very deep textures and cause higher drop-out rates. It is preferred that the β angle is as low as possible. This paragraph applies also to light-sectioning devices.

It is recommended that the sensor be moved in a direction perpendicular to the plane of the radiation; i.e. perpendicular to the plane of the figure.

For mechanical devices, α is not applicable and β shall be no more than 30°.



Key

1 emitting device

2 receiving device

3 surface normal

4 road surface

Figure 1 — Requirements regarding alignment of non-contact sensors above a road surface

5.6 Bandwidth of sensor and recording system

The bandwidth of the sensor and recording system shall meet at least the bandwidth induced by the filtering procedures described in 7.6.

NOTE 1 The bandwidth can be verified to be within the appropriate range by using surfaces machined to simulate textures with known profiles. For mobile devices, such surfaces (discs or drums) can be rotated underneath the sensing device. In this instance, the measurement device remains stationary.

NOTE 2 The lower and the higher texture wavelength limits given in 7.6 do not correspond to the definition of macrotexture according to 3.4. This is because:

— to some extent, this imitates the effect of the enveloping by rubber surfaces, such as a tyre,

— wavelengths smaller than 3 mm and higher than 140 mm do not play a major role in determination of MPD or ETD according to Figure 13 of Reference [15],

— many profilometers have poor performance in the range below 3 mm, and

— with a 3 mm limit, profilometers will give more uniform values less affected by erroneous transients.

5.7 Performance check

Regular performance checks shall be made by operating the sensor over a designated reference surface, utilising a stable profile.

Performance checks shall be designed such that differences as small as 0,1 mm between the recorded MPD and the actual MPD for the reference surface can be detected. The MPD of the reference surface should be at least 1,5 mm.

NOTE 5.2 requires that vertical resolution be 0,05 mm or better.

If the performance check shows a difference greater than 0,1 mm, or 5 % (whichever is the most stringent value), from the expected reference MPD value, the deviation should be reported. If the difference is greater than 0,2 mm, or 10 % (whichever is the most stringent value), it indicates that something might be wrong with the system and the problem should be investigated.

See Annex G regarding various reference surfaces and other suggestions. Annex G also explains how to calculate the MPD of these surfaces.

The type of reference surface used shall be reported.

5.8 Indication of invalid readings (drop-outs)

Invalid readings (“drop-outs”) can occur due to the photometric properties of the surface or shadowing of the light in deep troughs of the profile. Therefore, the system shall have means of identifying drop-outs.

In addition, laser diodes deteriorate over time, which can eventually result in excessive invalid readings. For this reason, and for checking that the intensity is within the manufacturer’s specification, it is recommended that there be a means of checking the laser intensity at certain intervals.

5.9 Sensitivity to vibrations

The sensor shall be maintained in a stable vertical position during the measurement of a full segment length (100 mm) at all operating speeds. The measurement system shall be designed so that vibrations have a negligible effect on the accuracy of the measurement, particularly vibrations associated with the natural suspension frequency of the sensor and/or its carrier.

6 Measurement procedure

6.1 Performance checks

The performance of the equipment shall be checked using a known profile according to 5.7. Such checks shall not be less frequent than on each measuring day. The data measured since the previous checking shall be analysed and deleted in case of a doubt.

6.2 Measurements

The profile of the test surface shall be measured using equipment in accordance with Clause 5 and meeting the requirements on evaluation length in Clause 4.

6.3 Continuous or spot measurements

Measurements may be made by devices that record the profile continuously over the test section, with minor interruptions permitted for data transfer or data processing (see 4.2.1). Continuous measurement systems are normally mobile equipment mounted on a testing vehicle. Measurements may also be made only on specific spots on the test section or on specimens in a laboratory (see requirements in 4.3 and Annex C), in which case the equipment is usually stationary but moveable.

7 Data processing procedure

7.1 General

Data processing in this document contains two basic parts. The objective of the first part (7.2 to 7.5) is to remove the spurious readings from the measured profile to make use of as much of the collected data as possible. The second part (7.6 to 7.11) aims at processing the cleaned data to obtain the required measures.

After the first part has been finished (7.2 to 7.5), the profile should have been cleaned and is ready to use also in other texture calculations, as outlined in ISO 13473-2[7], or specified in ISO/TS 13473-4[8] or ISO 13473-5[9].

7.2 Summary of data processing steps

The data processing procedure shall be as follows (the numbers refer to the subclause where the step is described).

Drop-out correction (7.3): Eliminate or correct for invalid readings (drop-outs).

Resampling data to required spacing in the spatial domain (7.4): Resample the data collected to the required resolution in the spatial domain, making use of all relevant raw data.

NOTE Resampling from temporal to space domain directly depends on the speed of the vehicle performing the measurements.

This resampling is needed also in the spatial domain if initial sampling was made at shorter intervals than the required 0,5 mm or 1 mm spacing.

Spike identification and reshaping the profile (7.5): Identify spurious readings (so called "spikes"; see Annex E) and remove the effect of these by reshaping the profile.

Removal of long-wavelength components and normalization of profile sharpness (7.6): Apply high-pass filtering to remove unwanted slopes and long wavelengths in the profile. Apply low-pass filtering to remove frequency components which are above a certain texture wavelength in order to normalize to a uniform sharpness of the profile.

Segment limiting (7.7): Select segments of the profile which are 100 mm long.

Peak determination (7.8): Divide each segment in two halves and detect the peak levels of the profile over each half of the segments.

MSD determination (7.8): Calculate the MSD as the average of the two peaks according to 7.8.

Extreme MSD value removal (7.9): Identify and remove MSD outliers (optional).

MPD determination (7.10): Determine the average of all MSD values for the profile and calculate the standard deviation.

ETD determination (optional) (7.11): Transform the MPD value to an ETD by applying a transformation formula.

The following subclauses elaborate on these individual steps. Refer also to the flow charts in Annex H.

7.3 Drop-out correction and interpolation

Care shall be taken to eliminate invalid readings from the profile. For example, invalid measurements can occur due to surface photometric properties or shadowing of light in deep surface troughs. Instead, the invalid part of the profile shall be replaced with interpolated data from the nearest valid points as explained in D.3.1.

As illustrated in Figure 2, several drop-outs may occur in succession. When a series of invalid samples is preceded and followed by valid samples, each of the invalid samples shall be replaced by an interpolated value. Simple linear interpolation shall be used.

With regard to linear interpolation, the invalid samples are replaced by an interpolated value z_i according to Formula (2):

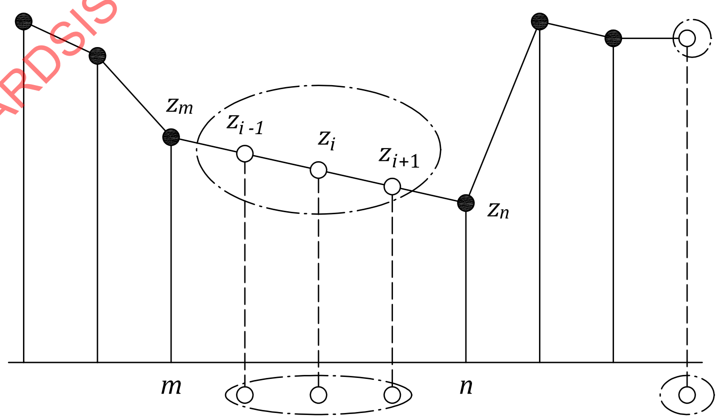
$$z_i = \frac{z_n - z_m}{n - m}(i - m) + z_m \qquad (2)$$

where

i	is the sample numbers where the value is invalid;
m	is the sample number of the nearest valid value before i;
n	is the sample number of the nearest valid value after i;
z_i	is the interpolated value for sample i;
z_m	is the value of sample m;
z_n	is the value of sample n.

When the invalid sample(s) constitute(s) the beginning or the end of a sampled profile, the invalid samples shall be replaced by the value of the nearest valid sample. This method of extrapolation shall be limited to a maximum length at either side of the sampled profile data series equal to 5 mm. If there are more invalid samples than 5 mm in the beginning or the end of a sampled profile the effected MSD value(s) should be discarded.

For the study of road surface singularities (like joints), such singularities can be intentionally included in the analysis, on condition that no drop-out readings of the sensor occur.



NOTE Drop-outs are illustrated by unfilled symbols.

Figure 2 — Illustration of interpolation and extrapolation of drop-outs

NOTE In the case illustrated in Figure 2, there are three intermediate consecutive drop-outs, which are linearly interpolated between the samples at positions *m* and *n*, and one extreme drop-out, which is extrapolated from the preceding sample.

The measurement on a particular pavement profile is considered valid only if the drop-out rate meets the following criterion[17]:

— Segments with loss of data due to drop-out greater than 10 % (of the total number of samples) shall be discarded.

7.4 Resampling to a certain spatial resolution

This requirement is applicable to the majority of profilometer systems, particularly those using the single-sensor triangulation principle. More advanced systems may not require this step if a similar process is performed within the measurement system.

Re-sample the signal to either 0,5 mm or 1,0 mm spacing; preferably 0,5 mm. Calculate the arithmetic average of all samples that fall within the required spacing.

In case the profile is extracted from a number of parallel profiles, such as when measuring a three-dimensional surface representation, the total width of the selected profile lines should be at most 1 mm.

This resampling is needed also in the spatial domain if initial sampling was made at shorter intervals than the required 0,5 mm or 1 mm spacing.

7.5 Spike identification and reshaping the profile

The spike removal procedure shall be as described in Annex E. Spike removal shall be performed. For the segment to be valid, the removed spikes should not correspond to more than 5 % of the total segment profile (after resampling).

7.6 Removal of long-wavelength components and normalization of profile sharpness

If the profile has been recorded continuously (4.2.1), high-pass filtering shall be made to reduce the effect of slopes or gradients in the profile curve (long-wavelength components) which are irrelevant to the determination of MSD and MPD. The filter shall be of the Butterworth type, 2nd order, and have a cut-off at 140 mm texture wavelength. The filtering shall be made in a forward-reverse filter in order to reduce phase distortion of the profile signal[18]. To achieve this, a second-order Butterworth filter with (- 3 dB) cutoff wavelength at 174,2 mm shall be designed and then applied in both forward and reverse directions. This will give the desired features.

The length of the profile to be recorded and filtered shall be at least 1 m.

NOTE 1 The maximum length is not specified, as it is determined by practical considerations rather than technical performance.

If there are no data available before and after the section to be computed, one should extend the signal by mirroring the first and the last segments before filtering.

If the profile has been recorded only at discrete spots (4.2.2), slope suppression is the preferred procedure to remove the long-wavelength component. It shall be applied to each segment. The slope of the profile curve within a segment according to Figure A.4 shall be suppressed by calculating the regression line through all profile values and subtracting this line from the profile. This does not apply to profiles measured in circles with a circumference of at least 200 mm, in which case high-pass filtering shall be applied.

Low-pass filtering shall be made in order to reduce the possible influence of noise and transients and to have a relatively uniform influence of narrow profile peaks. The filter shall be of the Butterworth type, 2nd order, and have a cut-off at 3,0 mm texture wavelength. The filtering shall be made in a forward-reverse filter in order to reduce phase distortion of the profile signal[18]. To achieve this, a second-order

Butterworth filter with (- 3 dB) cutoff wavelength at 2,40 mm shall be designed and then applied in both forward and reverse directions. This will give the desired features.

The selection of low-pass filter characteristics is very critical for determination of MPD and consistency between various equipment. Therefore, no filter other than the one required here shall be used.

NOTE 2 More information about the filtering, including suggested filtering constants, is given in Annex D as a guide.

NOTE 3 It is preferred to use the formula and coefficients in Annex D rather than to filter the data with a built-in filter from an add-in or similar. This reduces the risks of making errors or mistakes or impairing reproducibility.

7.7 Segment limiting

Each individual profile on which the following calculations are made shall have a segment which is 100 mm long. This is illustrated in Figure A.4.

7.8 Peak and MSD determination

The peak level of the profile over each half of the segment shall be identified. This requires that the segment of 100 mm be divided into two equal parts and that the highest peak in each part is determined.

The MSD for each individual segment is the arithmetic mean of the two peak levels minus the average profile level (which is close to zero after the high-pass filtering).

In some measuring devices, the profile signal can have been inverted and it is important to observe that the peaks considered above are those asperities of the profile with the highest elevation.

7.9 Extreme MSD value removal (optional)

Some MSD values occasionally appear as outliers. Reasons for this include for example leaves or other flying debris intersecting the laser light, occasional loose stones on the surface, a “hole” or a wide joint in the surface. To avoid the influence of MSD outliers on MPD, it is recommended to use a 3-point moving median filter. The idea of the median filter is to step through all the MSD values which constitute an MPD value, three by three in consecutive order, replacing each individual value with the median of the three neighbouring values, stepping forward by one MSD value each time. In this way, exceptionally high or low single values are sorted out and the median retained. The MPD value is then not affected by single extreme values.

When an MPD value has been processed to exclude extreme MSD values, this shall be reported.

This procedure is not recommended when extreme texture features are of interest.

7.10 Averaging of MSD to determine the MPD

A number of MSD values shall be measured and calculated to meet the requirements of 4.2 and 4.3. The final reported MPD values shall be:

— the arithmetic mean value of all valid MSD for the section or sample. The MPD value is valid if it is calculated from MSD values covering at least 50 % of the section;

— the corresponding standard deviation;

— the number of individual values on which the mean is based, including the number of measuring runs and the number of segments in each run.

7.11 Calculation of ETD (optional)

The ETD is a way of relating MPD measurements with measurements of MTD, which are measurements made with the volumetric patch method[13]. The main advantage of the volumetric patch method is that it requires only very simple equipment; another one is where space is too limited for a laser profilometer. The resulting formula, however, depends largely on the operator of the patch test, how that test is conducted and the set of surfaces included in the study.

The MPD value, d_{MPD}, may be transformed to an ETD, d_{ETD}, by applying the transformation Formula (3):

$$d_{ETD} = 1{,}1 \cdot d_{MPD} \tag{3}$$

where d_{ETD} and d_{MPD} are expressed in millimetres.

NOTE 1 In the industry and technical documents, the formula can be found with abbreviated terms instead of symbols.

The texture range where Formula (3) is reasonably accurate is approximately 0,3 mm < MPD < 3,0 mm for dense surfaces (refer to B.1 with regard to limited validity for porous surfaces).

Formula (3) reflects an average of recent results compiled when producing this document, but it shall be noted that the variation is large due to errors in determination of the MTD. Typically, individual studies of this relation give variations of the coefficient between 0,9 and 1,3.

NOTE 2 In the first version of this document, the formula was: ETD = 0,2 mm + 0,8 MPD, which was based on comprehensive measurements in an International PIARC Experiment and presented in Annex E of Reference [15]; ASTM E1845-15 also accepted that formula[10]. However, a compilation of later (unpublished) tests have led to the slightly different Formula (3).

8 Measurement uncertainty assessment according to ISO/IEC Guide 98-3

The measurement procedure described in this document is affected by several influencing factors that lead to variation in the results observed for the same subject. The source and nature of these perturbations are not completely known. The measurement uncertainty can be determined in accordance with ISO/IEC Guide 98-3.

According to ISO/IEC Guide 98-3, each significant source of uncertainty has to be identified. The following sources of uncertainty are identified and have to be processed according to the procedure described in ISO/IEC Guide 98-3:

— uncertainty due to operational variations,

— instrumentation uncertainty,

— uncertainty due to external disturbances.

Refer to Annex F for an example of a quantitative analysis.

The general expression for the calculation of the MPD value, d_{MPD}, is given by Formula (4):

$$d_{MPD} = d_{MPD,meas} + \delta_1 + \delta_2 + \delta_3 + \delta_4 + \delta_5 + \delta_6 + \delta_7 + \delta_8 \tag{4}$$

where

d_{MPD} is the quantity to be determined;

$d_{MPD,meas}$ is the MPD measured and calculated according to the procedure given in this document;

δ_1 is an input quantity to allow for any uncertainty due to lateral and longitudinal variations in the surface texture which is not picked up by the measurement;

δ_2 is an input quantity to allow for any uncertainty in texture measurement equipment;

δ_3 is an input quantity related to the tolerance allowed to the segment length;

δ_4 is an input quantity to allow for uncertainty due to secondary reflections of the laser light in the pavement;

δ_5 is an input quantity to allow for any uncertainty due to drop-out correction and spike removal;

δ_6 is an input quantity to allow for any uncertainty due to variations in the procedure for data processing;

δ_7 is an input quantity to allow for any uncertainty due to environmental influences on the instrument;

δ_8 is an input quantity to allow for any uncertainty due to environmental influences from the road surface moisture and other contamination.

The value of these input quantities shall be evaluated by the procedure given in ISO/IEC Guide 98-3. It can be based on existing statistical data, analysis of tolerances stated in this document and engineering judgment. The information needed from which to derive the overall uncertainty is given in Table 1. Table F.1 is a copy of Table 1 but includes also some typical values.

The combined standard uncertainty is calculated with Formula (5):

$$u(p)=\sqrt{\sum_{i=1}^{8}(c_i u_i)^2} \quad (5)$$

where p is the coverage probability and $c_i u_i$ is the uncertainty contribution.

Table 1 — Uncertainty budget for the determination of the MPD value

Quantity	Estimate	Probability distribution	Standard uncertainty u_i	Sensitivity coefficient c_i	Uncertainty contribution $c_i u_i$
δ_1	0	normal		1	
δ_2	0	normal		1	
δ_3	0	normal		1	
δ_4	0	normal		1	
δ_5	0	normal		1	
δ_6	0	normal		1	
δ_7	0	normal		1	
δ_8	0	normal		1	
Combined standard uncertainty [$u(p)$]					

The expanded uncertainty U is determined by multiplying the combined standard uncertainty $u(p)$ with the appropriate coverage factor for the chosen coverage probability as described in ISO/IEC Guide 98-3.

Annex F provides a detailed listing of the standard uncertainties and sensitivity coefficients of each source, as well as typical values for a surface giving an MPD value of around 1,0 mm and based on an average of 10 MSD values, resulting in an MPD over 1 m distance. Using these values, the uncertainty budget analysis results in a standard uncertainty in the MPD value of 0,05 mm.

Table 2 presents the expanded uncertainty and coverage probability in the case where the method is applied and individual source uncertainties are consistent with Table F.1.

Table 2 — Expanded uncertainty (*U*) and coverage probability (based on Table 1)

Coverage probability %	Expanded uncertainty, *U* mm
80	0,06
95	0,08

9 Safety considerations

WARNING — This document may involve hazardous operations when measurements are made on trafficked pavements. The personnel and the vehicles present on the measuring site shall be equipped with safety or warning devices as appropriate on that particular site at that particular time. Especially, one shall observe the need for protection of eyes against laser light (Reference [21]). Otherwise, this document does not purport to address the safety problems associated with its use. It is the responsibility of the user of this document to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

10 Test report

The test report for each pavement test surface shall contain data on the following items:

— identification of the measurement equipment, its operating organization and the operators;

— date of measurement;

— location and identification of the test section (starting point and length);

— track (transverse position) on the test site in which the measurement was made;

— description of the type of surface;

— description of surface contamination (if any); e.g. leaves, dirt, debris, sand, possible moisture;

— remarks about prominent surface conditions such as the existence of joints, excessive cracking, potholes;

— direction of the measured profile (longitudinal, transversal, circular, etc.);

— measurement speed, or range of speed;

— spatial resolution (0,5 mm or 1,0 mm);

— type of performance check, when it was made, and (if deviation exceeds 0,1 mm) its result;

— rate of invalid measurement/interpolated values (drop-outs);

— whether or not extreme MSD removal was applied;

— number of measurements (including number of runs over the tested surface and number of profile records in each run);

— MPD, for the pavement test surface as a whole, in millimetres;

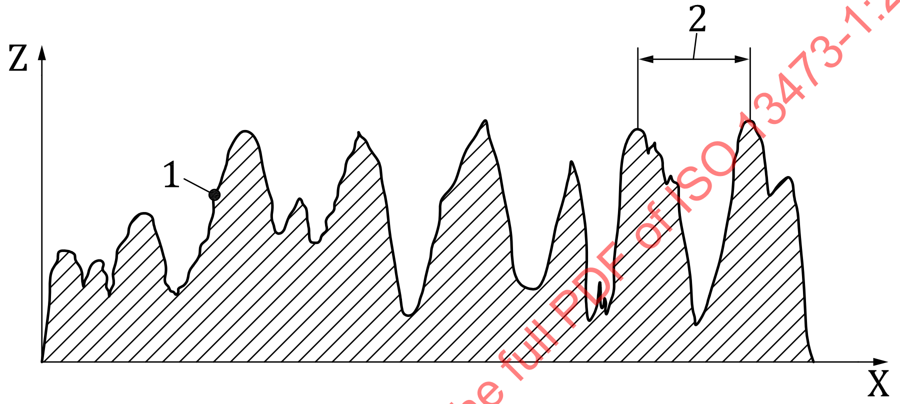
— standard deviation of the MSD values, in millimetres;

— estimated expanded uncertainty of the results, together with the associated coverage factor and coverage probability.

Annex A
(informative)

Texture ranges

A typical profile recording of a pavement surface is illustrated in Figure A.1 (vertical scale exaggerated), including the terms *profile, distance, vertical displacement* and *wavelength.* "Wavelength" in the figure is an illustration of a component of the profile related to the wavelength concept but it is not correct from a strictly mathematical point of view. Furthermore, the reference (bottom) line is arbitrary.



Key

1 profile

2 texture wavelength

X distance

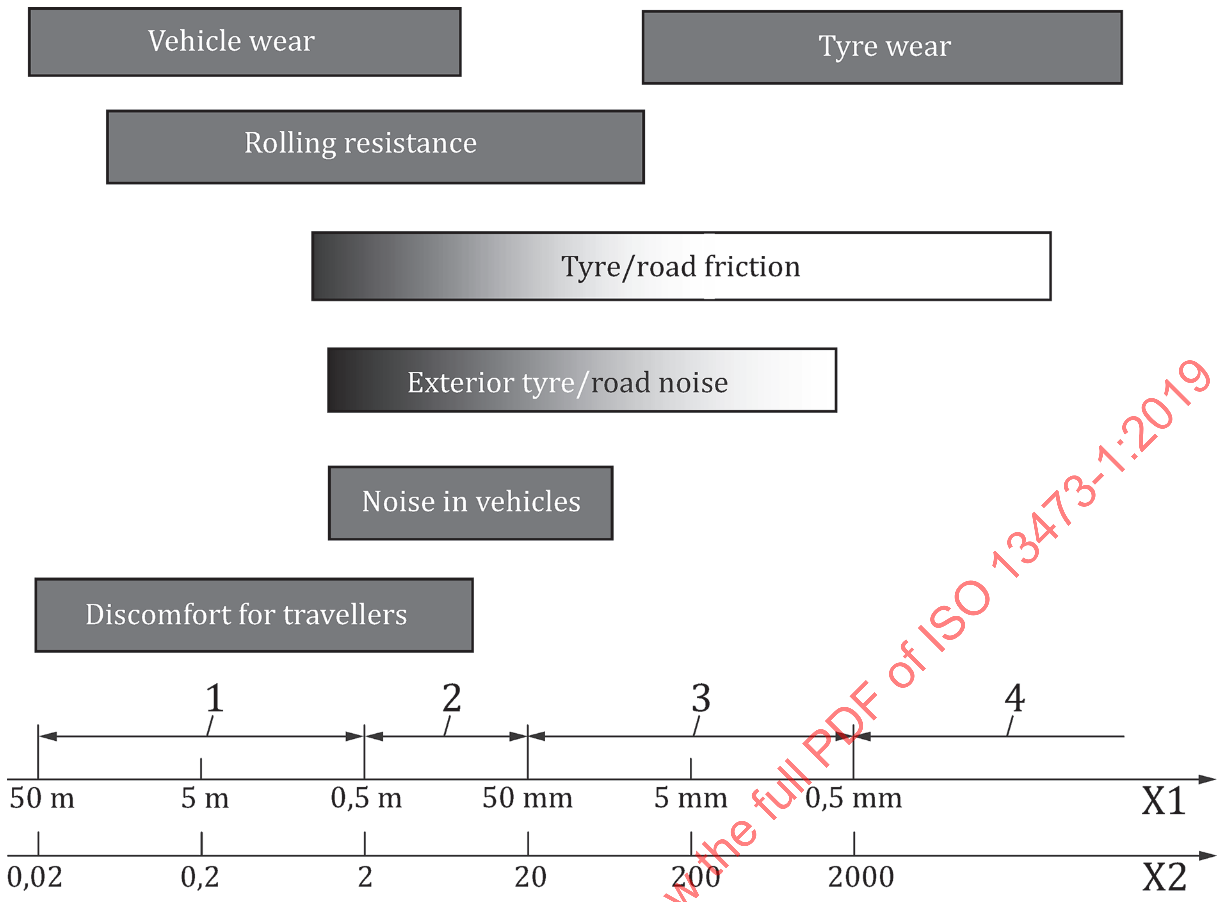
Z vertical displacement

Figure A.1 — Illustration of some basic terms describing pavement surface texture

Based on physical relations between texture and friction, noise, etc., the World Road Association (PIARC) has defined the ranges of micro-, macro- and megatexture earlier; see Reference [16]. Figure A.2 illustrates how these definitions cover certain ranges of surface texture wavelength and spatial frequency, and how various characteristics are influenced within these ranges.

Figure A.3 attempts to illustrate the texture of a pavement in the three-dimensional case, especially the term "texture depth", which is the distance between an arbitrary point on the plane down to the surface. The plane is supposed to go through the three highest peaks of the surface.

Figure A.4 illustrates the definitions of "segment" and "MSD". The reference (bottom) line is arbitrary and just for illustration purposes here. The average level is normally set at "zero" level as a result of the slope suppression procedure (see 7.6). The segment is 100 mm long.

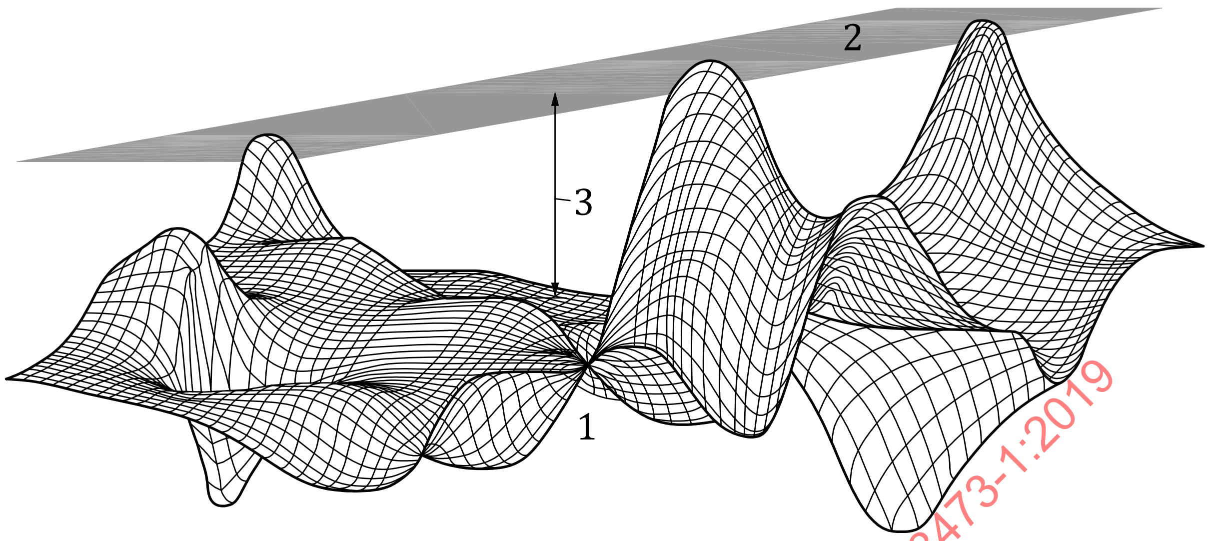


Key

1 unevenness
2 megatexture
3 macrotexture
4 microtexture
X1 wavelength
X2 spatial frequency [1/m]

NOTE A lighter shade indicates a favourable effect over this range and a darker shade indicates an unfavourable effect.

Figure A.2 — Ranges in terms of wavelength and spatial frequency of texture and unevenness and their most significant, anticipated effects



Key

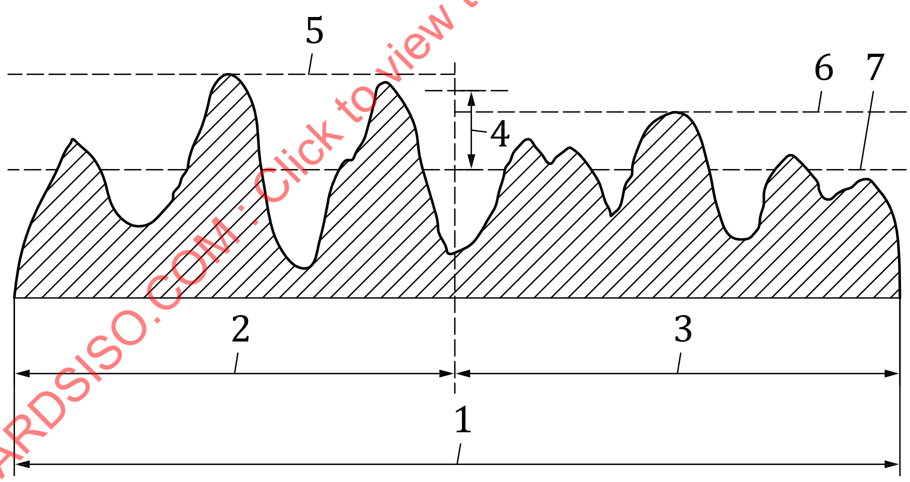
1 surface

2 plane through the three highest peaks of the surface

3 TD

NOTE The plane is watched from a position below the plane.

Figure A.3 — Illustration of the terms “surface” and “TD”



Key

1 segment (100 mm)

2 first half of segment

3 second half of segment

4 $\text{mean segment depth (MSD)} = \dfrac{\text{peak level}\left(1^{\text{st}}\right) + \text{peak level}\left(2^{\text{nd}}\right)}{2} - \text{average level}$

5 peak level (1^{st})

6 peak level (2^{nd})

7 average level

Figure A.4 — Illustration of the terms “segment” and “MSD”

Annex B
(informative)

Problems experienced on special surfaces

B.1 Porous surfaces

On porous surfaces, the most essential property is often the porosity (air voids) in the mixture. Friction and some noise characteristics rely on higher porosity, while rolling resistance, tyre wear and some noise characteristics are not significantly influenced by porosity. Porosity is a material property that is manifested within the material, and while evident at the surface, it cannot be measured with a profiling technique. In the volumetric patch method, some of the material used enter the pores, but due to particle friction, viscosity and particle size characteristics of the sand or glass beads, the "true" porosity can never be measured in this way.

Consequently, neither the volumetric patch nor the profiling method can measure the relevant characteristics covering all cases. Sometimes, the patch method gives a more relevant result on porous surfaces, while in other cases the profiling method is preferred.

Caution should therefore be exercised in interpreting measurements based on profiling techniques on surfaces with a high degree of porosity. This applies to calculations of both MPD and texture spectra. A profile-based measure such as the MPD can provide substantial over- and underestimations of the relevant effects.

If the intention is to characterize the drainage properties of such surfaces, for example to estimate its effect on wet skid resistance, hydroplaning or on noise emission and propagation, the profile gives an underestimation of the available drainage properties. The reason is that the profile curve does not appropriately show the effect of the pores in the structure since they are too deep to be possible to record by profiling techniques; the profile curve only represents the horizontal part of the drainage properties. In such cases, measurements of the vertical part of the drainage properties by means of a water outflow technique may be a suitable supplement[12][14].

On the other hand, if the intention is to characterize the potential vibration excitation in tyres, for example to estimate its effect on rolling resistance, on the hysteresis part of skid resistance or on noise emission, the profile gives an overestimation. The reason is that the tyre rubber is unable to envelop the deeper parts of the texture. To correct for the limited enveloping capability of typical tyres, the post-processing of profile curves by algorithms simulating the enveloping properties of tyres may be employed[19][20].

An additional source of error, at least when using a laser profiling technique, is the probable extra drop-out rate on porous surfaces, due to the likely shadowing of the laser spot as seen from the sensor position.

Even for non-porous surfaces with very deep textures (significant "negative" textures), the above mentioned effects can occur to some extent, depending on how well the profiling sensor is able to follow the true profile, and without drop-out, in the deeper parts of the texture.

Experience has shown that the profiling method generally "underestimates" the texture depth on porous surfaces when compared to corresponding texture depth values obtained with the volumetric patch method, or vice versa. This is true provided the profilometer works "correctly" on porous surfaces, i.e. without unacceptably high drop-out rates and without any erroneous transients, which is not the case for all devices. On porous surfaces which have become clogged, experience has indicated that the profiling method gives values which correlate well with the volumetric patch method.

B.2 Newly laid surfaces and humid/wet surfaces

Newly laid surfaces, mainly before exposed to traffic, in particular those of bituminous type, generally have a glossy and extremely dark appearance. Profilometers relying on optical beams might have problems with such surfaces because too little light is diffused in the direction towards the receiving element. Drop-out rates can become high and there can be transients at extreme transitions to/from dark/bright surfaces. The same applies to surfaces which are dark due to wetness or humidity. Therefore, drop-out rates should be monitored extra carefully when such conditions can occur.

B.3 Surfaces with directional finish (e.g. grooved, ground or tined concrete)

Texture measurement of longitudinally grooved pavements causes problems since, in most cases, mobile profilometers are unable to measure across such grooves unless the sensor is moved transversely during the measurement or operates in three dimensions. Stationary profilometers can be used effectively if they are oriented in the correct direction. It is also arguable as to what significance the texture profile or depth measured in a particular direction has to the tyre/road interaction, as illustrated by the following points:

— to characterise the effect on steering of a longitudinally grooved or tined pavement, a profile in the transverse direction is likely to be the best;

— to characterise the water drainage capability, a profile in the longitudinal direction is likely to be very unsuitable;

— to characterise the vibration excitation into a rolling tyre, a profile in the longitudinal direction is likely to be the best.

Regarding transversely grooved surfaces, in theory, the profiling method can somewhat underestimate the texture depth in relation to that measured with the volumetric patch method because most profilometers have problems in reproducing the very steep, almost vertical slopes in grooves. In practice, there are data which seem to support this but also other data which show no particular effect of the directional grooves. It is concluded that if there is an effect at all, it is an underestimation for grooved surfaces and it is just a minor effect which can be neglected in most cases.

For measurement on directional textures, the sensor, profiling along a longitudinal line, should be aligned such that the optical plane is transverse to the direction of the grooves. For a light sectioning device, this implies that the direction of the light section should be longitudinal for transverse grooving and transverse for longitudinal grooving.

A special (stationary) instrument designed to measure texture in various directions is the circular track meter, defined in ASTM E2157-15[11].

Annex C
(informative)

Procedure for sampling of mean segment depth values by spot measurements

C.1 Background

It might happen that one wants to monitor a road section of a certain length and only an instrument for spot measurements is available (e.g. a CTM, circular texture meter[11]). This annex outlines a procedure to select positions for spot measurements along a certain road lane under study. The procedure is suitable when the entire lane length cannot be measured and is intended to provide a smart way to pick out measuring points avoiding a selection which would otherwise be biased by some intentional or unintentional subjective judgements. It is an example and not a requirement.

By choosing appropriate numbers as described below, the results can be described in terms of statistics, e.g. the mean value (*mv*) and the standard deviation (*sd*) of the MSD:

— The mean value (*mv*): based on 18 measurements evenly distributed along one line segment of the pavement, the interval *mv* ±0,50 s includes the true mean value of the MSD in that line segment with a probability of 95 %. If there are five such line segments, then the interval *mv* ±0,21 s includes the true mean value of the MSD in the considered transversal position of the whole monitored road section, also with a probability of 95 %.

— The standard deviation (*sd*): based on 18 measurements evenly distributed along one line segment of the pavement, the interval 0,75 *sd* to 1,5 *sd* includes the true standard deviation of the MSD in that line segment with a probability of 95 %. If there are five such line segments, then the interval 0,87 *sd* to 1,17 *sd* includes the true standard deviation of the MSD in the considered transversal position of the whole monitored road section, again with a probability of 95 %.

C.2 Procedure

C.2.1 General

First, the transversal position(s) within the lane subject to testing is (are) determined; for example, the right wheel track, the middle of the lane or the left wheel track. The procedure in this annex then outlines how to select the longitudinal position(s) where mean segment depth (MSD) values shall be measured. For each selected longitudinal position, MSD will be measured in all a priori chosen transversal positions.

Two cases can be distinguished, Case 1 and Case 2 described below.

NOTE It is assumed that the entire lane length L is paved with the same type of surface of same age and condition.

C.2.2 Case 1: Lane length L is shorter than 1 000 m ($L \leq 1\,000$ m)

In this case, the whole lane length should be sampled at 18 points with spacing determined as follows.

Select the measuring points, at the chosen transversal position, at even intervals along the lane having a length of $L/18$. Select the first measuring point at random between 0 m and $L/18$ m. Select the second measuring point at a distance of $L/18$ from the first measuring point, and so on until the 18th measuring point is reached. See the upper part of Figure C.1.

C.2.3 Case 2: Lane length L is longer than 1 000 m (L > 1 000 m)

In this case, the total lane length L is divided into subsections, each with a fixed length of 100 m. Measurement of MPD is only done at spots within selected subsections. Essentially, a 100 m long subsection is selected for spot measurement, approximately one per 5 km (or, for lane lengths shorter than 15 km, at intervals at most 1/3 of the lane length). The procedure to achieve this in an unbiased way is as follows:

The selection of the subsections to be tested is a three-step procedure (see the lower part of Figure C.1):

1. Determination of the number of 100 m long subsections, N_{100m}, within the lane length L:

   $N_{100m} = L/100\ \text{m}$

   N_{100m} is then to be truncated to the nearest lower integer.

2. Determination of the number of subsections to be sampled (T). The number of subsections to be sampled, with a minimum of three, is calculated as follows:

   $T = L/5\ 000\ \text{m}$

   T is then rounded to the nearest integer.

3. Selection of the 100 m long subsections of the lane which shall be spot sampled:

   Calculate the quotient S:

   $S = N_{100m}/T$ (the final number to be truncated to an integer)

   Choose the first subsection of the lane to sample at random between the subsection 1 and the subsection S.

   The second subsection is then found by moving further away S subsections from the first subsection that was selected for spot sampling. The third one is found by moving along another S subsections, and so on until T subsections have been sampled.

4. Within the selected subsections, the MSD measurement positions should be chosen as explained for Case 1.

C.2.4 Example illustrating Case 2

In this example it is assumed that lane length L = 11 345 m.

Choose transversal position where to measure.

L > 1 000 m, hence Case 2 applies.

1. Number of subsections N_{100m}:

   $L/100\ \text{m} = 11\ 345\ \text{m}/100\ \text{m} = 113{,}45$

   Hence N_{100m} = 113 after truncation.

2. Number of subsections to be sampled:

   $T = L/5\ 000\ \text{m} = 2{,}269$

   As the minimum number of subsections to be sampled is 3, T will be 3.

3. Selections of the subsections to be sampled:

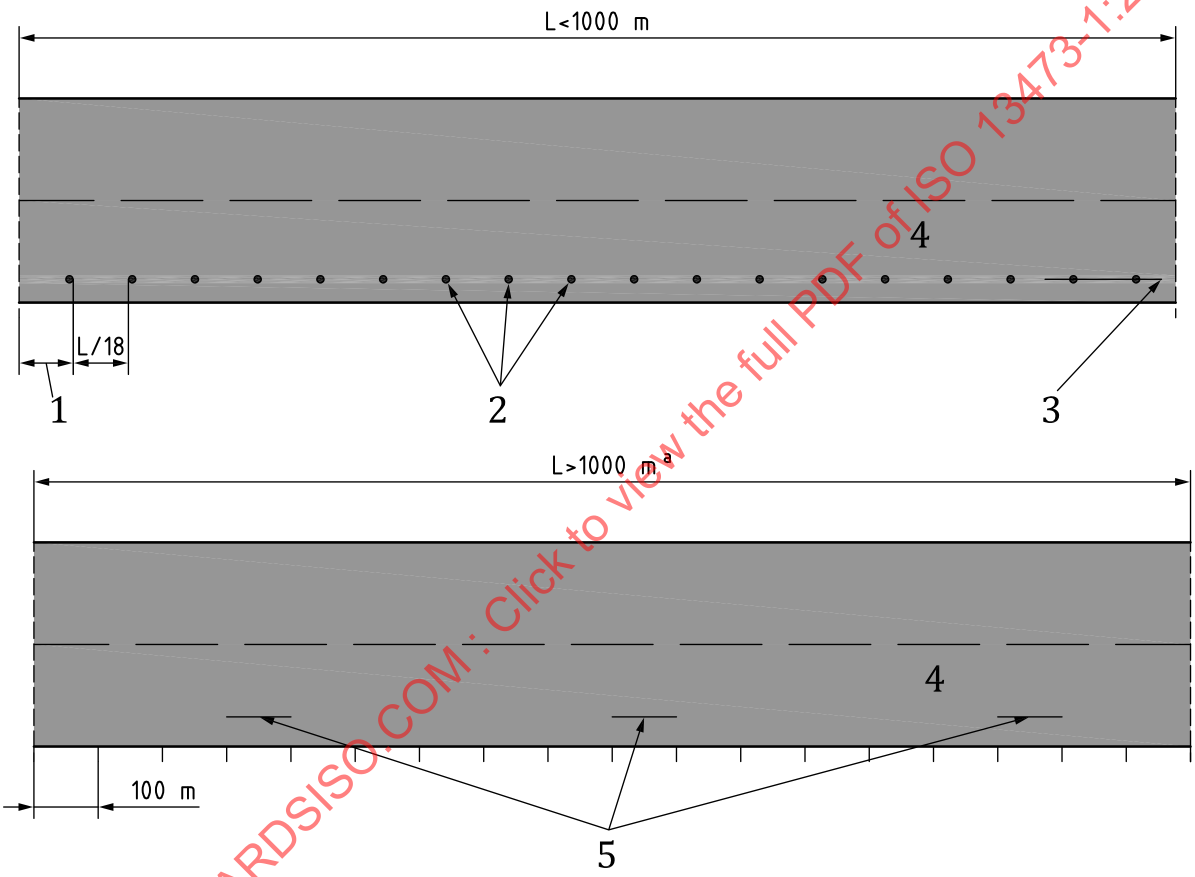
$S = N_{100m}/T = 113/3 = 37{,}67$

Hence the truncated number $S = 37$.

The $T = 3$ subsections of 100 m length to be sampled out of the 113 subsections available are then determined as follows:

The first subsection of the lane of 100 m to be spot sampled shall be chosen between the 1st and the 37th. Assume that one chooses e.g. the 22nd subsection to sample. The second subsection to be sampled is then 22 + 37 = 59th subsection, and the third subsection to be sampled is the 59 + 37 = 96th subsection of 100 m.

Within the subsections 22, 59 and 96, measure MSD values as outlined in Case 1.



Key

1 random offset (>0 and < L/18)

2 measurement points (18 in total)

3 selected transversal position (here right wheel track)

4 selected lane

5 three 100 m sections to be monitored like in Case 1; first section to be chosen at random between 1st and 6th (here 4th); second is 4th + 6 = 10th, and so on

a In this case, L = 1 800 m.

Figure C.1 — Selection of measurement points

Annex D
(normative)

Data quality-enhancing procedures

D.1 General

This procedure is designed with laser profilometers based on the triangulation procedure in mind, but it might at least in parts work well also for other types of profilometers.

Most contactless profilometers are based on lasers and sensors working according to the triangulation principle. When applied to a road surface, especially a newly laid asphalt surface (which is black and often glossy and contains some voids) or a porous asphalt surface (which contains deep voids), the reflected laser light is subject to several error mechanisms which can create serious errors in the measured profile curve.

For example, the reflection point on the surface can be hidden from being seen by the sensor by a higher part of the surface profile, or so much laser light is absorbed or diffused that the received light is below an acceptance threshold: one or more invalid point(s) is (are) obtained, mostly referred to as a “drop-out”. This may be compensated for by disregarding samples flagged as drop-outs and instead connecting the adjacent valid readings by a line; i.e. applying linear interpolation.

However, by far the most problematic error is short transients in the signal, which are generally called “spikes” as they look like such, whether directed upwards or downwards from the profile average line. The reason for these “spikes” is often that too weak laser light is reflected (and missed by the drop-out identification) or that so-called secondary reflections are created. The “spikes” create large errors in MSD and MPD calculations if they are not corrected for.

Despite all precautions against erroneous parts of the profile, the profilometer can record strange and unexpected features of the profile, which can create extreme MSD/MPD values. This can be caused by insects, dirt and other loose material on the surface, insects, leaves, sand or other lightweight objects crossing the laser path or the signal can simply go out-of-range. The optional solution to this is to remove all outliers of the MSD values.

Other problems that can occur and jeopardize reproducibility include background noise in the signal at the higher frequencies and varying laser spot size. A relatively large laser spot tends to smoothen the profile curve, while a relatively small spot reproduces fine details of the texture, but can, at the same time, create many more “spikes”. In order to enhance reproducibility, it is then necessary to standardize filters that reduce these problems while not affecting the true profile more than what is acceptable.

The data quality-enhancing procedures in this document aim to reduce the effects of imperfect measurement of the profile curve and to provide a data processing procedure which gives all devices that conform to the document equal and consistent performance, within reasonable tolerances.

After the procedure is applied, the MSD/MPD values shall be reasonably free of distorted parts of the profile curve in order that the measured profile is as similar as practical to the true profile and that the texture wavelength spectra shall be reasonably accurate (flat response) over the texture wavelength range from 1 mm to 500 mm.

Although this annex is normative and contains requirements, for example in terms of the high-pass and low-pass filter performance, there are parts of it that are only informative.

D.2 Summary of the specified data processing procedures

The procedures are summarized in Table D.1.

Table D.1 — Overview of the data quality-enhancing procedures

Number	Purpose	Method	Mandatory or optional	Domain	Notes
1a	Drop-out detection	Detection of drop-outs, due to low received laser light	Mandatory	Temporal or space (made in hardware)	
1b	Drop-out correction	Linear interpolation between the adjacent valid samples		Temporal or space (software)	
2	Maximum use of measured data	Re-sampling (to 0,5 mm or 1,0 mm spacing; prefer 0,5 mm if the system allows it[a,b])	Mandatory where applicable	Temporal and/or space (software)	Calculate arithmetic average of all samples that fall within the required spacing
3a	Spike identification and reshape profile	Identify spikes, according to Annex E	Mandatory	Space (software)	Effect quite small (compared to number 5 below)
3b	Spike identification and reshape profile	Interpolation according to 7.3 and Annex E. See also 1b above.			Can be needed only on critical surfaces, but as it is an “easy” procedure it can well be mandatory
5	Removal of long-wavelength components	High-pass filtering: 2nd order Butterworth, cut-off at 140 mm (for continuous data) or slope suppression (for discrete data)	Mandatory	Space (software)	Removes effect of vehicle bounce and uneven roads
6	Normalization of profile sharpness	Low-pass filtering: 2nd order Butterworth, cut-off at 3 mm	Mandatory[c]	Space (software)	Reduces effect of noise, and laser spot size
7	Extreme MSD value removal	Identification of MSD outliers and removal by 3-points median filter	Optional	Post-processing	Only for MSD values, not used when extreme features are of interest

[a] This requirement is aimed at the vast majority of present in-use profilometer systems, using the single-sensor triangulation principle. More advanced systems in the future are likely to provide better performance.

[b] In case the profile is extracted from a number of parallel profiles, such as when measuring a three-dimensional surface representation, the total width of the selected profile lines shall be at least 0,5 mm and at most 1 mm.

[c] D.4 provides informative hints regarding the design of this filter.

D.3 Brief description of the procedures

D.3.1 Drop-out identification (mandatory)

Drop-out identification shall be made in the laser sensor system. This system shall flag all samples that are measured to have a received laser light intensity below a certain limit, determined by the sensor producer. Data processing shall then be made as follows:

— Make linear interpolation between the previous and the next valid samples, surrounding the invalid sequence. In cases where the first or last samples of a segment are invalid, just set the value(s) equal to the nearest valid value.

D.3.2 Maximum use of data (mandatory where applicable)

In case sampling in the temporal domain is made with higher density than corresponding to 0,5 mm in the space domain, re-sample the signal to obtain a sampling density of 0,5 mm (two samples per mm).

This re-sampling shall be made by averaging all samples within each 0,5 mm interval into one average representing that interval. Disregard invalid samples. This is made in order not to lose valuable data and to reduce noise and errors.

D.3.3 Spike identification (mandatory)

The drop-out identification and interpolation removes most “spikes”. However, there will be spikes remaining in the signal, more or less depending on the kind of surface measured. The spike identification procedure has the purpose to determine whether these spikes are too sharp or not to be realistic and thus be “true” or “false”.

The low-pass filter takes care of most of the distorting effects of the spikes. Thus, if the spikes are few, the spike identification and removal have little extra effect. But there might be critical surfaces, such as glossy and black surfaces (such as newly laid asphalt), where the procedure can give significant improvements.

The procedure to be used is described in Annex E.

D.3.4 Reshape profile (space domain, mandatory)

Make interpolation between the previous and the next valid samples that are surrounding the spike.

Within a segment, the number of interpolated points due to spike removal shall not exceed 5 %.

The resulting profile is useful for spectral analysis and other types of analyses, if desired.

D.3.5 Removal of slope and long-wavelength components (mandatory)

If the profile has been recorded continuously (4.2.1), high-pass filtering shall be made to reduce the effect of slopes or gradients in the profile curve (long-wavelength components) which are irrelevant to the determination of MSD and MPD. The filter shall be of the Butterworth type, 2nd order, and the filtering shall be made in a forward-reverse filter in order to reduce phase distortion of the profile signal[18]. See D.4 for further details.

D.3.6 Normalization of sharpness by low-pass filtering (space domain, mandatory)

Despite the procedures above, the signal can contain more or less short-wavelength amplitudes (5 mm and less), depending on, for example, laser spot size, electronic noise and sampling rate, which can affect the MSD calculations. The efficiency of the spike removal can also have an influence here.

Therefore, in order to normalize the signal, a low-pass filter is applied. It should be Butterworth of 2nd order and the filtering shall be made in a forward-reverse filter in order to reduce phase distortion of the profile signal[18]. See D.4 for further details.

At this point in the processing, the total invalid readings of the profile (drop-out plus spike removal) should be counted (as a percentage of the total profile).

D.3.7 Extreme MSD value removal (space domain, optional, only for MSD determination)

Even if all procedures above are applied, when calculating MSD, there will be some extreme MSD values, some of which can be “true” or “interesting”. Examples of values not being “true”, include if some loose object or dirt flies between the surface and the laser sensor, or if there are loose stones or debris temporarily lying on the surface. Another reason can be that the signal hits a crack or joint between concrete slabs which is wide enough to be missed by the drop-out and spike detection. Finally, in some systems, the profile is sometimes so rough that the laser signal hits the surface at a point outside the valid measuring range.

For this reason, there is an option to disregard extreme MSD values. This procedure is a 3-point median filter; see 7.9.

D.4 Aid in designing the filters

This clause gives more informative hints regarding the design of the filters which are required for normalization of profile sharpness and for removal of slope and long-wavelength components. The filters shall be 2^{nd} order Butterworth filters, with a low-pass filter with cut-off at 3 mm, and a high-pass filter with a cut-off at 140 mm wavelength. The filtering shall be made in a forward-reverse filter in order to reduce phase distortion of the profile signal[18]. To achieve this, a second-order Butterworth filter with an (-3 dB) adjusted cutoff wavelength at 2,40 mm shall be designed and then applied in both forward and reverse directions. This will give the desired features. For the high-pass filter, the adjusted (- 3 dB) cutoff wavelength is 174,2 mm.

A digital filter can easily be implemented by a recursive relationship. For a 2^{nd} order Butterworth low-pass filter, by applying a first-order filter in the forward-reverse directions to a discrete sequence, *x* (i.e. data), this can be written as

$$y_i = \left(x_{i-2} + 2x_{i-1} + x_i\right) / A_0 + A_1 y_{i-2} + A_2 y_{i-1} \tag{D.1}$$

where A_0, A_1 and A_2 are coefficients that are determined by the cut-off frequency and the resolution using the bilinear transform method. The filtered data is then given in *y*. However, the first two data values are unchanged. Formula (D.1) shall then be applied twice, the second time being for data in the reverse order.

For a 2^{nd} order Butterworth high-pass filter applied in the forward-reverse directions to a discrete sequence, *x* (i.e. data), this can be written as

$$y_i = \left(x_{i-2} - 2x_{i-1} + x_i\right) / A_0 + A_1 y_{i-2} + A_2 y_{i-1} \tag{D.2}$$

Also Formula (D.2) shall then be applied twice, the second time being for data in the reverse order.

The formulae can be implemented easily in a spreadsheet or any programming language. The coefficients and necessary filter parameters are presented in Table D.2. They were calculated using MATLAB®2). All decimals should be used to avoid poor filter performance.

After applying the 2^{nd} order filters in both directions, the cut-off slope will resemble that of a 4^{th} order filter, i.e. it will have cut-off slopes around 24 dB/octave.

Due to the unavoidable instability of the signal at the start and end of each filtering process, one shall consider the first and the last MSD segments as invalid. This requires that the filtered signal contains segments both before and after the valid section of the profile. These end segments are not used for calculation of MPD.

Table D.2 — Filter parameters for 2^{nd} order Butterworth low-pass and high-pass filters in forward-reverse application, resulting in a cut-off wavelength of 3 mm and 140 mm, respectively, when applied in both directions

Resampling interval mm	Cut-off wavelength mm	A_0	A_1	A_2
Low-pass				
0,5	3 (2,40)	4,541 435 369 517 87	-0,188 345 160 884 045	0,307 566 359 792 21
1,0	3 (2,40)	1,450 734 151 687 5	-0,477 592 250 072 517	-1,279 632 424 997 81
High-pass				
0,5	140 (174,2)	1,012 833 907 191 07	-0,974 817 997 723 097	1,974 496 861 900 19
1,0	140 (174,2)	1,025 832 570 015 15	-0,950 270 130 608 283	1,949 001 657 906 79

2) MATLAB® is the trademark of a product supplied by MathWorks. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of this product.

Annex E
(normative)

Spike removal procedure

E.1 General

As stated in 5.8 and in Annex D, it is recommended that laser profilometers be equipped with a system to detect invalid readings. For every data point, the observed light intensity of the laser spot should be measured and, if the light intensity is below a given threshold, the corresponding data point should be labelled as invalid or “drop-out”. Nevertheless, this system can make mistakes and sometimes drop-outs are not recognized as such. This can lead to “phantom” peaks (spikes) in the profile, which can seriously bias the results (e.g. the MPD calculated with the profile).

Therefore, it is wise to apply an a posteriori procedure to a measured texture profile to remove “suspect” high and sharp peaks from the profile. The procedure outlined in this annex is intended to be inserted in the data processing chain *after* the handling of the invalid readings as described in 7.3; i.e. the drop-out readings are replaced by values which are interpolated between the closest valid readings before spike removal takes place. Spike removal, thus, intends to remove spikes which “slip through” the drop-out procedure.

The procedure basically consists of assigning the status of “invalid” reading to data points which meet certain criteria, even if they were not recognized as a drop-out during the measurement. The procedure, called the “excessive slope” procedure, is very simple:

Consider a profile with amplitude z_i, belonging to horizontal position index i and step size Δx. The criterion for assigning a posteriori the status of invalid reading to the i^{th} data point is:

$$\left| z_i - z_{i-1} \right| \geq \alpha \cdot \Delta x \tag{E.1}$$

where α is a constant factor ($\alpha = 3$).

NOTE It has been found that $\alpha = 3$ is a good choice[21].

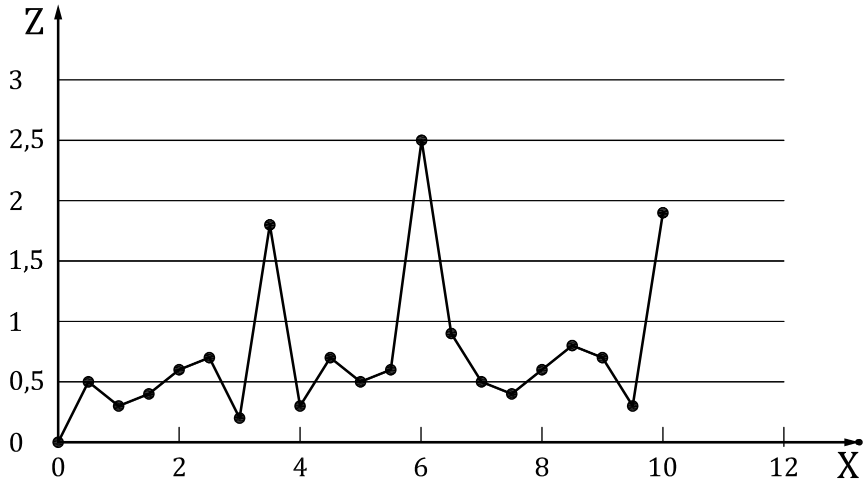
The criterion (E.1) is checked for all the data points i of the profiles. After this, the procedure shall be repeated but done in the reverse direction. The spikes are first identified in forward and reverse direction before replacing them with the interpolated value.

It has been found that the much more complicated spike removal procedure by VTTI, presented in Reference [22], gives results almost equal to the procedure described above. Nevertheless, the VTTI procedure should not be used in this application since there is a risk that results on some surfaces differ a little between the procedures.

Subsequently, an interpolation procedure for the drop-out treatment, as described in 7.3, is applied.

E.2 Example

The procedure is illustrated with an example; see Figures E.1, E.2 and E.3.

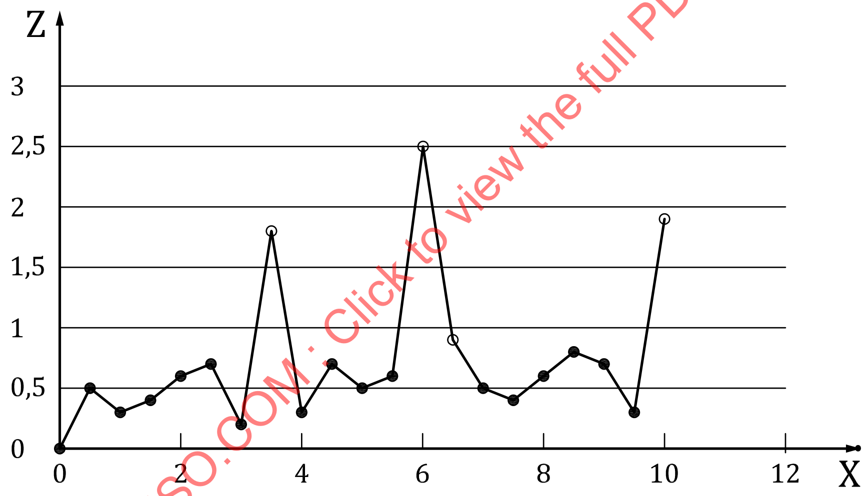


Key

X distance, mm

Z amplitude, mm

Figure E.1 — A measured profile (as illustrated above) is subject to analysis

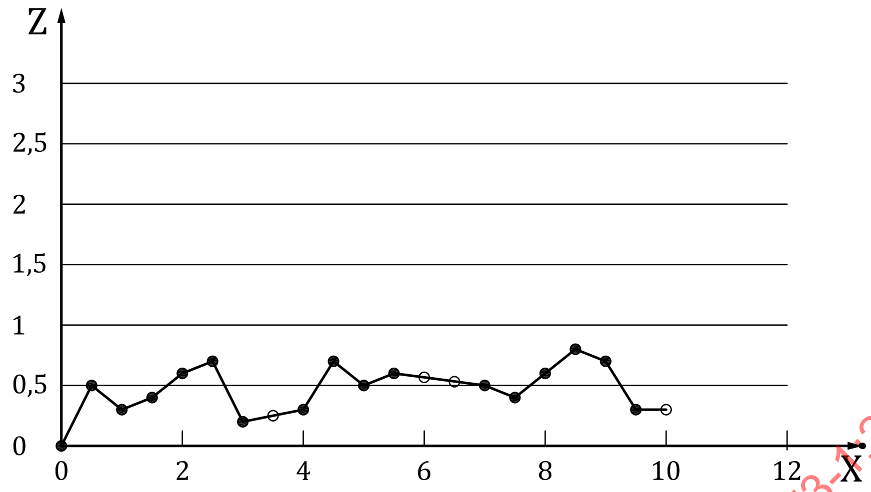


Key

X distance, mm

Z amplitude, mm

Figure E.2 — Step 1: As a result of the spike removal identification procedure, four points are detected as suspect readings (indicated as unfilled circles)



Key

X distance, mm

Z amplitude, mm

Figure E.3 — Step 2: The invalid readings are replaced by interpolated values between the nearest valid readings (indicated as unfilled circles)

Annex F
(informative)

Measurement uncertainty

F.1 General

The result of the application of the procedure described in this document is subject to disturbance by several factors and processes. The cause and nature of these disturbances are either known but randomly distributed in an uncontrollable way, or are of a systematic nature, but affect the result in an unpredictable way.

The uncertainty of results obtained from measurements according to this document can be evaluated by the procedure given in ISO/IEC Guide 98-3, or by interlaboratory comparisons in accordance with Reference [4]. Since extensive inter- and intra-laboratory data were not available, the procedure given in ISO/IEC Guide 98-3 was followed to estimate the uncertainty associated with this document.

In accordance with ISO/IEC Guide 98-3, the effects are evaluated on the basis of their contribution to the combined standard uncertainty and then a coverage probability is defined, resulting in a coverage factor k by which the combined standard uncertainty is multiplied, yielding the expanded uncertainty.

Regarding validity of the method, limitations are discussed in Annex B.

F.2 Expression for the calculation of the MPD value

The general expression for the determination of the MPD is given by the following formula.

$$d_{\text{MPD}} = d_{\text{MPD,meas}} + \delta_1 + \delta_2 + \delta_3 + \delta_4 + \delta_5 + \delta_6 + \delta_7 + \delta_8 \quad \text{(F.1)}$$

where

d_{MPD} is the quantity to be determined;

$d_{\text{MPD, meas}}$ is the MPD measured and calculated according to the procedure given in this document;

δ_1 is an input quantity to allow for any uncertainty due to lateral and longitudinal variations in the surface texture which is not picked up by the measurement;

δ_2 is an input quantity to allow for any uncertainty in texture measurement equipment;

δ_3 is an input quantity related to the tolerance allowed to the segment length;

δ_4 is an input quantity to allow for uncertainty due to secondary reflections of the laser light in the pavement;

δ_5 is an input quantity to allow for any uncertainty due to drop-out correction and spike removal;

δ_6 is an input quantity to allow for any uncertainty due to variations in the procedure for other data processing;

δ_7 is an input quantity to allow for any uncertainty due to environmental influences on the instrument;

δ_8 is an input quantity to allow for any uncertainty due to environmental influences from the road surface moisture and other contamination.

F.3 Sources of uncertainty

The sources of uncertainty are explained below:

δ_1 The MPD is considered to be representative of a certain test section. However, due to longitudinal and lateral variation in the surface texture, the actual measurement path and the choice of segment locations cause a stochastic uncertainty in the MPD result.

δ_2 The equipment used for measuring the texture of the surface (or better the distance between the sensor and the road surface) exhibit limited accuracy due to calibration, noise in the sensor, non-linearity and resolution uncertainty in the sensor. Contaminated lenses might be another source.

δ_3 The tolerance allowed to the segment length can lead to some uncertainty.

δ_4 Secondary reflections of the laser light (where applicable) in the pavement, as well as other optical influences of the surface material or of dust in the air, might unintentionally influence the reading of the sensor signal, especially for surfaces which are to a certain extent glossy and where reflectivity can vary substantially. Secondary reflections tend to be of importance only when the laser illumination hits deep down on slopes of valleys in the profile. Other optical influences might be light spreading properties of stones in the texture; in particular due to crystalline structure.

δ_5 The application of drop-out interpolation and spike removal involve sources of unwanted deviations from the true profile. Especially spike removal is sensitive, since the method relies on proper peak detection. An only partly removed spike might have an asymmetric effect: the peak value is always higher and not lower. Also, the method of interpolation can have a (marginal) influence.

δ_6 In a next step, slope correction (for discontinuous measurements), high-pass filtering (for continuous measurements) and low pass filtering are applied in order to obtain true segment profiles from which finally the MSD's are calculated. Depending on how these procedures are applied, bounces of the carrying vehicle and the unevenness profile, uncertainties can occur.

δ_7 The environment can influence the measurements; for example if the sensor is disturbed by sunshine or other external light, some sensors can be sensitive to temperature.

δ_8 The environment can influence the measurements; for example, moisture on the surface can have an effect in some cases.

In Clause F.4, an example is given for a typical measurement of a road section and with a system meeting the requirements stated in the main body of this document.

NOTE 1 It has been noticed that the effect of electronic background noise in the sensor system has a small effect on the MPD value. It is not possible at the time of publication to present a correction procedure for this, but indications suggest that modern sensor systems can increase (or, in some cases, decrease) the measured MPD values by maximum 0,04 mm. This can thus have a significant effect, primarily when measuring very smooth surfaces.

NOTE 2 The input quantities in Formula (F.1) to allow for uncertainties are those thought to be applicable according to the state of knowledge at the time when this document was being prepared, but further research could reveal that there are others.