REVIEW OF INSTRUMENTS FOR MEASURING THE TEXTURE PROFILE OF ROAD SURFACES

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Transit New Zealand Research Report No. 63

ISBN 0-478-10521-5
ISSN 1170-9405

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Cenek, P.D. 1996. Review of instruments for measuring the texture profile of road surfaces. *Transit New Zealand Research Report No.63*. 88 pp.

Keywords: macrotexture, measurement, megatexture, microtexture, New Zealand, profilometers, road, road surface, roughness, texture spectrum

AN IMPORTANT NOTE FOR THE READER

The material contained in this report is the output of research and should not be construed in any way as policy adopted by Transit New Zealand but may form the basis of future policy.

ACKNOWLEDGMENTS

The assistance of Drs Michel Boulet and Yves Delanne (Section des Caractéristiques de Surface, Laboratoire Central des Ponts et Chaussées, LCPC, Nantes) is acknowledged for supplying LCPC and PIARC publications for review and their many helpful comments.

LIST OF ABBREVIATIONS

AASHO	American Association of State Highway Officials (before 1973)
AASHTO	American Association of State Highway & Transportation Officials
AEIPR	Accelerometer-based Inertial Profiling Reference system
APL	Longitudinal Profile Analyser (Analyseur du Profile en Long bitrace)
ARAN	Automatic Road ANalyser
ARRB	Australian Road Research Board
ASTM	American Society for Testing & Materials
BI	Bump Integrator
BPN	British Pendulum Number
BPR	Bureau of Public Roads
BPT	British Pendulum Tester
BSN	Brake Slip Number
CT1	Technical Committee of Surface Characteristics
FF	French francs
FHWA	Federal Highways Administration
GMR	General Motors Research
HRM	High speed Road Monitor
HSV	High speed Survey Vehicle
Hz,kHz,MHz	Hertz, kilohertz, megahertz
IFI	International Friction Index
IRI	International Roughness Index
IRRE	International Road Roughness Experiment
ISO	International Organisation for Standardisation
LCPC	Laboratoire Central des Ponts et Chaussées
m	metres
MERLIN	Machine for Evaluating Roughness using Low-cost INstrumentation
MPD	Mean Profile Depth
MRM	Multi-function Road Monitor
MTM	Mini-Texture Meter
NAASRA	National Association of Australian State Road Authorities
NCHRP	National Cooperative Highway Research Program
OECD	Organisation for Economic Co-operation & Development
PCA	Portland Cement Association
PD	Profile Depth
PIARC	Permanent International Association of Road Congresses
PSD	Power Spectral Density
PSV	Polished Stone Value
rad	radians
RMS	Root Mean Square
RST	Road Surface Tester
RTM	Response-Type Meter
s	seconds
SAAB	Swedish Road Administration
SCRIM	Sideways-Force Coefficient Routine Investigation Machine
SFC	Side Force Coefficient
SN, SN_B, SN_R	Skid Number: for blank tyre; for ribbed tyre
TDsc	Texture Depth, sand circle method
TNZ	Transit New Zealand
TRB	Transportation Research Board, Washington DC
TRL	Transport Research Laboratory, Crowthorne, UK (after 1991)
TRRL	Transport & Road Research Laboratory, Crowthorne, UK (until 1991)
UK	United Kingdom
UMTRI	University of Michigan Transportation Research Centre
USA	United States of America
VTI	Swedish Road & Traffic Research Institute

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EXECUTIVE SUMMARY

1. Introduction

The interactions that occur between a road surface and a vehicle traversing it are important to engineers, planners and managers. The need to accurately quantify the texture profile of road surfaces has therefore brought many instruments onto the market, ranging from rather simple devices to quite complicated systems. These instruments fall into two distinct classes:

1. those which allow the road surface profile to be described as a continuous function of spatial frequency; and

2. those which attempt to describe the road surface profile within a specific wave band of interest by a single numeric.

The first class of instrument is desirable from a research and diagnostic perspective, whereas the second class of instrument finds application in acceptance controls for road construction and inventory surveys of the condition of a roading network.

2. Scope of Review

This report briefly describes the main measurement principles employed by instruments in use throughout the world for quantifying road surface characteristics. It also catalogues profilometric instruments available as at 1995 so that researchers, roading authorities and the road construction industry can select the most appropriate measurement systems for their particular application.

A comparative assessment of instrument performance in field situations is not included as the results from the Permanent International Association of Road Congresses (PIARC) international experiment to compare and harmonise texture and skid resistance measurements were not published until late 1995. These results will be used to guide current and future Transit New Zealand research on road surface texture and skid resistance.

3. Conclusions and Recommendations

1. Valid methods for measuring surface irregularities are highly desirable so that the relationships between characteristics of common New Zealand pavement surfaces and their performance with regard to safety, environmental impact, comfort and user cost can be better understood, leading to improved surfacing design and construction.

2. No instrument in present use is capable of measuring the complete texture profile of a pavement surface. A continuous spectrum over the entire range of road surface texture wavelengths of interest (from

microns to tens of metres) can only be generated by combining several spectra pertaining to specific wavelengths, given current technology.

Profilometric instruments used for research purposes should therefore be selected which allow some degree of overlap in measured wavelengths, to enable precise matching of spectra over the duplicated wavelengths.

3. Profilometers must be validated at some time to prove their accuracy. A "calibration by correlation" approach is advocated, that needs reference instruments with which to compare the measurements. These reference instruments ideally should not change over time. The reference instruments recommended are for:

• Microtexture:	mechanical needle profilometer;
• Macro/Megatexture:	Swedish Road and Traffic Research Institute (VTI) stationary laser profilometer;
• Roughness:	Rod and Level, or "Dipstick".

4. Roughness wavelengths which approach the footprint length of a tyre have a detrimental effect on road holding, noise and vibration, and extra fuel consumption from increased rolling resistance.

   The introduction of megatexture and short wavelength roughness specifications for road construction should be considered to complement existing Transit New Zealand skid resistance and water drainage-related texture specifications.

5. For network monitoring of skid resistance, the following two parameters need to be simultaneously measured:
   - Friction of the wet pavement (at a fixed standard measuring speed); and
   - Mean macrotexture depth.

   These parameters can be used to estimate the friction–speed gradient which is closely related to the drainage capacity of the pavement.

   The suitability of two wheel skid trailers and/or variable slip skid testers for measuring, at a network survey level, the friction–speed gradient of porous surfaces, as well as the more prevalent surface types found on state highways, should be investigated.

6. Efficient and rational control and monitoring of roughness can be best effected by classifying roughness by wavelength. This allows a systematic approach to assessing, classifying and locating surface defects both at the construction stage and when monitoring the serviceability of the network under traffic.

Transit New Zealand should require analyses of road roughness measurements in terms of different discrete wave bands, in addition to generating IRI or NAASRA roughness numerics. This will enable the type and cause of the pavement roughness condition to be identified, leading to more effective utilisation of maintenance budgets.

7. It is essential that the same range of wavelengths are covered when comparing road profiles and the associated roughness numerics obtained by different profilometers or the same profilometer for different measuring speeds. For most uses, a wavelength range between 0.15 m and 60 m has proven adequate.

   Transit New Zealand should insist that whenever dynamic profilometry is being used to measure longitudinal roughness, the shortest as well as the longest wavelength included in the filtered road profile should be specified. The extreme wavelengths should remain invariant with speed over the profilometer's normal operating speed range.

8. For control of pavement construction, the following measuring methods are recommended on the basis of being able to make fairly rapid measurements of reasonable accuracy:

   - British Pendulum Tester (for microtexture);
   - Outflow Meter, and Volumetric Patch Method (ASTM Test Designation E965-87) (for surface drainage, macrotexture);
   - MERLIN, and ARRB Walking Profilometer (for roughness).

9. A promising stationary device suitable from both construction and research perspectives for measuring texture over 0.05 mm to 600 mm wavelengths (spanning microtexture to megatexture) is the Yandell-Mee texture meter.

   A series of evaluation trials have been conducted as part of Transit New Zealand Research Project PR3-0134, *Frictional interaction between tyre and pavement*, to assess its comparative performance under typical New Zealand conditions and to establish correlations with the more accepted means of pavement friction and macrotexture measurement. Preliminary results were included in a technical paper presented at a PIARC symposium in 1996*.

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* In *Proceedings of Third International Symposium on Pavement Surface Characteristics* (B.Heaton Ed.), Christchurch, New Zealand, 3-4 September 1996.

ABSTRACT

A complete road profile ranges from large scale topographic features to microscopic asperities on the surface of aggregates. No instrument in present use is capable of measuring the complete road profile. For technical reasons, the profilometric instruments that were available in 1995 can cover only a limited range of wavelengths associated with microtexture (<0.5 mm), macrotexture (0.5 mm to 50 mm), and structure texture (>50 mm).

This report catalogues commercially available profilometric instruments, as at 1995, under each of these wavelength ranges and describes their general mode of operation. Where possible, recommendations are provided as to the most appropriate measurement methods for construction control, network survey, and research applications.

1. INTRODUCTION

Increasing consideration is being given by roading authorities worldwide to characteristics of pavements that bear on user comfort, vehicle operating cost, the environment, and safety requirements. Three orders of pavement surface irregularity have been identified as influencing pavement performance (Lees 1983).

First Order of Surface Irregularity : Microtexture (profile wavelengths less than 0.5 mm). This surface texture, measured at the micron scale of harshness, is known to be a function of aggregate particle mineralogy and petrology for given conditions of climate, weather and traffic action. For asphaltic and concrete pavements, it includes the texture of the bituminous and cement mortars between the exposed coarse aggregate particles. The main economic and environmental factors over which microtexture exerts an influence are tyre wear, accident risk (for all traffic speeds), and high frequency noise generation.

Second Order of Surface Irregularity : Macrotexture (profile wavelengths between 0.5 mm and 50 mm). Macrotexture is a measure of the surface relief of a pavement. It is related to the drainage capacity between a tyre and the pavement surface. Included are size, shape, spacing and arrangement or distribution of aggregate particles, grooves, and surface to internal pore connections as present in pervious surfacings. Rolling resistance (affecting fuel and oil costs), accidents (those in the medium to high traffic speed range and those affected by spray-impaired visibility), and low frequency noise generation are influenced by this order of texture.

Third Order of Surface Irregularity : Structure Texture (profile wavelengths between 0.05 m and 50 m). Included under this order of irregularity are roughness (varying in frequency and amplitude), ruts, potholes, and major joints and cracks ranging in width, level and complexity. Such major structural defects affect riding comfort, road holding, dynamic wheel loads and vehicle wear.

Surface texture is sometimes subdivided into the following two wavelength ranges:

1. *Megatexture* (profile wavelengths between 50 mm and 500 mm). This texture has wavelengths in the same order of size as the tyre–road interface and is often created by potholes or "waviness". It is an unwanted characteristic and results from defects in the surface.

2. *Unevenness* (profile wavelengths between 0.5 m and 50 m). This type of surface roughness causes vibrations that affect ride comfort, road holding and wear of vehicles.

The above orders of wavelength apply for measurements along a longitudinal profile of a highway lane.

The temporal frequency of vibrations experienced by a tyre traversing a pavement is related to the wavelength by the relationship:

$$\text{temporal frequency (Hz)} = \frac{\text{axle speed (m/s)}}{\text{profile wavelength (m)}}$$

Therefore a tyre moving at an axle speed of 100 km/h (27.8 m/s), traversing a sinusoidal undulation with a wavelength of 27.8 m, would experience vertical displacement excitations at a frequency of 1 Hz. Since human body sensitivity to vibrations extends to frequencies at least as low as 0.5 Hz and since the ear's sensitivity to noise extends upwards of 10 kHz, the undulations in the second and third orders of surface irregularity are those that significantly affect driving comfort.

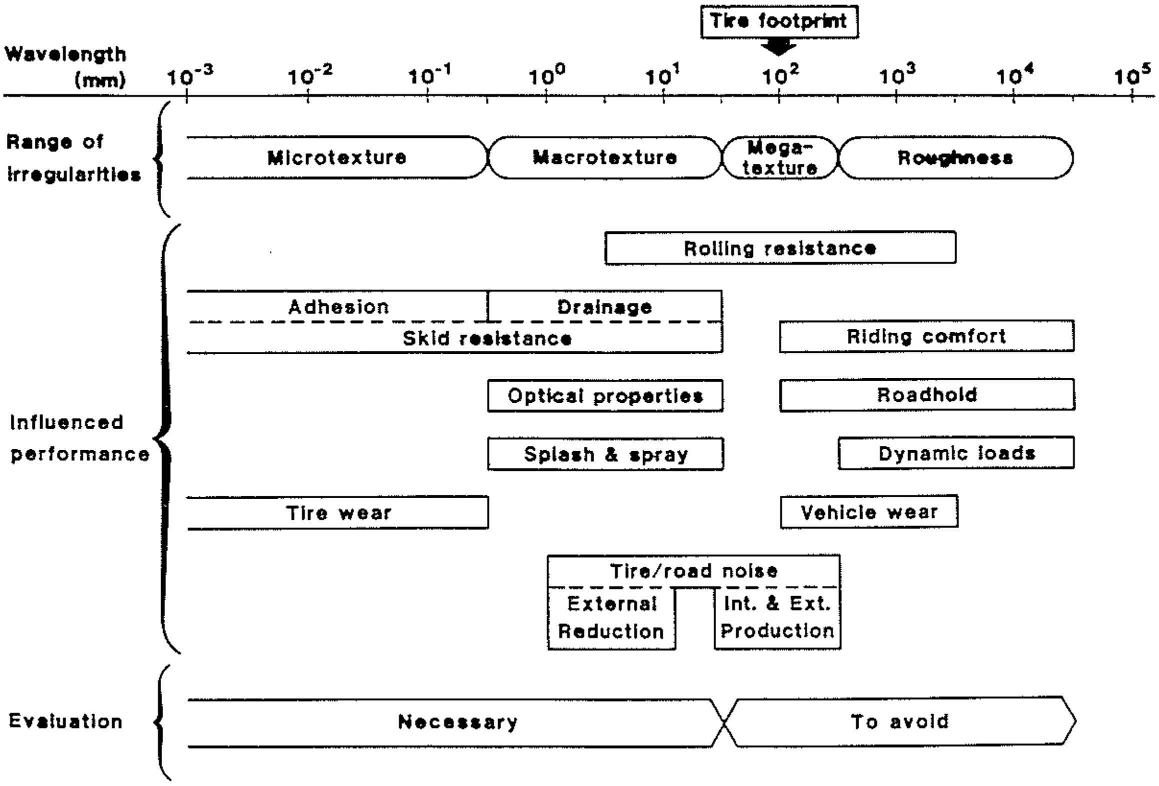
The need to accurately quantify pavement texture amplitudes in each of the wavelength ranges shown in Figure 1.1, has brought many instruments onto the market, ranging from rather simple devices to quite complicated systems. This report attempts to catalogue the more commonly used, commercially available instruments that were available in 1995.

The instruments fall into two distinct classes:

1. those which allow the road profile to be described as a continuous function of spatial frequency, and
2. those which attempt to describe the road profile within a specific wave band of interest by a single numeric.

The first class of instrument is desirable from a research and diagnostic perspective whereas the second class of instrument finds use in routine monitoring of both construction practices and road condition. Accordingly, instruments have been catalogued on the basis of the wavelength range measured and also whether or not they have the ability to provide continuous output of the elevation profile of the road surface, thereby allowing spectral analysis of the measured parameter.

Figure 1.1 Pavement surface wavelength spectrum (from Huschek 1990).



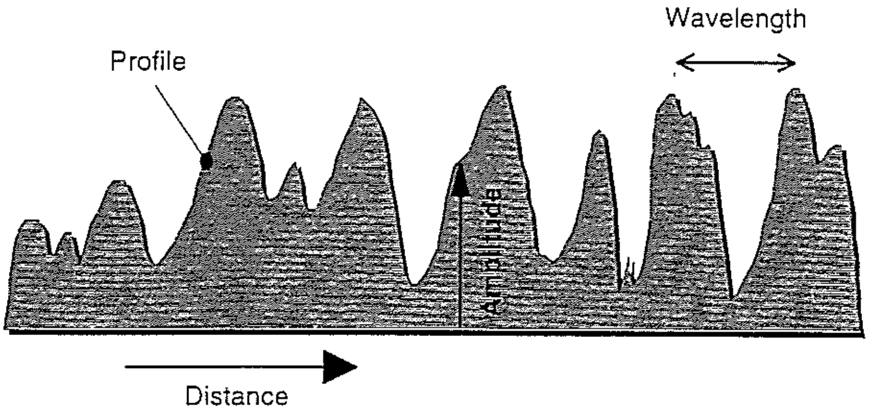
2. DEFINITIONS OF TEXTURE PROFILE MEASURES

The following definitions have been reproduced from the International Organisation for Standardisation (ISO) committee draft for characterisation of pavement texture (ISO/TC43/SC1/WG39 N17, 1994) and are used in this report.

2.1 Texture and Texture Profiles

Pavement texture is the deviation of a pavement surface from a true planar surface, within the wavelength orders defined in Section 1. If a sensor, like a tip of a needle or a laser spot, continuously touches or shines on the texture while it is moved along the surface, a "profile" of the surface is generated (Figure 2.1). The profile is a two dimensional representation of the surface.

Figure 2.1 Illustration of some basic terms describing pavement surface characteristics.



2.2 Texture Wavelength

The profile of the surface is described by its displacement along the surface and its displacement in the direction normal to the surface. The former is called "distance" and the latter is called "amplitude" in this report (Figure 2.1).

The distance may be in a longitudinal or lateral (transverse) direction in relation to the travelling direction on a road surface, or any direction between these. In a Fourier analysis, the profile curve can be mathematically described by a series of Fourier coefficients combined with sinusoidal curves with certain frequencies and wavelengths.

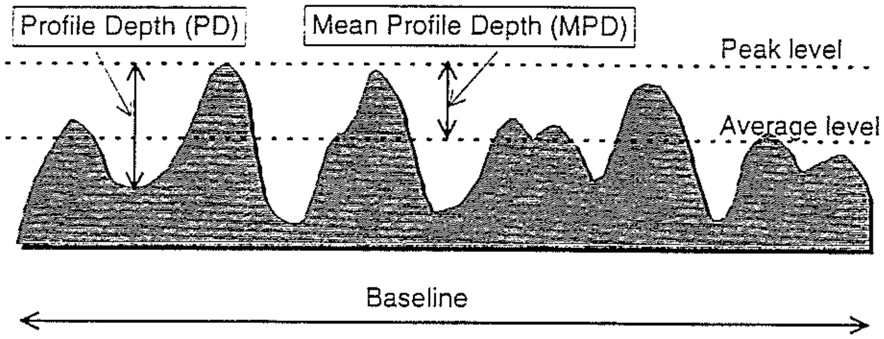
Wavelength is defined here as the (minimum) distance between periodically repeated parts of the curve. For normal surface profiles, a profile analysed by its Fourier components contains a continuous distribution of wavelengths.

The term "texture wavelength" (measured in m or mm) is used to describe the wavelengths of a profile taken from a pavement. The inverse of texture wavelength is called "spatial frequency" (cycle/m) which, when multiplied by the factor 2π, is called "texture wave number" (rad/m).

2.3 Profile Depth

In the two dimensional case, i.e. when studying a profile, the term "profile depth" (PD) means the difference, within a certain longitudinal or lateral distance in the same order of length as that of a tyre–pavement interface, between the profile and a horizontal line through the top of the highest particle within this profile (Figure 2.2). The average value of the profile depth over a certain distance (baseline) is called "mean profile depth" (MPD).

Figure 2.2 Illustration of the terms "baseline", "profile depth" (PD), and mean profile depth (MPD).



2.4 Texture Spectrum

When a profile curve has been analysed by either mathematical Fourier techniques or corresponding filtering processes in order to determine the amplitude of its spectral components (wavelengths or spatial frequencies), then a "texture spectrum" is obtained.

2.5 Profilometer Method

The profilometer method is a method in which the profile of a pavement surface is obtained for subsequent analysis. The data are used for calculation of certain mathematically defined measures. In some cases the profile is recorded for subsequent analysis, in other cases it may be used only in real time calculations.

3. TECHNIQUES USED FOR MACRO- AND MICROTEXTURE MEASUREMENTS

3.1 Introductory Comments

The construction and operation of safe pavements requires the preservation of a sufficiently high level of resistance to skidding. Skid resistance is a combination of the effects of macro- and microtexture, with the frictional performance of a pavement being governed by microtexture at low traffic speeds and by macrotexture at high traffic speeds. Many of the techniques described below have therefore arisen out of the need to assess the safety level of pavements. These techniques can be classified under the following four broad categories:

1. Direct texture measurement.
2. Tyre–friction measuring systems.
3. High resolution photogrammetry.
4. Non-contact profilometers.

3.2 Direct Texture Measurement

Examples of direct methods include:

- The "volumetric patch" method, where a known quantity of material such as sand, glass beads or putty is spread over the pavement and the diameter of the resulting circle is measured. The smaller the diameter of the circle the coarser is the texture (ASTM Test Designation E965-87 which is based on the use of glass beads). New Zealand has a variant of the volumetric patch method called the "sand circle" method (Transit New Zealand Standard Test Procedure T/3 1981). The sand circle method is suitable for the measurement of non-porous surfaces with average texture depths greater than 0.45 mm.

- Tracing the pavement surface with a stylus. An example is the "Dromometer", developed in Austria (Augustin 1990) and shown in Figure 3.1.

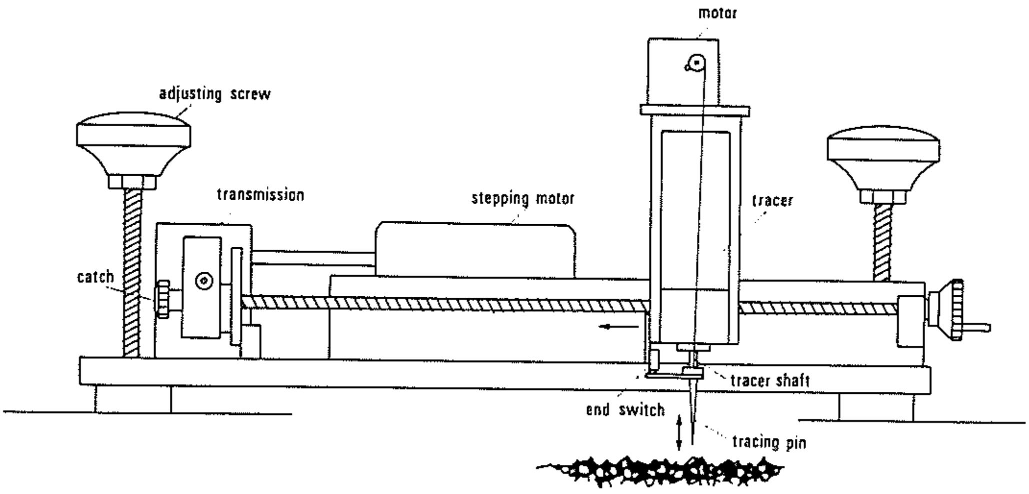
- Making a plaster cast of the surface, smearing the cast with paint, and measuring the area that received paint.

- Placing foil on the pavement, beating it with a mallet, and counting the number of holes made in the foil.

- Measuring the time required for a given volume of water under a given initial head to escape beneath an annular surface seal of given diameter and annulus proportion (Hegmon and Mizoguchi 1970). This is known as the "outflow meter measurement". The coarser the texture the quicker the water will escape.

Rose et al. (1973) provide a comprehensive review of the above methods.

Figure 3.1 Dromometer tracing unit (from Augustin 1990).



3.3 Tyre–Friction Measurement

The magnitude of the coefficient of wet pavement friction (skid resistance) at any given traffic speed depends only on the harshness of the pavement texture (or microtexture); and the slope of the friction versus traffic speed characteristic at any given traffic speed depends only on the mean void spacing (or macrotexture). Accordingly, skid resistance is commonly used to evaluate pavement texture.

A number of vehicle- or trailer-based systems are available for measuring skid resistance of a pavement section. These systems differ widely but can be classified into three types:

1. The locked wheel method, which relates to longitudinal skid resistance, produces a skid number (SN) as a function of test speed.

2. The slip method, which also relates to longitudinal skid resistance, produces brake slip numbers (BSN) as a function of percent slip and test speed.

3. The side force method, which relates to lateral skid resistance, produces side force coefficients (SFC) as a function of yaw angle and test speed.

The results from longitudinal and lateral slip systems are generally closely related. However, pavement skid resistance can show differences in longitudinal and lateral directions depending on road alignment and the directional polishing effect of traffic.

The most widely used method to measure skid resistance is the locked wheel skid trailer (ASTM Test Designation E274-90). Wet peak friction is measured by applying a brake to the trailer's test wheel and recording the average braking effort for one second after the wheel becomes fully locked (100% slip). The test wheel can be fitted with either a blank tyre (ASTM Test Designation E524-76) yielding SN_B values or ribbed tyre (ASTM Test Designation E501-76) yielding SN_R values.

Other common on-road devices are the μ (Mu) Meter (ASTM Test Designation E670-87) and the SCRIM (Sideways-Force Coefficient Routine Investigation Machine) developed by the Transport and Road Research Laboratory (TRRL) (Salt 1977). Both involve the measurement of the side force developed in a blank tyre placed at an angle to the direction of travel.

As part of a comprehensive study into the relationship between tyre–road friction and road surface texture conducted by Sandberg (1990), it was demonstrated that the Mu Meter correlates well with both micro- and macrotexture. The same is true for the ASTM blank tyre. However, the SCRIM and ASTM ribbed tyre appear to be much less sensitive to macrotexture, and so good correlations were obtained only for microtexture.

The friction–speed gradient has been found to be strongly correlated with macrotexture parameters such as the mean profile depth (MPD) and sand circle derived texture depth (TD_{SC}) (Leu and Henry 1978). An estimate of the macrotexture of a pavement section can be derived from its friction–speed gradient obtained in one of the following three ways:

1. Skid resistance measurements conducted over a range of test speeds.

2. One pass of a transient slip friction measuring device that operates at varying slip ratios: the data from a transient test allow friction versus traffic speed to be plotted at different slip ratios as the test wheel is braked from travel speed to fully locked.

3. The difference between blank and ribbed tyre friction in a locked wheel test: at the same test speed, the ribbed tyre measures the drained skid resistance (friction related to microtexture) while the blank tyre measures the undrained skid resistance (friction related to macrotexture).

The principal laboratory and field test skid resistance measuring device that can be used for evaluating the microtexture of a surface is the British Pendulum Tester. Its design and operation are described in detail by Kummer and Moore (1963). Essentially, the apparatus consists of a pendulum arm fitted with a rubber slider swinging from a known height, and the edge of the slider strikes, over a known distance, the surface under examination (Figure 3.2). The energy transferred in overcoming the friction is measured from the reduction in the upswing of the pendulum and gives a value for the skid resistance of the surface. The value is designated the British Pendulum Number (BPN).

Sandberg (1990) showed that BPN values correlate with texture at short wavelengths (2-5 mm). Its principal disadvantage is that each test covers only a very small area of the road surface (about 0.01 m^2), so that large numbers of tests are necessary to obtain a representative value. Furthermore, meaningful results are generally more difficult to obtain with the British Pendulum Tester on coarser surfaces (such as chipseals), for which the standard deviation of the BPN values is up to twice as high as that on smooth surfaces (Sandberg 1990).

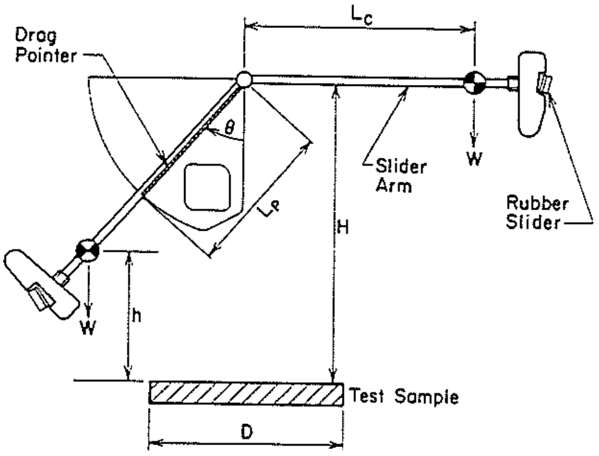


Figure 3.2 Diagram of British Pendulum Tester (from Kummer and Moore 1963).

3.4 High Resolution Photogrammetry

High resolution photogrammetry is a technique for recording a two dimensional representation of the pavement surface and then obtaining whatever subsequent texture measures are required. A detailed appraisal of pavement texture can be obtained through stereo optics. Schonfeld (1974) has developed a quasi-subjective six parameter scheme for rating textures from stereo photograms (ASTM Test Designation E770-80). His observations include aggregate height, width, angularity, surface density, and two microtexture parameters related to surface harshness.

3.5 Non-Contact Profilometers

With these instruments measurements are of the texture profile, and of the parameters characterising the pavement that can be derived from the profile. Again, emphasis was first on wet skid resistance, and attempts have been made to relate texture profile parameters such as root mean square (RMS) height, mean slope magnitude, and meander length per metre of scan to the skid resistance of the pavement (or the percent rate of change of skid resistance with test speed).

Profile spectral analysis has more recently become a common basis for characterisation. A typical texture spectrum for a coarse chipseal with crushed, sharp chippings is shown in Figure 3.3. It is characterised by a sharp drop-off in spectral density with decreasing wavelength. The spectral peak spans the 11 to 18 mm wavelengths indicating a predominant chip size of about 14 mm.

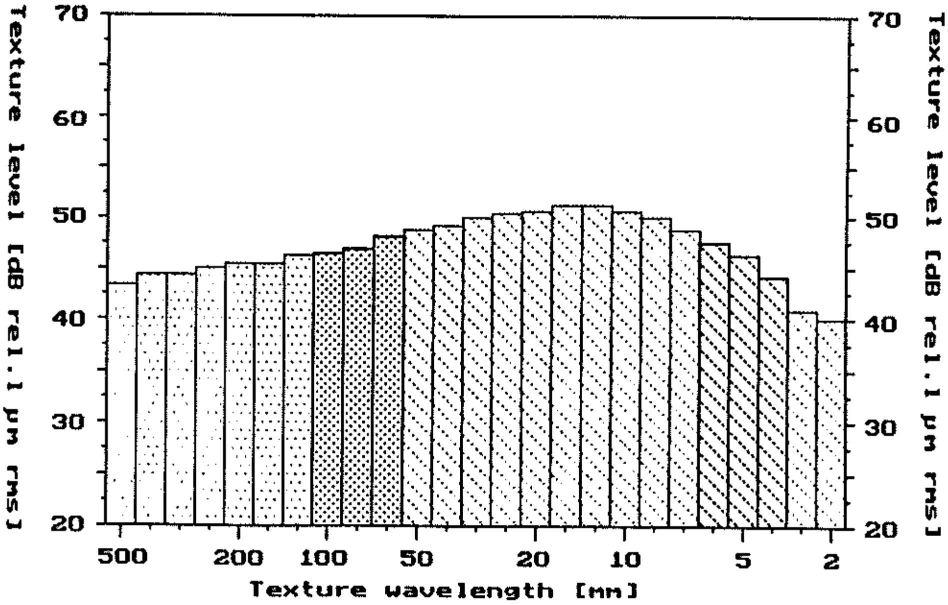


Figure 3.3 Texture profile spectrum of typical coarse textured chipseal.

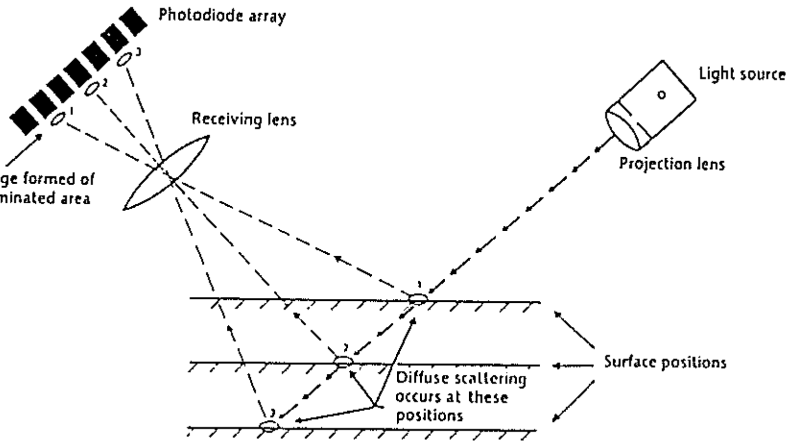


Figure 3.4 Principle of operation of laser texture meter
(from Kennedy et al. 1990).

Instruments which are capable of providing texture profiles generally utilise laser technology. The principle of the non-contact laser transducer is based on the optical system shown in Figure 3.4, and is described in detail in Willis et al. (1986). It consists of a projection unit and a receiving unit mounted on a rigid beam. A lens in the projection unit focuses the energy from a pulsed semi-conductor laser to illuminate a small area on the road surface. A proportion of the energy is diffusely scattered, and a lens in the receiving optical system collects a fraction of the scattered light and focuses an image of the illuminated area onto a linear array of photodiodes. When the surface is displaced vertically, the position of the illuminated area moves along the line of the projected beam. Since the axis of the projected beam and the receiving axis are orthogonal, the image of the illuminated area moves across the photodiode array and remains in focus. The position of the road surface with respect to the transducer may then be determined by detecting which photodiodes in the array have been illuminated.

Characteristics of present generation laser-based texture profilometers are such that these devices are not accurate in wet conditions, have high drop-out[1] rates caused by shadow, are not generally capable of covering the shortest macrotexture wavelengths (0.5-2 mm), and cannot reliably measure the porosity of porous surfaces such as friction course.

Laser-based texture profilometers are categorised according to their measuring speed:

- stationary (less than 0.15 m/s)
- walking speed (between 1 and 2.5 m/s)
- high speed (greater than 10 m/s)

Table 3.1 summarises the measuring and data processing parameters of current generation (1995) profilometers.

Table 3.1 Comparison of measuring and data processing parameters of texture profilometers.

Parameter	**Unit**	**Device**				
		ARAN	**SCRIMTEX UK**	**TRRL MTM**	**VTI RST**	**VTI Stationary profilometer**[a]
Measuring speed	m/s	25	14	2	25	0.02
Sampling rate	kHz	62.5	4	0.5	32	16 (2)
Sampling interval	mm	0.4	3.5	4	0.8	0.01
Sample length	mm	400	?	10000	1000	1000
Calculation baselength	mm	50	300	300	1000	70
Horizontal resolution	mm	0.5	0.4	?	0.8	1.0 (0.1)
Vertical resolution	mm	?	?	0.01	0.032	0.016 (0.001)
Minimum wavelength	mm	0.8	7	8	2	2 (0.2)
Maximum wavelength	mm	400	4000	300	>500	1000 (5)
Maximum drop-out rate	%	?	<10	<70	<10	<10

[a] Note: For the VTI stationary profilometer, bracketed figures pertain to the micro probe; unbracketed figures pertain to the macro probe.

TRRL = now TRL; MTM = Mini texture meter; RST = Road surface tester;
VTI = Swedish Road & Traffic Institute

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[1] Drop-out insufficient energy received by the sensing element following the transmission of a pulse of laser light.

The table highlights considerable differences between the instruments even though they all rely on electro-optical principles. It will be noted that the minimum wavelength that can be measured is a function of measuring speed and sampling rate of the laser. The relation is:

$$\text{Minimum wavelength (mm)} = 2 \times \frac{\text{measuring speed (m/s)}}{\text{laser sampling rate (kHz)}}$$

Therefore by decreasing the measuring speed and/or increasing the laser sampling rate results in the ability to measure shorter wavelengths.

The minimum wavelength that can be measured is also dictated by the laser spot size and band width of the laser and the associated recording system. The laser spot size causes an integration of the profile within the laser spot, which smooths out the sharp details of the texture profile. In order to reduce the possible influence of electrical noise and transients, the output from the laser is normally low pass filtered to remove high frequency components. This filtering may be achieved with either analogue or digital filters. All or part of the filtering effect may be achieved by the finite size of the laser spot.

The draft ISO standard for characterisation of pavement texture (ISO/TG43/SC1/WG39 N17, 1994) recommends for accurate measurement of MPD:

(1) A sampling interval of not more than 1 mm.

(2) A laser spot size no greater than 1 mm.

(3) Removal of spatial frequency components which are above 400 cycles/m, and corresponding to a texture wavelength of 2.5 mm.

The low texture wavelength limit resulting from (3) does not correspond to the definition of macrotexture according to Section 1. This is by intention because, to some extent, this imitates the effect of the enveloping by rubber surfaces (such as a tyre) and also because wavelengths less than 5 mm do not play a major role in determination of MPD.

Most laser texture profilometers, as seen in Table 3.1, are able to measure both macrotexture down to 2 mm wavelengths and megatexture, but the ARAN, by virtue of the very high sampling rate of its lasers (62.5 kHz), is the only high speed texture profilometer which can measure microtexture wavelengths. However, both the UK-sourced texture profilometers, the TRRL mini texture meter (MTM) and SCRIMTEX (which essentially is a high speed version of the MTM mounted on a SCRIM), failed to comply with the minimum ISO performance specifications detailed above.

The Yandell-Mee texture friction meter is one of the few commercially available non-contact texture profilometers that does not utilise the electro-optical principle (Yandell and Sawyer 1994). Instead light sectioning is used, in which a profile of 600 mm length is read to an accuracy of 0.05 mm by means of a black and white video camera viewing the image of a laser line projected at an angle onto the surface

(Figure 3.5). This profile, recorded digitally as 12,000 ordinates, is divided into four wavelength bands with a fifth order Bessel filter. The filtered profiles are subsequently analysed to provide texture depth statistics (average, RMS, and peak values), and predictions of side force and locked wheel wet skid resistance at three speeds (16 km/h, 48 km/h and 80 km/h). Detailed profile representations of both microtexture and macrotexture that can be obtained with this portable stationary device, are shown in Figure 3.6.

Figure 3.5 Schematic view of Yandell-Mee texture friction meter (from Yandell and Sawyer 1994).

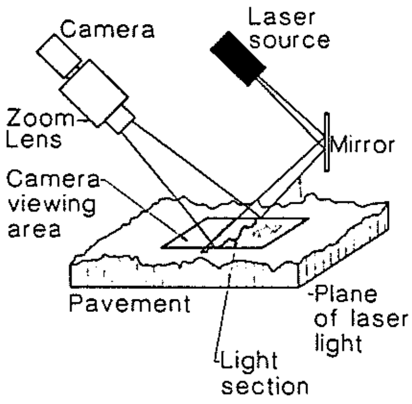
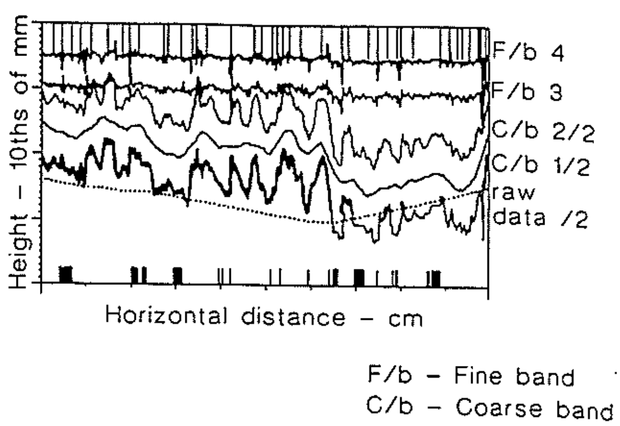


Figure 3.6 Total recorded texture and its four components (from Yandell and Sawyer 1994).



3.6 Operational Experience

An inventory of equipment used for measuring surface texture characteristics has been compiled by the Permanent International Association of Road Congress's (PIARC) Technical Committee of Surface Characteristics (CT1). This inventory presents 113 technical record forms describing the equipment and methods used throughout the world for measuring, analysing and recording surface characteristics. The breakdown of equipment that was available in 1995 is as follows:

• evenness (longitudinal and transverse)	32 forms
• cracks	16 forms
• texture	25 forms
• skid resistance/friction	30 forms
• multi-functional	10 forms

The PIARC reference is 01.03.B *"Inventory of Surface Characteristics Measuring Equipment"*, which was published in 1995 (PIARC 1995a). Technical summary sheets supplied by PIARC for a range of instruments, covering all the operating principles described above, have been reproduced in Appendix 1 for ready reference.

A comparative assessment of some of the devices listed in Appendix 1 has been carried out as part of an international experiment developed by the American Society for Testing and Materials (ASTM) Committee E17 on Pavement Management Technologies in co-operation with PIARC (1991). The experiment is to quantify repeatability and measurement errors associated with various existing types of road friction and surface texture measuring devices. Details of this experiment, which involved 34 friction and 18 texture devices being operated on 54 pavement sections, are given in Appendix 2. An analysis of the results and associated conclusions has been published in PIARC Publication 01.04.T-1995 *"International PIARC experiment to compare and harmonize texture and skid resistance measurements"* (PIARC 1995b).

The main results from the international experiment released to date are as follows:

1. The degree of correlation in friction measurement between devices of the same type are comparable to that between dissimilar devices.

2. Non-contact texture profiling systems were shown to be highly consistent, correlating with one another to better than R=0.94, and that their relative standard deviation lay between 10-20%.

3. The preferred algorithm to process any profile signal to obtain the most relevant macrotexture characterisation is the so-called mean profile depth (MPD), as it takes into account whether a profile is "negative" or "positive", i.e. if peaks are directed downwards or upwards in the profile.

4. Good correlation between outflow duration and MPD-based measurements ($0.86 < R < 0.94$) was obtained, indicating that the outflow meter could be an appropriate low cost device for measuring the macrotexture and drainage potential of pavements, including friction course.

In New Zealand a variety of devices are routinely used for measuring texture, including the British Pendulum Tester, the Mu Meter, SCRIM, the GripTester (a fixed slip friction tester), the volumetric sand circle method, and the laser-based MTM (a hand-operated device designed to check newly laid surfacings and short lengths of road associated with high accident rates). However, none are capable of providing texture profiles, although these profiles are often required for research purposes.

3.7 Summary

Of all the devices listed in Appendix 1, only the stationary laser profilometer, developed by the Swedish Road and Traffic Research Institute (VTI), gives a comprehensive quantification of road macrotexture and megatexture (0.5 mm to 0.5 m wavelengths) and approaches the microtexture range. It appears ideal as a research instrument because it can be replicated at comparatively low cost, the voltage output from the laser, once digitised, can be processed to yield any measure of texture required, and its configuration allows the ready interchange of lasers. Any advances in laser technology can therefore be utilised to decrease the minimum measurable wavelength.

The VTI stationary laser profilometer has been replicated by Works Central Laboratories according to the specifications supplied by VTI, and modified for use in New Zealand, as a subsequent stage to Transit New Zealand Research Project PR3-0054 (Cenek et al. in prep.).

If texture spectra with high resolution are required in the microtexture range, the only recourse available at present is to use mechanical needle profilometers, such as the Dromometer tracing unit, which is capable of making height measurements to an accuracy of 0.01 mm in steps of 0.0125 mm, or the Yandell-Mee texture friction meter.

Recent (1995) research concerning those texture measuring devices presently used by New Zealand roading contractors, has shown that the MTM texture measurements demonstrate a speed dependency, with significant resonance effects observed at operating speeds of 5 km/h and 8 km/h (McNaughton et al. 1994). The recommendation is that, if MTMs are to be incorporated in end product specifications for chipseal pavements, they will have to be:

- modified to include an operating speed indicator; and
- operated at a constant speed of 3 km/h.

Under such operational constraints, MTM values of texture depth were shown to be highly correlated with sand circle derived texture depths (R=0.98).

Both the British Pendulum Tester and the volumetric sand circle method should continue to be used by contractors, as they enable fairly rapid texture measures of reasonable accuracy to be made. However, consideration should be given to the use of outflow meters for determining the drainage potential of road surfaces, especially those that are intended to be porous, e.g. friction course.

4. TECHNIQUES USED FOR STRUCTURE TEXTURE–ROAD ROUGHNESS MEASUREMENT

4.1 Background

In its broadest sense, road roughness has been defined as *"the deviations of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads and drainage"* (ASTM Test Designation E867-89). The upper and lower wavelength limits of the roughness range are not specified, but typically fall somewhere within the range of 0.1 to 100 m (0.3 to 300 ft).

Road roughness of new pavements is caused by less than perfect control of the paving process, including the preparation of the basecourse and the subgrade, and by wear and tear in the paving equipment. Careful quality control can minimise this initial roughness. However, roughness will develop even on the smoothest pavement. Moisture, unequal thermal expansion, and freeze-thaw cycles will cause the pavement to deform.

Pavements will also deform under the load of passing wheels, and some of this deformation on flexible pavements is permanent, resulting in longitudinal roughness and rutting in the wheeltracks. Also, wheel load is dynamic, which means the instantaneous force exerted by the wheel on the pavement may be greater or smaller than the static wheel load. This dynamic effect is excited by imbalances in the vehicle drive train and by road roughness. Therefore the rougher the road, the greater the dynamic force component causing more roughness.

Measurements of road roughness qualities are generally limited to those related to the longitudinal profile of the road surface which cause vibrations in road vehicles. Most often, these measurements are defined simply as "the roughness number produced" by whatever combination of equipment and methodology is being used to characterise the road condition. The popular approaches toward describing road roughness can be divided into five categories:

1. **Response Type Measuring Systems (RTMs):** These systems consist of a vehicle driven or towed over a road while instrumented with a road meter to indicate the vehicle vibration.
2. **Measurement and Analysis of the Longitudinal Road Profile:** A road profile can be obtained by making amplitude measurements along the path followed by a wheel of a vehicle (wheeltrack). The large number of individual measurements are processed mathematically to obtain a single numeric describing the condition of that wheeltrack.
3. **Subjective Panel Ratings:** A road is judged by one or more persons and the opinions are converted to a numerical scale (Weaver and Clark 1977).
4. **Geometric Profilometers** (sometimes called **Profilographs**): This type of instrument is designed to produce a continuous signal related to the true profile

of the road by the geometry of its construction. An example would be a rolling straightedge that indicates a mid-chord deviation (Figure 4.1).

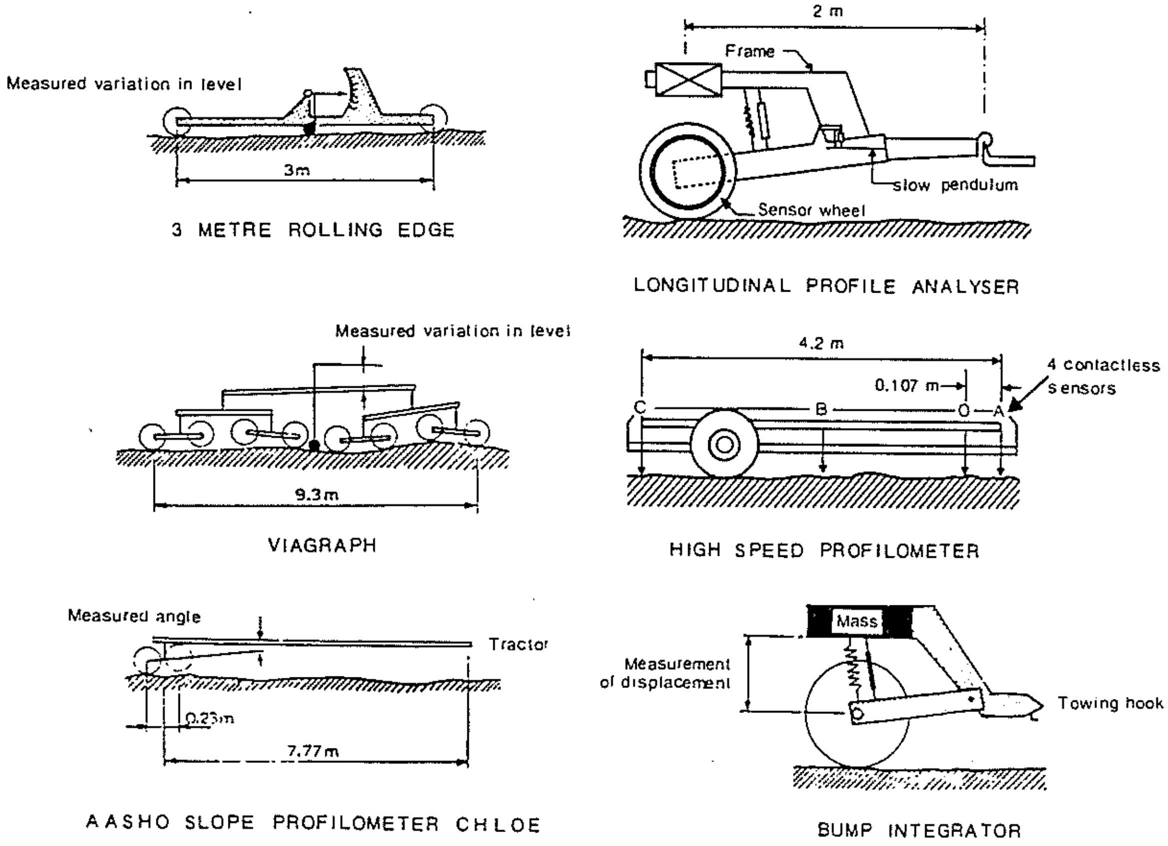
5. **Spot Check Measurements:** Approximate measurements are taken to assist in a subjective rating. Examples are deviations under a straightedge, the number of cracks per unit of area, and the number of pothole patches per length.

The subjective panel rating approach (category 3) is neither stable over time nor transportable unless the ratings are somehow "calibrated" to an objective reference. Spot check measurements (category 5) are used only to supplement another method and are not suited to large scale surveys. Consequently the measurement of longitudinal roughness is generally made with devices which employ either of the following two measuring principles:

- Those which measure a characteristic "response" of the vehicle (e.g. vertical acceleration or displacement of the axle or body) to surface irregularities;
- Those which record the irregularities of the road profile with respect to a geometric or inertial reference.

The measurement principle of some commercially available road roughness measuring instruments is schematically illustrated in Figure 4.1.

Figure 4.1 Measurement principles of some instruments for determining road roughness (OECD 1984).



4.2 Devices for Measuring Longitudinal Road Roughness

4.2.1 Response Type Meters

A response type meter (RTM) consists of a single axle trailer with one or two wheels, or a passenger car with a rigid rear axle. The physical characteristic to be measured is the distance between the vehicle body and the trailer axle or, in the case of a car, the rear axle. Two axle lorries have also been used for those measurements, in Russia at least.

The road roughness measure obtained with these instruments consists of the accumulated vertical displacement of the body and axle mass relative to each other divided by the length of the measured road section. The dimension of the measure is m/km or mm/m, to give the same roughness values. The information obtained is thus the mean value of the roughness of the measured road section.

RTMs are reasonably cheap to purchase and use. The measurements do not require especially skilled operators. The drawbacks with the instruments are that the measurement result contains very little information, does not lend itself to any further analysis, and the characteristics of a specific instrument will change from time to time caused by, for example, differences in shock absorber fluid temperature, balance of the wheel(s), or caused by wear of the mechanical links and the tyre(s). Therefore calibration is frequently required which calls either for a road section with constant unevenness, which normally is not available, or another instrument supposed to be invariant over time, with which to compare the measurements. The requirement in the latter case is to be sure that this control instrument really has not changed. The solution would be to use a non-mechanical profilometer as the control. However, if a profilometer was available, it would be better utilised to make actual road roughness measurements and not as a control.

Furthermore, even if several examples of the instrument are manufactured according to the same specification, inevitably some differences will exist between them. To be able to compare measurement results from different examples of the same type of meter, they must be directly compared at the same time and on the same sample of road sections covering the entire roughness spectrum to be studied. This will also, of course, be the case if measurement results from different types of RTMs are to be compared.

The most widely used RTMs measure the vertical motion of an axle relative to the vehicle body (ASTM Test Designation E1082-90). Instruments using this principle include, among others, the Portland Cement Association (PCA) road meter (Brokaw 1967), the Mays road meter (Walker and Hudson 1973), and the Australian NAASRA roughness meter (Scala and Potter 1977). For all these instruments, the host vehicle is a passenger car and the instrument is mounted on the body, directly above the centre of the rear axle.

The best known RTM is the bump integrator of British design (Buchanan and Catudal 1941) from which a number of variants have been produced: Soiltest CT444 roughometer, TRRL bump integrator (BI) trailer, Bureau of Public Roads (BPR) roughometer. In this case, the instrument is mounted on the frame of a single wheeled trailer to one side of the wheel, directly above the axle.

Rather than measuring vertical displacements, some RTMs directly use the measured accelerations of an axle or a sensor carrying arm. Examples are the Swedish road surface tester (RST - SAAB) described by Arnberg (1981), and the Shock-meter.

Table 4.1 summarises the characteristics of the main RTMs and the OECD countries where they are used.

4.2.2 Profilometers

A profilometer will produce a more or less detailed "picture" of the longitudinal profile of the road. The detail of the picture depends on the filter characteristics of the individual profilometer. All existing profilometers inevitably filter the profile, so that the shortest as well as the longest wavelengths will be removed or at least attenuated. The pass frequencies of the filters differ between different profilometers, and may also be affected by the measurement speed so that longer wavelengths will be recorded at higher speed than at low speed. However, some profilometers have a compensating system so that the measurement result will be speed independent within a certain speed range.

In contrast to RTMs, profilometers offer the opportunity to study the road profile in detail. By obtaining the wavelength spectrum of the road profile, relationships between wavelengths of the road profile and resonance frequencies of road vehicles can be investigated. A further possibility for the use of profilometers, albeit not thoroughly investigated yet, is to study specific irregularities such as potholes, and joints between concrete slabs or on bridge decks.

Profilometers in common use fall into two categories:

1. manual quasistatic systems, and
2. high speed profilometer systems.

The high speed profilometer systems are more popular in developed countries, whereas the manual systems are a practical alternative in developing countries. Table 4.2 provides a summary of the main characteristics of some commercially available profilometers.

4.2.2.1 Quasistatic systems

Quasistatic systems of measuring a road profile are normally considered to be those in which the profile is recorded at a speed significantly slower than that of the regular traffic on the road.

Table 4.1 Characteristics of main "response" type measuring systems (from OECD 1984).

Name of measuring system	**Parameter measured**	**Placing of sensor**	**Reference datum**	**Output parameter**	**Recording**	**Measuring speed (km/h)**	**Use**	**Countries where used**
BI trailer BPR roughometer	Vertical displacement	Hub	Trailer chassis	Cumulative vertical displacement	Counter Magnetic tape	32-50	Network management Strengthening	Denmark, Spain, Netherlands, United Kingdom, USA
PCS road meter	Vertical displacement	Axle	Vehicle chassis	Cumulative vertical displacement	Counter	Up to 80	Network management	USA
Mays road meter	Vertical displacement	Axle	Vehicle chassis	Cumulative vertical displacement	Paper	Up to 80	Network management	USA – Texas
NAASRA roughness	Vertical displacement	Axle	Vehicle chassis	Cumulative vertical displacement	Counter	50-80	Network management	Australia, New Zealand
Road surface tester (RST-SAAB)	Acceleration	Arm with wheel	When at rest	Acceleration (second power mean)	Built-in computer (disks)	30-120	Network management	Sweden
Shock-meter	Acceleration	Axle	When at rest	Maximum acceleration over 7.5 m	Paper	?	?	Sweden

Table 4.2 Classification and main characteristics of a few profilometers (from Boulet 1988).

Parameter measured	**Reference**	**Measuring speed (km/h)**	**Restitution of profile**	**Wavelength detected**	**Examples of systems (country of origin)**
Elevation of profile	Fixed horizontal (absolute)	Static	Yes	From a few cm to infinity (in theory)	Topograph systems TRRL beam (UK)
Elevation of profile	Geometrical mechanical (rolling rigid straightedge)	A few km/h	Yes	Up to twice the reference length	Viagraph (F,B) Planograph (D) Planimeter (D,CH)
Slopes and radius of curvature of longitudinal profile		A few km/h	No		AASHO and CHLOE profilometers (USA) Stuttgarter Neigungsmesser(D) Goniograph (CH) Winkelmessgerat (CH)
Elevation of profile	Geometrical (straightedge) "calculated"	50 to 100	Yes	Up to 6 m (3 m rolling straightedge)	Komatsu ZR04LY (J) Road Recon 1/3 (J)
		5 to 80	Yes	0.5 to 100 m	HRM (UK)
Elevation of profile	Inertial pseudo-horizontal (pendulum)	20 to 120	Yes	Depends on speed (up to 85 m at 120 km/h)	APL (F) ARS (E)
Acceleration of chassis of a vehicle (sprung mass)	Distance between chassis and pavement surface	50 to 100	Possible but not systematic, by double integration of acceleration	0.5 to 60 m	Laser RST (S) and most systems from USA; KJ Law 690, FHWA profilometer, SIRST (USA)
Acceleration of sprung and unsprung masses of a vehicle		30 to 110	Possible but not systematic, by double integration of acceleration	0.5 to 100 m	ARAN (CAN) and PURD (CAN)

Abbreviations for country of origin:

B = Belgium
CAN = Canada
CH = Switzerland
D = Germany
E = Spain
F = France
J = Japan
S = Sweden
UK = United Kingdom
USA = United States of America

Surveyor's Rod and Level: One of the first methods used to measure a road profile was that using a surveyor's rod and level. This well known method determines the profile in relation to a horizontal reference and monitors without distortion all wavelengths longer than about twice the sampling distance. It is basically very accurate, but sensitive to operator errors which are difficult to detect afterwards. This means that the measurements should be repeated, preferably by other surveyors. The accuracy of the amplitude measurement is typically around 1 mm. By following procedures given in ASTM Test Designation E1364-90, the rod and level method gives road roughness profiles of sufficiently high precision to enable calibration of other roughness measuring devices.

Beam Profilometer: The TRRL beam profilometer is an instrument for making somewhat more automated static profile measurements than are possible using a surveyor's rod and level. This instrument consists of a 3 m long beam with a sliding carriage and a follower wheel. The beam is levelled up on two stands (one at each end) and then the carriage is slid from one end to the other. As it slides, the follower wheel tracks the road profile and on-board instrumentation digitises the elevation with 1 mm resolution at intervals of 100 mm along the beam length. The beam is then moved forward and the procedure is repeated.

With a capability of measuring approximately 2560 wheeltrack metres with a two-man crew in an 8-hour day (Sayers et al. 1986a), this method is faster than a rod and level, but is nevertheless still suitable only for profiling road sections of special interest rather than for the routine measurement of road roughness.

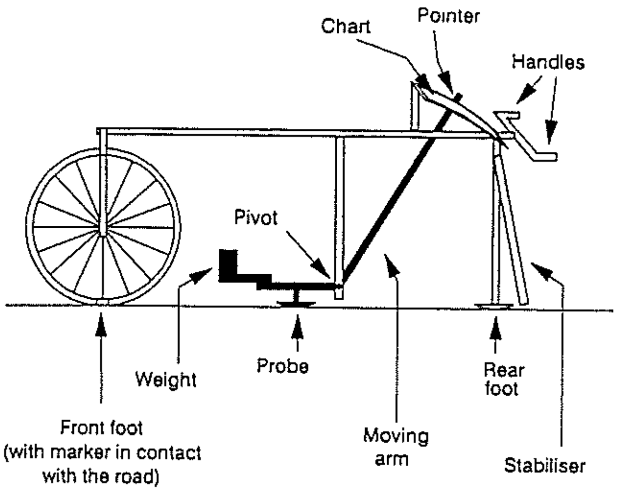
Dipstick: Another device for measuring road profiles at walking speeds is the so-called dipstick (Bertrand 1988). This instrument was originally developed for measuring the flatness of floors. It is basically a pendulum contained in a rectangular box with one leg at each end that measures the difference in elevation between these legs. There are two versions of the dipstick, having the base lengths 0.3 m and 1 ft respectively. The dipstick is operated by one man and, according to the manufacturer, it is possible to measure, record and analyse 180 m of road in one hour with an accuracy of 0.15 mm for the metric version. It was observed that only 970 readings (corresponding to a surveyed distance of 291 m) could be done before the data had to be downloaded (Bertrand 1988).

The dipstick gives outputs that record the International Roughness Index (IRI), and can also be used to record the longitudinal profile. To obtain the latter, however, is very laborious and the dipstick gives hardly any advantage over the conventional rod and level method.

In a comparative study of the dipstick and the TRRL beam, Bennett (1991) found that the dipstick produced data that were more consistent than the TRRL beam data, and that the data did not exhibit as large variations in the reference roughness. The dipstick also had the advantage that systematic errors did not appear to have an effect on the IRI statistic. Bennett therefore concluded that the dipstick is more appropriate than the TRRL beam for establishing the reference roughness for calibrating RTMs.

MERLIN: A simple roughness measuring device designed by TRRL especially for use in developing countries is called the MERLIN (Machine for Evaluating Roughness using Low-cost INstrumentation). It consists of a metal frame, 1.8 m long, with a wheel at the front, a foot at the rear, and a probe midway between them that rests on the road surface (Figure 4.2). The probe is attached to a moving arm at the other end of which is a pointer that moves over a chart. The position of the components is such that a movement of 1 mm of the probe will move the pointer by 1 cm. The device is placed at successive locations along the road and the positions of the pointer are recorded on the chart to build up a histogram. The chart consists of a series of columns, each 5 mm wide, and divided into boxes. The width of the resulting histogram correlates well with IRI roughness, the coefficient of correlation (R) being 0.991 (Cundill 1991). The MERLIN is in use in a number of developing countries. It can usually be replicated locally at a current typical cost of NZ$400.

Figure 4.2 Schematic diagram of the MERLIN measuring device (from Cundill 1991).



ARRB Walking Profilometer: The ARRB (Australian Road Research Board) has developed a walking profilometer that conforms to World Bank class 1 profilometer requirements (Section 4.3). It generates a surface profile by continuously recording the relative amplitude of successive points at fixed intervals of slightly less than 250 mm. The primary accuracy of relative height measurement from one point to the next in sequence is of the order of ±0.005 mm. This corresponds to an expected final amplitude accuracy of about ±1 mm over a 50 m profile run. An on-board computer is used to process the relative amplitude measurements. Graphical displays of the surface profile are provided, and the supplied software allows for point by point examination of the amplitude and corresponding distance in engineering units as well as outputting IRI values. Its price is about NZ$30,000, which includes a Notebook computer.

Profilographs: Low speed roughness measurements with profilographs (or various types of straightedges) are used in acceptance testing of newly paved surfaces. A profilograph is basically a long beam supported by several wheels at each end, carrying a test wheel in the centre. The vertical motion of this test wheel relative to the beam is a measure of the road roughness. The accumulated motion of the test wheel along the test section is normalised over a unit distance and reported in m/km or in in./mile. ASTM Test Designation E1274-88 *"Test Method for Measuring Pavement Roughness Using a Profilograph"* describes the apparatus and its use.

The precision of profilographs is low because their responses are not uniform over the wavelength of interest (Kulakowski and Wambold 1989), and variations in profilograph construction affect the results. The most familiar profilographs are the various versions of rolling edge, the Viagraph, the Planograph, and the rolling Planimeter (OECD 1984).

Slope Profilometers: These geometric profilometers use a principle in which the output signal corresponds to an angle between two axes, the slope of which is linked to the road profile. Commonly used examples are the AASHO slope profilometer, Neigungsmesser, CHLOE profilometer, Goniograph, ISETH Winkelmessgerat (OECD 1984). Together with the TRRL beam profilometer, dipstick, MERLIN and ARRB walking profilometer, these are in effect straightedge profilometers. The straightedge may be a beam, vehicle chassis or truss, with three position sensing devices - one on each end and one in the centre. The centre sensor only detects how much the road is curved between the ends of the straightedge. The larger the curvature (or displacement of the centre sensor), the larger the bump in the pavement. No absolute measurement of the pavement profile is made. Consequently only variations in the profile that are shorter than the wheelbase of the straightedge can be detected. Wavelengths longer than the wheelbase of the vehicle, which may significantly affect the ride of a vehicle, go undetected. Yoder and Witczak (1975) provide a review of straightedge and slope profilometers.

4.2.2.2 High speed systems

Two independent approaches to the design of equipment capable of dynamic profilometry have been developed. In France, the Laboratoire Central Francais des Ponts et Chaussées (LCPC) has developed a dynamic longitudinal profile analyser (l'analyseur du profile en long bitrace (APL)). In the United States, General Motors Research (GMR) developed the GMR-type of profilometer (also known as the surface dynamics profilometer). Both of these approaches make use of an on-board inertial reference from which the profile is measured.

APL: The longitudinal profile analyser (APL) consists of a one wheel trailer towed at a constant speed between 20 and 120 km/h. The bicycle-type test wheel is mounted at the end of a trailing rigid arm which, via a spring and a shock absorber, carries the ballasted frame of the trailer. A low frequency inertial pendulum which has the same rotation axle as the wheel arm serves as a pseudo-horizontal reference, and the parameter to be measured is the angle between the wheel arm and this pendulum.

Two versions of the APL exist: the APL25 originally developed for quality control of road construction, and the APL72 for evaluating the condition of roads in service. For further information refer to Bonnot and Boulet (1987).

The APL has recently been upgraded to have a frequency response function equal to unity in the frequency range 0.4 to 20 Hz, independent of the movements of the towing vehicle. This means that the upgraded APL will measure the road profile within a wavelength band depending on the measuring speed:

$\lambda_{min} = v/20$

and $\lambda_{max} = v/0.4$

where λ = wavelength (m)

v = measurement speed (m/s)

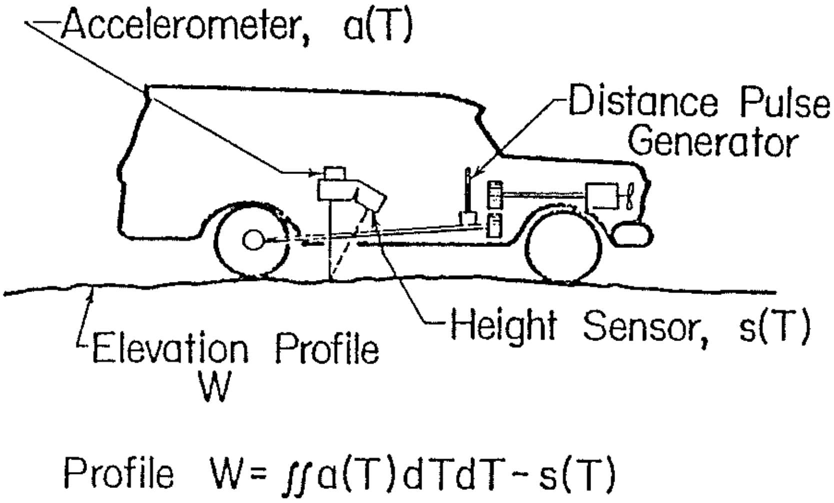
The wavelength range to be measured can thus be easily selected by choosing the measurement speed accordingly. For example, if the minimum wavelength of interest is 1 m, the tow speed of the APL would be set at 20 m/s (72 km/h). At this speed the maximum wavelength measured would be 50 m. During a single measurement traverse, the speed should be kept constant so that the same wavelength range can be observed over the entire road section. However, research in progress aims to develop a filtering process that will minimise distortions caused by speed fluctuations which may occur during the traverse.

The performance of the new APL has been put through numerous tests on a vibrating bench as well as on the LCPC test track. The measurement error consists of two parts: an instrumental error that has been shown to be less than 0.5 mm, and a random error on digitised profile amplitudes with a Gaussian distribution and a standard deviation around 3% of the maximum amplitude.

The APL was originally designed to give only an unevenness index that is representative for the measured road section. Recent research carried out at the University of Michigan Transportation Research Institute (UMTRI) has shown that it is possible to derive the road profile from the time history of the recorded parameter (Sayers and Gillespie 1986). The profile information is, however, not obtainable in real time but has to be developed in the laboratory after measurement.

Accelerometer-Based Inertial Profilometers: A second approach to the dynamic measurement of road profiles is that originated by GMR in 1966, and consists of measuring the distance from a moving platform (the vehicle) to the road surface and concurrently measuring the vertical motion of this platform by means of accelerometers. The first profiling systems used small wheels for tracing the road roughness. Current profiling systems use non-contacting distance sensors (optical or ultrasonic) to measure the height above the road surface. The difference between the height profile and the (doubly integrated) acceleration profile is the road roughness profile. These may be measured in one or in both wheeltracks. In addition, the speed and travel distances are measured and recorded. The key elements of an accelerometer-based inertial profiling reference (AEIPR) system are shown in Figure 4.3.

Figure 4.3 Key elements of an accelerometer-based inertial profilometer (from Watugala 1984).



All profiling systems available in 1995 use digital recording. The height and acceleration records are sampled on a time or distance basis. Recording on a distance basis maintains a constant sample interval, independent of speed. However, sudden speed changes must be avoided because of the effect on the vertical acceleration measurement.

K J Law Engineers Inc. of Novi, Michigan, USA, acquired a patent licence from General Motors and is now the commercial source of the Model 690DNC surface dynamic profilometer. Other AEIPR systems which are based on the GMR design include the PRORUT system developed by UMTRI for the Federal Highway Administration (FHWA), the laser road surface tester (RST) developed by the Swedish Road and Traffic Research Institute (VTI), Roadware Corporation's laser SDP sub-system fitted to ARAN vehicles, the South Dakota ultrasonic-based system, and the ARRB laser-based highway speed profilometer.

These systems have similar hardware configurations but use a different displacement transducer and different software for signal processing and profile analysis. A review of AEIPR methods is given by Pong and Wambold (1992). Procedures for measuring and recording road profiles using AEIPR systems is given in ASTM Test Designation E950-83.

The limitations of GMR measurement method are confined to:

- The need for a high sampling rate to capture very short wavelength roughness requiring specialised data acquisition systems with sufficient computational speed and memory.

- The need for highly sensitive accelerometers to capture very long wavelength roughness.

- Conditioning of the accelerometer signals by filters to remove displacement components at topography wavelengths, and also to eliminate spurious high frequency noise. Two road profiles obtained with AEIPR systems can therefore be directly compared only if both cover the same range of wavelengths.

- Reliable operation of the non-contacting distance sensors (optical or ultrasonic) is limited to only when the road surface is dry.

Measurements using AEIPR systems can normally be carried out at any speed between 30 and 100 km/h. Modern versions of the GMR profilometer do not require the speed to be kept constant during measurement. The accuracy of the commercially available meters are not reported but the resolution of the transducer measuring the distance to the road surface is better than 0.25 mm.

Other commercially available systems capable of dynamic profilometry are the accelerometer based "Smart Roughness profiler" sub-system used on ARAN vehicles and straightedge-based systems developed by TRRL.

The Smart Roughness profiler sub-system is a vehicle-mounted module that uses accelerometers to measure longitudinal profile and/or roughness of the roadway. The module comprises one or more pairs of accelerometers. Each pair includes an axle-mounted accelerometer and a corresponding body-mounted accelerometer. Movement of the chassis or the vehicle axle are reconstituted through double integration of the measured accelerations. The system meets profile/roughness measurement requirements specified by ASTM Test Designation E950-83.

TRRL (now TRL, UK) has developed the high speed road monitor (HRM), high speed survey vehicle (HSV), and the multi-function road monitor (MRM). The HRM dates to the early 1980s. It is built on a single axle trailer with two wheels. Four distance measuring lasers are mounted in a straight line along the chassis of the trailer, one at each end, and one in the middle. These three lasers are 2.0 m apart. The fourth laser is positioned 0.1 m behind the first laser. Those lasers actually form two profilometers, one consisting of lasers 1, 3 and 4 and one consisting of lasers 1, 2 and 4 measuring wavelengths in the range 0.5 to 20 m. Both profiles are subsequently combined to give a single profile containing all the wavelengths measured by the two systems.

The HRM is towed by a van which houses the computer for the signal processing as well as providing a work place for the operator. Measurement speed is 5 to 80 km/h.

Wavelength response of the profilometer is independent of speed within this range, but the measurement error will increase with increasing speed. According to Still and Jordan (1980), maximum measurement errors of wavelengths less than 3, 10 and 25 m are 1.5, 2.0 and 4.2 mm respectively.

The HSV uses the same measurement system as HRM, but is built on a van and includes some further measurement facilities not previously found on the HRM. The MRM is the commercial version of HRM.

The calibration requirements of AEIPR-based profilometers are relatively simple. The displacement transducers can be readily calibrated against a length standard following their manufacture or at any time throughout their service lives. The calibration of the accelerometers used to determine the frame displacements can be performed relatively easily using a small portable shaker. Both the displacement transducers and the accelerometers can be expected to remain stable over time, thereby minimising the requirement for frequent recalibration. The resources required to calibrate a GMR-type profilometer are significantly lower than those required either for an RTM or for an APL trailer. The shaker required to calibrate the accelerometers of a GMR-type profilometer is also much smaller (and hence less expensive) than that required for an APL trailer.

Profilometers based on lasers and accelerometers, once they have been verified to be functioning satisfactorily, can be expected to do so as long as they function at all. A non-functioning transducer or a failure in the computer system will probably give easily detected wrong results, whereas a mechanical system may give a small but increasing error that is not immediately recognisable. The calibration of a profilometer can be performed using rod and level or dipstick. These are rather laborious procedures but calibration does not have to be carried out very often, and they allow comparable measurements of different examples of profilometers to be made without having to bring the instruments together.

Profilometers of the AEIPR type have the disadvantages of being expensive and of complex technology, requiring specially trained measurement personnel. These disadvantages are greater when the profilometers are incorporated in multi-functional measurement systems used for collecting pavement management data.

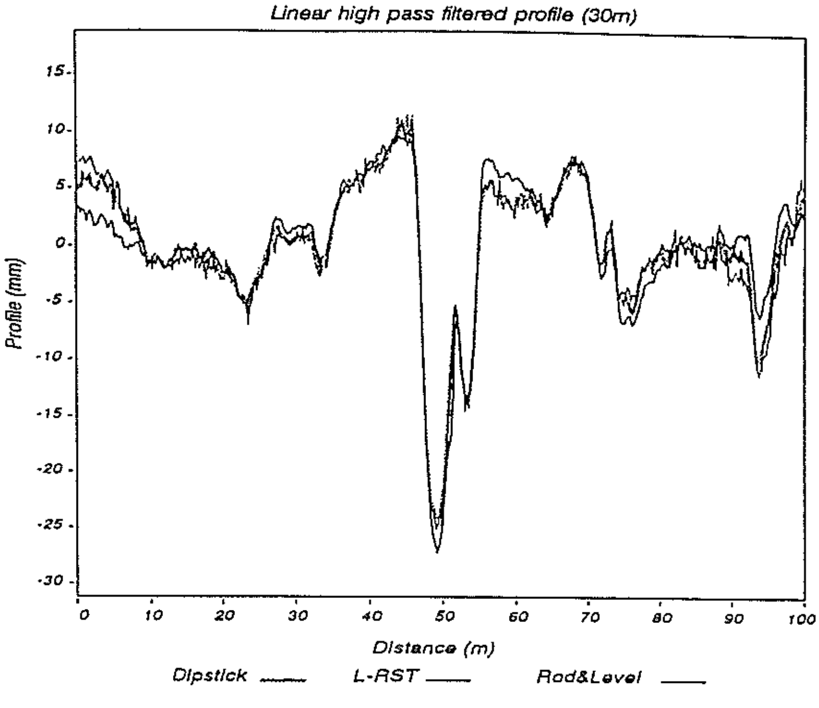
Commercially available inertial and straightedge profilometers also do not provide the true road profile because they do not record the profile with respect to an unchanging datum. However, a new method has been proposed by Elton and Harr (1988) which uses a simple mathematical algorithm to interpret distance measurements made from a rigid beam to the pavement. The method requires four non-contacting distance transducers mounted as a rigid beam and is capable of measuring true pavement profile, deflection and texture from a moving vehicle.

A prototype system has been constructed to test the method. Although good profile and texture results have been obtained, pavement deflection measurements showed wide variability which was attributed to the sensitivity of the distance transducers to proper alignment. It is expected that the method, once fully developed, will find particular application in evaluating the condition of airport runways.

4.2.2.3 Profile representations

Road profiles recorded by profilometers will in the first place be represented by an array of equi-distant amplitude numbers, the deterministic profile, which subsequently may be the subject of some type of data reduction. As mentioned previously, AEIPR systems inevitably will filter the true profile in some way, discarding or at least attenuating the shortest as well as the longest wavelengths. GMR-based profilometers will also, to some extent, distort the profile related to frequency dependent phase shift between the two signals making up the profile and caused by the high pass filtering of the profile. However, this distortion can be rectified by filtering the profile again but this time backwards through the same high pass filter. These two filtering steps will together form a linear high pass filter. Figure 4.4 illustrates the level of agreement obtained between a profile established by rod and level, and dipstick and laser RST-derived profiles.

Figure 4.4 Comparison of road profile reproductions (Pong and Wambold 1992).

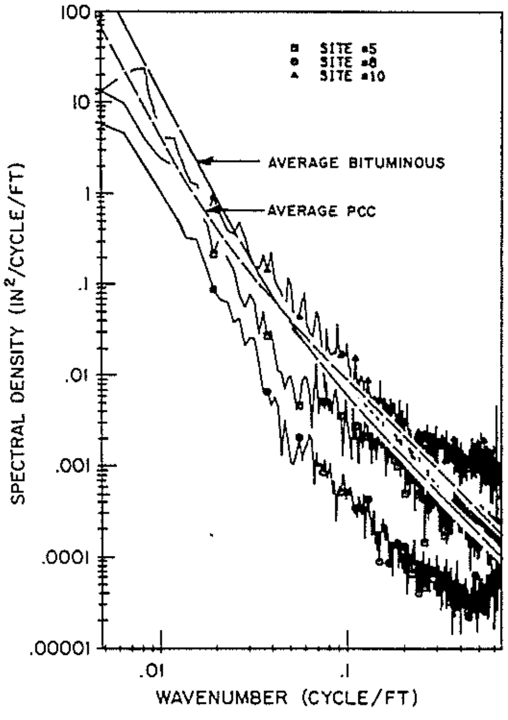


Road profiles fit the general category of "broadband random signals" and so can be described either by the profile itself or its statistical properties. One of the most useful representations is the power spectral density (PSD) function. Like any random signal, the deviation profile measured over a length of road can be decomposed by the Fourier transform process (Bendat and Piersol 1971) into a series of sine waves varying in their amplitudes and phase relationships. A plot of the amplitudes versus spatial frequency is the PSD. Spatial frequency is expressed as the "wave number" with units of cycles/metre, and is the inverse of the wavelength of the sine wave on which it is based.

When the PSDs are determined, plots such as those shown in Figure 4.5 are typically obtained. These plots have been reproduced from an American source (Gillespie 1992), hence the use of empirical units. Although the PSD of every road section is unique, all roads show the characteristic drop in amplitude with wave number. This simply reflects the fact that deviations in the road surface of the order of hundreds of feet in length may have amplitudes of inches, whereas those only a few feet in length are normally only fractions of an inch in amplitude. The general amplitude level of the plot is indicative of the roughness level, with higher amplitudes implying rougher roads. The wave number range in Figure 4.5 corresponds to wavelengths of 200 feet (61 m) on the left at 0.005 cycle/foot (0.016 cycle/metre), to about 2 feet (0.6 m) on the right at 0.5 cycle/foot (1.6 cycles/metre).

Figure 4.5 Typical spectral densities of road elevation profiles (from Gillespie 1992).

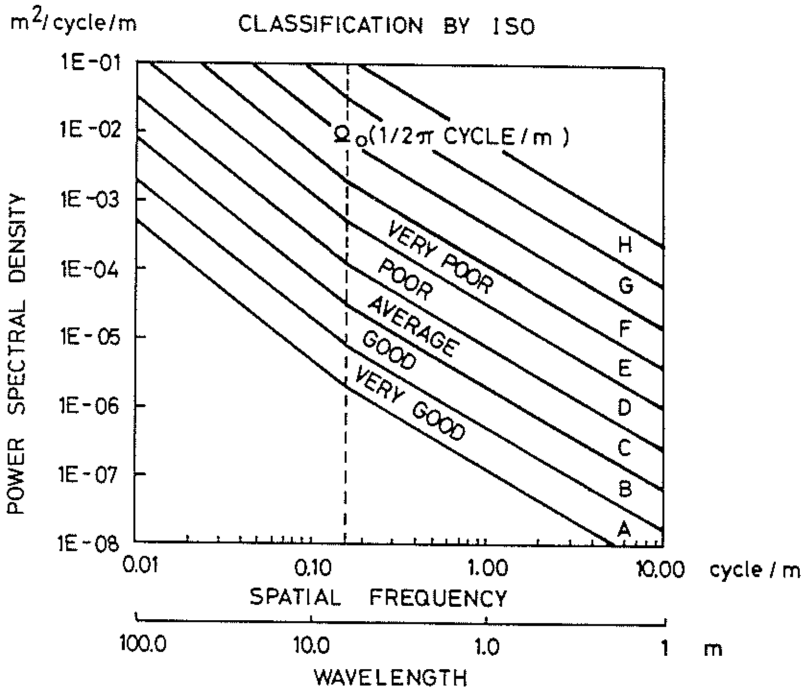
Note: Site 5 = Asphalt road
Site 8 = Portland cement concrete overlaid with bituminous asphalt
Site 10 = Portland cement concrete



The uppermost PSD curve (site 10) in Figure 4.5 is a deteriorating Portland cement concrete (often called "rigid pavement") road surface. Note a marked periodicity in the range of wave number between 0.01 cycle/foot (0.03 cycle/metre) and 0.01 cycle/foot (0.3 cycle/metre), which is related to the fixed slab length used in construction of the road. The lowest PSD curve (site 8) is a similar road overlaid with a bituminous asphalt surface layer yielding a much smoother surface (the PSD amplitude is reduced by an order of magnitude). The reduction is especially pronounced in the high wave number range. The intermediate PSD curve (site 5) is a typical asphalt road (often called "flexible pavement").

In order to find road profiles representing good, medium and bad roads, the ISO draft standard *"Reporting Vehicle Road Surface Irregularities"* (ISO/TC 108 /SC2 /WG4 B57 1982) may provide some guidance based on the PSD of the profiles. Figure 4.6 shows the classification proposed by ISO.

Figure 4.6 PSD classifications of surface roughness as proposed by ISO (1982).



4.2.2.4 Data reduction

All the profilometers considered above will give profile results which will lend themselves to further analysis and different data reduction methods. As the resonance frequencies of vehicles lie within very narrow ranges, it is possible, by means of frequency analysis of the profiles, to find any connections between resonance frequencies of vehicles and increase over time of amplitudes of different wavelengths present in the road profile.

Profilometers will, however, also permit the calculation of a great variety of road unevenness indices including IRI and the RMS for some specified wavelength ranges of the profile. The latter method is utilised by the Swedish laser RST, where the RMS values are calculated for five wavelength ranges. Table 4.3 shows some indices which are currently used. Detailed descriptions of these and a comparison between them are available (Sayers et al. 1986a, 1986b).

Table 4.3 Examples of evenness indices calculated from longitudinal profiles (from Boulet 1988).

Characteristic of profile used	**Type of analysis**	**Evenness index (country, system)***	**Prior filtering of profile**	**Wave-lengths influencing the index**	**Usual parameter for calculation of index**		**Countries where used**
					Section length	**Filtering bases**	
Elevation y (x)	Mean of absolute values of differences between measured profile and filtered profile	CAPL25 (F; APL)	No†	Those contained in the profile. The influence of the longest is dominant	25 m	The measuring speed (6m/s) of the APL25 limits the wavelengths detected to 20m	France, and all countries using the APL25
		CP_b (B; APL)	Sliding mean with base length b (low pass wavelength filter)	Up to at least 2b (65% attenuation at 2b)	100 m	b=2.5m, 10m, 25m, 40m	Belgium France Morocco
	RMS deviation between the measured profile and the filtered profile	RMSD (UK; HRM and TRRL beam)	Sliding mean with base length b (low pass filter)	Up to at least 2b (65% attenuation at 2b)		b=1.8m to calibrate the bump integrator b=3m, 10m, 40m	UK France
		Energy and APL72 index (F; APL)	Electronic filters, pass band b1-b2	b1-b2	200 m	b1-b2=1-3.3m b1-b2=3.3-13m b1-b2=13-40m	France Morocco
Slope dy (x)/dx	Mean of absolute values ("quarter car analysis")	RARSv (USA; GM profilometer)	No but influence of speed, v, taken into account	Depends on model parameters, in particular speed, v	Not fixed	NCHRP parameters, v-50km/h, 80km/h. IRI is calculated with v=80km/h	USA Sweden Finland Denmark
	Slope variance	SV (USA; CHLOE)	No	Those contained in the profile	Not fixed	Slope calculated for 25cm segments	USA France Netherlands Germany Switzerland etc.
Spatial acceleration $d^2y(x)/dx^2$	Root mean square (RMS)	$RMSVA_b$ (USA; topo-graphic $QI_T=k_1x$ $RMSVA_{b1}+K_2$ $RMSWA_{b2}+k_3$§	Method of rolling straightedge of length 2b	Wavelength up to 4b	Not fixed	b1=1.0m b2=2.5m	USA Brazil France etc.

* Country where index was developed and system that delivered the profile for which the index was developed.

† In the case of APL profile surveys, wavelengths in excess of v/0.3 (where v is the measuring speed in m/s) are filtered out when the measurement is made.

§ A special version of the QI_T is used in the USA (Texas) in which the results are in inches/mile; it is called "MO", and the filtering bases are b_1 = 1.22 m and b_2 = 4.88 m.

NCHRP = National Cooperative Highway Research Program

International research has made many attempts to correlate longitudinal evenness indices. The list includes:

- PIARC study in Switzerland, 1972 (PIARC 1975)
- International road roughness experiment (IRRE) in Brazil, 1982 (Sayers et al. 1986b)
- Joint study United Kingdom/Belgium, 1982/83 (Cooper 1985)
- Ann Arbor profilometer meeting in the US, 1984 (Sayers and Gillespie 1986)
- Joint study France/United Kingdom in France, 1985 (Bonnot and Boulet 1987).

The conclusions of these correlation studies, which involve a large number of devices and indices, are not given in this report.

4.3 Accuracy and Resolution Requirements

Although accelerometers and pendulums are often distinguished as "absolute" instruments, they also invariably measure the motion of a "sprung" mass, just as do "response type" instruments. Spatial and frequency filtering is therefore inherent in the so-called "absolute" systems too. The differences in the two categories are really differences in the natural responses of the two types of systems.

The "absolute" systems have flat, or controlled, responses over a temporal frequency range corresponding to or exceeding the range of frequencies produced by traversing the undulation wavelengths relevant to road roughness at measurement speeds.

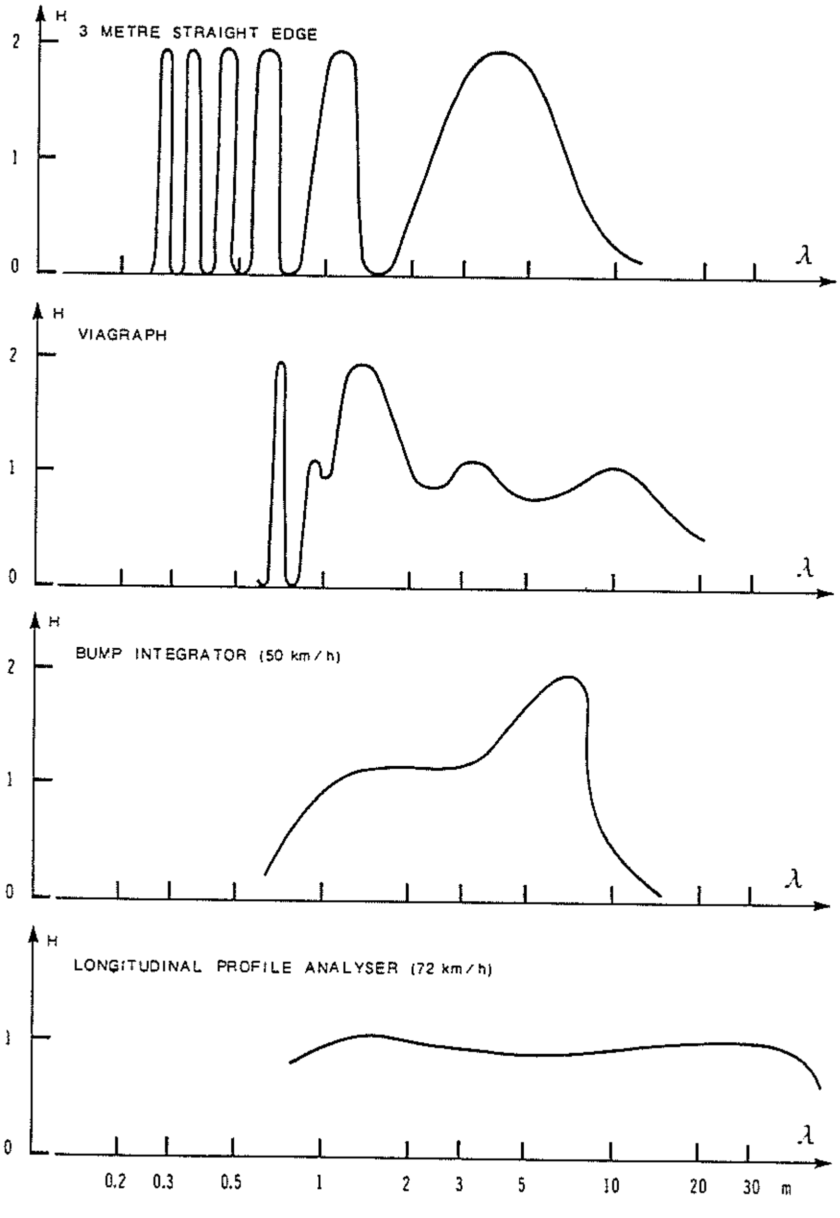
The "response type" instruments have responses with resonance peaks inside the desired range. As is well known, the response behaviour of a mechanical system is most sensitive to minor perturbations in its element properties in the vicinity of its resonances. For these and other previously mentioned reasons, there have been difficulties in maintaining calibration of the "response type" instruments. Moreover, the reduced sensitivity of "response type" systems to undulations at wavelengths corresponding to off-resonant frequencies makes accurate reconstruction of the true road profile by inverse filtering difficult. The necessary inverse filters magnify measurement errors in this wavelength regime.

Figure 4.7 shows representative transfer functions for four commonly used road roughness measuring devices. The transfer function gives the ratio between the signal recorded and the amplitude of the defect as a function of wavelength. Ideally the transfer function must be as flat as possible because the "peaks" will over-estimate certain defects and the "troughs" will exclude the assessment of others.

Profilometers have been grouped into four classification classes. These classes enable roughness measurement methods to be categorised on the basis of how directly their measures pertain to IRI, which in turn affects the calibration requirements and the accuracy associated with their use.

Figure 4.7 Transfer functions of four road roughness measuring devices (OECD 1984).

H = transfer function, λ = wavelength



Class 1 profilometers. Basically, profilometers rated class 1 in connection with *"The International Road Roughness Experiment"* (Sayers et al. 1986b) give the highest obtainable accuracy of measurement. These instruments are static devices such as rod and level, the dipstick, the TRRL beam, and the like. For practical and economic reasons they are less suitable when lengthy road sections are to be measured. Furthermore they are more sensitive to operator errors than is the case for more automatic measurement methods.

Class 2 profilometers. In a decreasing scale of accuracy, class 2 profilometers includes all "true" profilometers, i.e. all devices capable of producing a geometric representation of the longitudinal road profile. However, this class contains a variety of devices with very different accuracies.

Note that profilometers rated class 1 yield less than 1.5% bias in the IRI numeric, whereas those in class 2 yield less than 5% bias.

Class 3 profilometers. A method for measuring roughness qualifies as class 3 if it uses the "calibration by correlation" approach. RTMs qualify as a class 3 roughness measurement method, as do any instruments capable of generating a roughness numeric reasonably correlated to the IRI. Typical bias in the IRI numeric is about 14%, although this bias varies both with roughness and surface type.

Class 4 profilometers. The final class pertains to subjective ratings and uncalibrated measures. Uncalibrated RTMs fall within this class.

Generally, information about the accuracy of existing profilometers seems to be almost unobtainable, while the resolution of the equipment is frequently stated. This is not surprising, as the statement about the accuracy of the recorded profile in terms of amplitude would call for a comparison with a very accurately measured and very closely sampled profile. A practical method for such reference measurements would be to use the dipstick or some other type of class 1 profilometer. The only high speed profilometer for which an accuracy statement has been found is the TRRL HRM.

The requirement for profile measurement accuracy is dictated by the targeted accuracy for the prediction of the dynamic wheel load variation. Supposing a linear system, an X% accuracy of wheel load prediction would call for an X% accuracy of profile amplitude measurement. A required accuracy of 10% would probably be met by laser profilometers of the GMR type, at least for wavelengths longer than 0.5 m.

The road profile wavelengths exciting the bounce resonance frequency of heavy vehicles, typically 1.5-3.5 Hz corresponding to wavelengths 5.5-13 m at 70 km/h, would be measured to satisfactory accuracy with any good quality high speed profilometer.

4.4 Summary

Numerous devices have been developed to survey directly or indirectly the longitudinal profiles of roads and bridges. Profilometer devices, more particularly the dynamic profilometers, present many advantages at an operational level through high measurement speed and stability of the operational and measuring characteristics. Laser-based profilometers also lend themselves to the measurement of joints between road pavements and bridge decks and, if very high data acquisition rates are employed (greater than 16,000 samples/sec), the macrotexture of the pavement can be simultaneously recorded.

5. ROAD PROFILING EQUIPMENT CURRENTLY USED IN FRANCE

5.1 Background

5.1.1 Road Surfaces in France

In France, high quality roads are regarded as being of great social and economic importance, with the result that every municipality sets a goal of having the smoothest and safest roads in the country (Y. Delanne, pers. comm. 1994). As a consequence, the French Road Research Laboratories (Laboratoire Central des Ponts et Chaussées, LCPC) has led the world in investigation of surface properties, because road surface quality affects driver comfort and vehicle operating costs.

As previously discussed, surface quality of pavements and bridges is important in regard to skid resistance, tyre wear, rolling resistance, and the dynamic behaviour of vehicles. Surface irregularities may be classified on the basis of their geometric characteristics, as summarised in Table 5.1.

Table 5.1 Classification of road surface irregularities on the basis of their horizontal and vertical dimensions (PIARC 1987).

Profile texture		**Range of dimensions**	
		Horizontal	**Vertical**
Microtexture		0 - 0.5 mm	0 - 0.2 mm
Macrotexture		0.5 - 50 mm	0.2 - 10 mm
Megatexture		50 - 500 mm	1 - 50 mm
Unevenness	Short wavelengths	0.5 - 5 m	1 - 20 mm
	Average wavelengths	5 - 15 m	0.5 - 5 cm
	Long wavelengths	15 - 50 m	1 - 20 cm

5.1.2 Effect of Road Surface on Riding Comfort

One of the most important amenities a road can offer the user, whether driver or passenger, is riding comfort (OECD 1984).

The conception of comfort is particularly subjective as every road user will assess it in terms of the vehicle he/she is driving, and his/her judgement will depend on such factors as speed, driving habits, trip purpose and length, etc. Therefore there is no exact correlation between evenness measurements and the assessment by users as revealed by surveys. Comfort is most often evaluated quantitatively in terms of the accelerations felt by the vehicle passenger over a certain range of frequencies.

However, comfort is not only a question of subjective assessment. Ergonomic studies have revealed links between certain vibrations and a number of physiological disturbances such as loss of visual acuity or attention, changes in breathing and heart activity, experienced as "carsickness". The frequencies at which these disorders occur lie between 2 and 15 Hz corresponding to wavelengths of between 1.3 and 10 m (for a speed of 72 km/h). Some frequencies may be amplified by resonance phenomena within this range: this can occur for the vehicle chassis (1-3 Hz) and for the passenger on his/her seat (5-10 Hz). Table 5.2 indicates the range of wavelengths that affect driving comfort for different speeds.

Table 5.2 Wavelength ranges affecting driving comfort and road safety respectively (OECD 1984).

Speed (km/h)	**Wavelength range (m) affecting principally**	
	Road safety	**Driving comfort**
40-60 (urban)	0.6 to 1.6	3.7 to 16.6
90 (national road)	1.25 to 2.5	8.3 to 25
130 (motorway)	1.8 to 3.5	12 to 25

Both the level of acceleration and its spectral composition to which the passenger is subjected are a function of road profile, speed, suspension and seat characteristics. The amplitude of evenness defects that can be considered "acceptable" depends on speed, range of wavelength, type of vehicle concerned, and length of journey. Evenness requirements therefore are more stringent for motorways than for local roads.

For short wavelengths (1-3 m) and for a "light" motor vehicle, the perception threshold corresponds to an amplitude of the order of a millimetre, and the discomfort level would be in the order of 6 mm. For longer wavelengths (13-40 m) the corresponding values would be 5 and 50 mm.

Table 5.3 gives examples of thresholds that were considered acceptable as derived from a survey of users of the French road network (OECD 1984).

Table 5.3 Average amplitudes of evenness defects considered to be acceptable or unacceptable (from OECD 1984).

Thresholds	**Wavelengths**		
	Very short 1 to 3.3 m	**Short 3.3 to 13 m**	**Long 13 to 40 m**
Acceptable	2 mm	4 mm	14 mm
Unacceptable	3 mm	8.5 mm	27 mm

5.1.3 Effect of Road Surface on Safety

Another area in which evenness can affect safety is skid resistance, for two reasons:

1. In rain the water film on the pavement significantly reduces the coefficient of friction between tyre and pavement, especially at high speed. In extreme cases this may lead to aquaplaning. Poor evenness, especially rutting, can impede proper drainage (PIARC 1975).

2. The skid resistance, which is available for braking and maintaining a vehicle in its path, depends not only on the road surface and the tyre, but also on the vertical force applied to the wheel. Any oscillations caused by surface irregularities bring an additional random component to this force which can result in variations in turning and deceleration forces. This phenomenon is particularly marked at frequencies similar to those causing resonance in the non-suspended parts of the vehicle such as the wheels, i.e. around 10-15 Hz corresponding to wavelengths of between 1 and 4 m according to speed.

Table 5.2 presents the range of wavelengths for different speeds, which is of particular importance to road safety.

5.1.4 Requirements of a Road Surface

In summary, a road surface should meet a certain number of requirements:

- A safety obligation, related to the alignment, to the quality of vehicles, and to construction specifications related to drainage and skid resistance.
- A comfort obligation to reduce fatigue and disturbances caused by vehicle body and tyre vibrations.
- An overall economy obligation to reduce the social cost of accidents, the cost of construction, the cost of maintenance, and the cost of operating a vehicle.

These obligations must be met as soon as the road is opened to traffic, and also throughout its service life. For pavement maintenance, the roading agency must consequently follow the evolution of surface characteristics relative to these obligations. In France, as in New Zealand, these characteristics are essentially:

- wet pavement skid resistance
- evenness/roughness of pavements.

Rolling noise and rolling resistance are not considered during the surveying of pavements. These characteristics only come into play when the decision about the nature of resurfacing work has to be made because the road surface has become too rough.

It is therefore of interest to briefly review devices used in France for surveying surface characteristics relative to user safety and comfort. Such surveys have been carried out since 1974 and so considerable experience has been gained about the operation of different commercially available devices. The following two sections are excerpts taken from correspondence received from Dr Michel Boulet of the LCPC.

5.2 Texture Measurement

"To provide effective measurement of texture depth, two pieces of equipment based on laser technology are used. The first, the Mini Texture Meter (MTM) manufactured in the United Kingdom by WDM Ltd, is a hand operated device used for the control of road works. For monitoring the rate of deterioration of texture on in-service pavements, LCPC have developed a specialised high speed apparatus, the RUGOLASER, which employs a non-contacting 32 kHz diode laser detector. The measurement is generally carried out as a single longitudinal scan of the kerbside wheeltrack. The texture profile is recorded in 12.5 cm (6 inch) segments, separated by 12.5 cm gaps. Calculated in real time are the arithmetic (Ra) and quadratic (Rq) means of the profile amplitudes with the results averaged over 10 m intervals. The RUGOLASER must be attached to a vehicle. In particular, it is attached to the SCRIM, also manufactured by WDM Ltd, for the simultaneous measurement at 60 km/h of the average texture depth and the sideways force coefficient (SFC), and also the multi-functional SIRANO (Systeme d'Inspection des Routes et Autoroutes per Analyses Numériques et Optiques - Optical and Numerical Analysis and Inspection System for Roads and Motorways) apparatus designed by LCPC which provides simultaneous measurements at 72 km/h of longitudinal and transverse roughness, macrotexture and road geometry. Measurements with the RUGOLASER can be made up to vehicle speeds of 100 km/h.

"For both the MTM and RUGOLASER, and in fact for all equipment using laser optics, the road surface must be absolutely dry and preferably not glossy." (M. Boulet, pers. comm. 1992).

5.3 Longitudinal Roughness Measurement

"France has employed profilometers of various types (the 3 m rolling edge, the Viagraph, and the APL (longitudinal profile analyser)) over the years. The APL has been in use for 20 years and is the main apparatus for continuous measurement of the longitudinal roughness of pavements. The APL is made up of one or two lightweight trailers towed by a powerful vehicle. Each trailer records the longitudinal profile along a line in each wheeltrack (two trace version with two trailers), or either in a wheeltrack or on the crown of the road (when using a single trailer). The signal is recorded as a set of numbers in 5 cm steps.

"Measurements are generally carried out at 21.6 km/h (to detect wavelengths from 0.5 to 15 m, APL25) for road works, and at 72 km/h (to detect wavelengths from 1 to 45 m, APL72) for annual pavement surveying programs. From the resulting profiles it is possible to calculate the majority of roughness indices in use around the world. The use of the APL trailer is not affected by wet weather conditions." (M. Boulet, pers. comm. 1992).

5.4 Summary

5.4.1 Monitoring for Roughness

Although New Zealand pursues a policy similar to France for constructing and maintaining roads, it is clear that efficient and rational control and monitoring of roughness is possible only by classifying roughness by wavelength. This permits a systematic approach to assessing, classifying and localising surface defects both at the construction stage and when monitoring the serviceability of the network under traffic. New Zealand's reliance on the NAASRA roughness meter, which is a response type meter, precludes the opportunity to investigate the wavelength content of the measured roughness. Using this instrument means it is not possible to distinguish road sections with profiles which are detrimental to driving comfort, safety and dynamic wheel loads.

5.4.2 Monitoring for Skid Resistance

Another significant difference is in the monitoring of wet pavement skid resistance. The parameters that play a role in tyre-to-road friction are well known. They are associated with:

- surface texture (micro and macrotexture);
- the vehicle (speed, tyres);
- weather conditions (surface water film, season, temperature).

Surface texture characteristics may change under the action of traffic. It is therefore important to periodically evaluate these changes using high output measuring equipment. In New Zealand, SCRIM surveys of the state highway network have recently begun. However, the measured sideways force coefficient (SFC) has been found to correlate well only with microtexture (Sandberg 1990). Based on the French experience and that of other countries, the average texture depth has to be measured in conjunction with SFC to obtain a more reliable assessment of the wet pavement skid resistance characteristics of New Zealand roads.

Also France conducts SCRIM/RUGOLASER network surveys more frequently (two yearly intervals) than APL roughness network surveys (four yearly intervals). In comparison, New Zealand presently conducts yearly NAASRA roughness network surveys, with the first SCRIM survey undertaken in 1990 and the next is scheduled for 1994/95 summer season. This suggests that France's network maintenance policy is safety driven, whereas in New Zealand it is driven by economics (maintenance costs/vehicle operating costs).

Table 5.4 summarises the relationship between road irregularities and road user qualities. There are two categories of irregularities: one that must be present (microtexture and macrotexture), and another whose presence is undesirable (megatexture and roughness). The limit between the two is approximately 50 mm of wavelength.

5.4.3 Monitoring for Safety

Pavement performance specifications concerned with safety have been recently introduced by Transit New Zealand. These are specifically related to skid resistance (through minimum polished stone value (PSV), for roading aggregates which are based on requirements to achieve desired skid resistance under different traffic conditions) and water drainage (through macrotexture depth as measured by the sand circle test). As it will take some time for these regulations to take effect, more frequent network surveys of skid resistance and macrotexture than is presently practised are advocated.

5.4.4 Detrimental Effects of Roughness

Megatexture and roughness have a detrimental effect on road holding, noise and vibration, and extra fuel consumption from increased rolling resistance. Both megatexture and short wavelength roughness can originate from the construction process, e.g. vibrations of the paving machine, the action of the smoothing beam, etc., or it can be a by-product of the way macrotexture is achieved. The introduction of megatexture and short wavelength roughness specifications for road construction should therefore be considered.

Table 5.4 Effects of road irregularities (Delanne 1994).

Road irregularities	Dynamic comfort	Safety	Noise/vibration	Fuel Consumption
Long wavelength, 15-50 m	Bad	Bad	Not directly related	Bad
Medium wavelength, 5-15 m	Bad	Bad	Not directly related	Bad
Short wavelength, 0.5-5 m	Very bad	Very bad	Bad	Very bad
Megatexture, 0.05-0.5 m	Very bad	Very bad	Very bad	Bad
Macrotexture, 0.5-50 mm	Not related	Good for high speed	Very bad	Bad
Microtexture, <0.5 mm	Not related	Good for high speed	Not directly related	Not directly related

Medium and long wavelength roughness is sometimes associated with poor quality initial construction, but is more often caused by load or environment induced pavement deformation in any of the layers, from surfacing to subgrade. Measurement of roughness over 5 m wavelengths can be used to monitor the structural condition of the road as a warning of impending structural distress.

5.4.5 Roughness Surveys of New Zealand Roads

Roughness surveys of the entire state highway network in New Zealand have been performed on an annual basis since 1984. Although the NAASRA roughness numeric obtained has proved useful for allocating maintenance and rehabilitation funding, it does not allow the type and the cause of the pavement roughness condition to be recognised. For example, where two road sections are characterised by the same NAASRA roughness value, one may be very smooth except for the occasional severe pothole, while the other may have an unbroken surface with long "waves" which result from instability of the subgrade.

The French solution of measuring roughness over different discrete wave bands addresses this type of problem, and a similar approach should be adopted for New Zealand to allow better identification of road sections requiring treatment.

6. CONCLUSIONS AND RECOMMENDATIONS

Systems and methods for measuring the texture profile of pavements vary widely from country to country and sometimes within a country. This report therefore has attempted to cover the main measurement principles employed and to catalogue commercially available profilometric instruments. It should be noted that not every request for information from suppliers was replied to and so the instrument listings provided are not exhaustive. Furthermore, a comparative assessment of instrument performance is not included as the results from the PIARC international experiment to compare and harmonise texture and skid resistance measurement were not published until late 1995 (PIARC 1995b). Nevertheless, the following conclusions and recommendations can be drawn from the review undertaken of the work available before 1995.

6.1 Need for Describing Texture Profiles of Pavements

Requirements for pavement performance have traditionally centred on safety, but are currently being extended to such concerns as the environment, comfort and user costs. The following aspects must now be considered:

- For safety: skid resistance, road holding qualities, splash and spray reduction, and visibility of the pavement and pavement markings.

- For economy: reduction of fuel consumption, tyre and vehicle wear, and dynamic loads that may shorten the life of the pavement.

- For user comfort and the environment of roadside residents: reduction of tyre noise and vibrations inside and outside vehicles.

Each feature of pavement performance is chiefly or partly determined by surface irregularities over different wavelengths, which span from microns to tens of metres.

Recommendation: Valid methods for measuring surface irregularities are highly desirable so that the relationships between characteristics of common New Zealand pavement surfaces and their performance with regard to safety, environmental impact, comfort and user cost can be better understood, leading to improved surfacing design and construction.

6.2 Profilometric Methods

Texture profile characterisation can be best affected by combining modern laser or light sectioning profilometric methods with spectrum analysis. This approach allows the texture profile to be effectively described as a continuous function of wavelength. However, no instrument in present use is capable of measuring the complete texture profile of a pavement surface. For technical reasons, current generation profilometric instruments can cover only a limited range of wavelengths associated with microtexture (<0.5 mm), macrotexture (0.5 mm to 50 mm), megatexture (50 mm to 500 mm), and roughness (0.5 m to 50 m).

A continuous spectrum over the entire range of road surface texture wavelengths of interest (from microns to tens of metres) can only be generated by combining several spectra pertaining to specific wavelengths, given current technology.

Recommendation: Profilometric instruments used for research purposes should therefore be selected which allow some degree of overlap in measured wavelengths, to enable precise matching of spectra over the duplicated wavelengths.

6.3 Validation of Profilometric Instruments for Measuring Surface Irregularities

Profilometers must be validated at some time to prove their accuracy. A "calibration by correlation" approach is advocated, necessitating reference instruments with which to compare the measurements. These reference instruments ideally should not change over time.

Recommendation: The following instruments are recommended to provide baseline measurements of profile texture for comparison purposes.

- Microtexture: Mechanical needle profilometers are at present the only devices capable of reliably generating texture spectra with high resolution in the microtexture range.

- Macro/Megatexture: A stationary laser profilometer, such as developed by the Swedish Road and Traffic Research Institute (VTI), has two significant advantages over vehicle-based systems in this application:

    1. It measures relative amplitude with respect to a stationary beam instead of a vehicle body, and so pavement-induced vibration effects have a negligible influence; and

    2. Greater horizontal resolution is possible because it is run at much slower measuring speeds, which results in a better definition of the profile's peaks and troughs.

- Roughness: At the present time, only devices like the rod and level, the TRRL beam, and the dipstick have been demonstrated to give the highest obtainable accuracy of roughness measurement. As such, these devices are rated class 1 profilometers in connection with the IRRE (International Road Roughness Experiment) and so are suitable for determining reference IRI values over a broad range of roughness levels and road types. Considering the relative merits of these class 1 profilometers, experience to date suggests that the dipstick is more appropriate than the TRRL beam for establishing the reference roughness for calibrating roughness meters. However, its reliability in field situations has proven a little suspect.

All the recommended instruments provide a voltage output directly proportional to the relative amplitude which, once digitised, can be processed to yield any measure required.

6.4 Megatexture and Short Wavelength Roughness Pavement Specifications

Megatexture and roughness wavelengths which approach the footprint length of the tyre have a detrimental effect on road holding, noise and vibration, and extra fuel consumption from increased rolling resistance. Both megatexture and short wavelength roughness can originate from the construction process, e.g. vibrations of the paving machine, the action of the smoothing beam, etc., or it can be a by-product of the way macrotexture is achieved.

Recommendation: The introduction of megatexture and short wavelength roughness specifications for road construction should be considered to complement existing Transit New Zealand skid resistance and water drainage-related texture specifications.

6.5 Network Monitoring of Skid Resistance

Two parameters need to be simultaneously measured:

- Friction of the wet pavement (at a fixed standard measuring speed) and
- Mean macrotexture depth.

The two parameters can define the friction available at the test speed and estimate the friction–speed gradient, which is closely related to the drainage capacity of the pavement, so that the friction available at a particular traffic speed of interest can be calculated. The macrotexture depth alone cannot define the friction–speed gradient in all circumstances, with friction course surfaces being the notable exception.

The most popular instrument system for this purpose is the Sideways Force Coefficient Routine Investigation Machine (SCRIM) fitted with a laser-based profiling system to measure macrotexture. However, a recently proposed alternative is to measure the difference between blank and ribbed tyre friction in a locked wheel, necessitating the use of a two wheel skid trailer. The ribbed tyre measures the drained skid resistance (friction related to microtexture), while the blank tyre measures the undrained skid resistance (friction related to macrotexture). This concept merits further evaluation as it is applicable to friction course surfaces, whereas the laser SCRIM system is not because of the inability of lasers to measure the drainage potential of porous surfaces.

Recommendation: The suitability of two wheel skid trailers and/or variable slip skid testers for measuring, at a network survey level, the friction–speed gradient of porous surfaces, as well as the more prevalent surface types found on state highways, should be investigated.

The reliable determination of the friction–speed gradient for all surface types will enable the reporting of the condition of the entire state highway network in terms of the recently established International Friction Index (IFI) which combines both microtexture and macrotexture effects.

6.6 Network Monitoring of Roughness

Efficient and rational control and monitoring of roughness can be best effected by classifying roughness by wavelength. This allows a systematic approach to assessing, classifying and locating surface defects both at the construction stage and when monitoring the serviceability of the network under traffic. AEIPR (Accelerometer Established Inertial Profiling Reference) systems have a high throughput of data (typically 600 samples/second/channel) necessitating high speed real time signal processing to minimise data storage requirements. Usually only the amplitude of the road surface at a given distance along the test section of the road is generated in real time. These road profile data are then post-processed to provide a single roughness numeric which can be used to characterise the roughness of the test section.

The most common roughness numeric generated by AEIPR systems, such as the ARRB laser profilometer, ARAN and the laser RST, is the IRI which is based on a quarter car simulation. The IRI analysis acts as a filter, eliminating all possible information outside a 1.3-30 m waveband, and constituting the roughness felt by a passenger car at speeds near 80 km/h. However, other roughness measures may serve as better indices of various qualities of pavement condition or specific components of vehicle cost.

The discrete waveband analysis applied by the French LCPC appears to hold the most promise, because the spectral content of the road is investigated through numerics that are more suited for survey purposes than power spectral density functions. In the LCPC analysis, the road profile signal is fed into three band pass filters to obtain road profiles at short, medium and long wavelengths (1.0-3.3 m, 3.3-13 m, 13-40 m) corresponding to road safety, driving comfort, and pavement subgrade stability considerations. The signal from each filter is squared and integrated over a road test length of 200 m to obtain three distinct energy values. The energy values in each waveband are indicative of the road roughness within the specific band. In France, a rating index scale ranging from 1 (the worst) to 10 (the best) has been developed based on the energy levels measured with this technique.

Recommendation: Transit New Zealand should require analyses of road roughness measurements in terms of different discrete wave bands, in addition to generating IRI or NAASRA roughness numerics as at present. This will enable the type and cause of the pavement roughness condition to be identified, leading to more effective utilisation of maintenance budgets.

6.7 Comparison of Road Profiles Recorded by Dynamic Profilometry

It is essential that the same range of wavelengths are covered when comparing road profiles and the associated power spectral densities or roughness numerics obtained by different dynamic profilometers or the same profilometer at different measuring speeds, For most uses, a wavelength range between 0.15 and 60 m (0.5 and 200 ft) has proven adequate.

Recommendation: Transit New Zealand should insist that, whenever dynamic profilometry is being used to measure longitudinal roughness, the shortest as well as the longest wavelength included in the filtered road profile should be specified. The extreme wavelengths should remain invariant with speed over the profilometer's normal operating speed range.

6.8 Control of Pavement Construction

A roading contractor is required (as at 1996) to demonstrate compliance with polished stone value (PSV) and macrotexture depth requirements specified by Transit New Zealand. To improve the overall performance of New Zealand pavements, contractors should also know how their construction techniques influence the megatexture and roughness of the road surface that is finally produced. Ideally for the contractor, texture profile methods for the control of road works should be simple, comparatively inexpensive, require minimal calibration, and be able to make fairly rapid measurements of reasonable accuracy.

Recommendation: The following measuring methods are therefore recommended:

- **British Pendulum Tester:** Measures wet pavement friction at 10 km/h as a surrogate for microtexture. Directly correlated to PSV.

- **Outflow Meter** (fitted with electronic timer to measure outflow time): Measures surface drainage of all surfacing types, including friction course. Outflow duration has been shown to be strongly correlated to MPD and RMS texture measures.

- **Volumetric Patch Method:** Measures mean texture depth of non-porous surfaces. For international standardisation, only glass spheres have been recommended. Consideration should therefore be given to replacing the sand circle method specified by Transit New Zealand Standard Test Procedure T/3 (TNZ 1981) with ASTM Test Designation E965-87, which is based on the use of glass beads and is less operator dependent.

- **MERLIN:** Measures roughness over wavelengths greater than 1.8 m. Provides a good estimate of roughness in terms of IRI.

- **ARRB Walking Profilometer:** Measures roughness wavelengths greater than 0.25 m, hence it is suitable for controlling the upper end of megatexture. Conforms to class 1 profilometer requirements.

Use of non-contact texture measuring equipment, based on laser or other electro-optical or sound transmission principles, is not advocated until the manufacturers of this equipment can demonstrate full compliance with the ISO standard for characterisation of pavement texture. This standard is being prepared with the aim of standardising sampling requirements and analysis of texture data (ISO/TC43/SC1/WG39, 1994).

6.9 Yandell-Mee Texture Meter

The Yandell-Mee texture meter is still in its developmental phase but appears to be a very promising stationary device for measuring microtexture, macrotexture and megatexture (i.e. 0.05 to 600 mm wavelengths). Its high degree of automation, coupled with flexibility in processing the acquired profile data, makes this device suitable for both construction and research purposes. However the Yandell-Mee texture meter was not included in the PIARC (1995b) international experiment.

A series of limited evaluation trials were conducted at WCL when the meter became available for one month (in July 1995). These trials are part of Stage 2 of Transit New Zealand Research Project PR3-0134, *Frictional interaction between tyre and pavement*, and preliminary results were presented by Cenek et al. (1996) at the PIARC Third International Symposium (PIARC 1996). The trials assessed the meter's comparative performance under New Zealand conditions, and its correlations with other devices for measuring pavement friction and macrotexture.

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ASTM Test Designation E303-83. Standard test method for measuring surface frictional properties using the British pendulum tester.

ASTM Test Designation E501-76. Specification for standard tyre for pavement skid resistance tests.

ASTM Test Designation E524-76. Specification for smooth tread standard tyres for special purpose skid resistance tests.

ASTM Test Designation E670-87. Standard test method for side force friction on paved surfaces using the Mu meter.

ASTM Test Designation E770-80. Standard test method for classifying pavement surface textures.

ASTM Test Designation E867-89. Standard definitions of terms relating to travelled surface characteristics.

ASTM Test Designation E950-83. Standard test method for measuring the longitudinal profile of vehicular travelled surfaces with an inertial profilometer.

ASTM Test Designation E965-87. Standard test method for measuring surface macrotexture depth using a volumetric technique.

ASTM Test Designation E1082-90. Standard test method for measurement of vehicular response to travelled surface roughness.

ASTM Test Designation E1170-91. Standard practices for simulating vehicular response to longitudinal profiles of a vehicular travelled surface.

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APPENDIX 1

TECHNICAL SPECIFICATIONS OF COMMERCIALLY AVAILABLE ROAD TEXTURE AND PROFILE MEASURING INSTRUMENTS

Selected instruments taken from PIARC Publication 01.03.B, 1995a,
and listed in alphabetical order

EQUIPMENT:	Acoustical Imaging System
OPERATION:	Ultrasound generator transmits ultrasound down to road surface and receives the echo. The measured travel time, or phase difference, is a function of the displacement of the surface
PARTS:	1 MHz ultrasound generator and transmitter signal receiver and transducer, horizontal moving device for transducer, frame
OUTPUT:	Surface profile
MEASURE:	Acoustical signal travel time
SPEED:	150 mm trace may take
NO.OPERATORS:	1
RESOLUTION:	1% of wavelength vertical, 0.3 mm horizontal
RATE:	
METHOD:	Texture spectra
USERS:	Netherlands
OPERATIONS:	Profile
COST:	
ADVANTAGES:	The sound spot size may be decreased to allow microtexture measurement
DISADVANTAGES:	Sound speed fluctuates with air density and temperature. Slow for getting good precision and resolution.
COMMENTS:	Needs considerable development effort for field use at reasonable speed
CONTACT:	R Breeuwer, J Vogel (head, Instrumentation Department) TNO-Institute of Applied Physics P O Box 155 2600 AD Delft THE NETHERLANDS Phone: 31 15 692 000 Fax: 31 15 692 111

EQUIPMENT:	CRR Static Optical Profilometer
OPERATION:	Measures the displacement of the road texture with respect to a beam structure supported by 3 small rubber tyres
PARTS:	Laser sensor, trailer, processing unit, computer
OUTPUT:	Profile curve, profile spectrum, texture depth
MEASURE:	Digital output of relative height
SPEED:	1.5 min. per measurement
NO.OPERATORS:	2
RESOLUTION:	0.05 mm vertical, 2 mm wavelength
RATE:	Trailer can be moved to any spot location
METHOD:	RMS of texture height. Also simulated sand patch texture depth calculation. Spectrum analysis.
USERS:	CRR, Belgium
OPERATIONS:	Profile
COST:	
ADVANTAGES:	Macrotexture and megatexture
DISADVANTAGES:	Cannot cover 0.5-2 mm wavelength. Large survey is impractical. Cannot use in wet weather.
COMMENTS:	Prototype only.
CONTACT:	G DESCORNET, Belgian Road Research Center, 42, Bd de la Woluwe, B - 1200 Brussels BELGIUM Phone: 32 - 2 - 767 51 11 Fax: 32 - 2 - 772 33 74

EQUIPMENT:	Defocalisation Sensor
OPERATION:	Sensor interprets the area of projected light spot which is proportional to surface height
PARTS:	Laser beam splitter, sensor, processing unit
OUTPUT:	Profile
MEASURE:	Digital output of light spot area
SPEED:	70 km/h for 1 mm lower wavelength
NO. OPERATORS:	1
RESOLUTION:	0.05 mm vertical. Depends on light spot size longitudinal.
RATE:	Arbitrary
METHOD:	
USERS:	LCPC, France
OPERATIONS:	Profile
COST:	
ADVANTAGES:	Free of drop-out due to shadow, small light spot, high speed possible
DISADVANTAGES:	Requires dry surface. Sensitive to light reflection properties within the light spot area.
COMMENTS:	Measuring principle still under development
CONTACT:	LCPC (Laboratoire Central des Ponts et Chaussées, National Road Research Laboratory) Pavement Maintenance Management Division Centre de Nantes BP 19 - Route de Pornic 44340 BOUGUENAIS (FRANCE) Phone: 40 84 58 37; Fax: 40 84 59 98; Telex: 710 805 F

EQUIPMENT:	DIRA Tester
OPERATION:	Low contact scanning by special process
PARTS:	Intermittent needle scanner with step motors, computer
OUTPUT:	Digital data of profile curve
MEASURE:	Vertical displacement
SPEED:	up to 5 points per s (second)
NO.OPERATORS:	1
RESOLUTION:	0.002 mm vertical; to 0.002 mm horizontal; stylus radius to 0.005 mm
RATE:	Depends on measurement purpose, usual trace length 200 mm
METHOD:	Texture spectra
USERS:	West Germany
OPERATIONS:	Profile
COST:	US$30,000 approximately
ADVANTAGES:	Enables texture spectral analysis down to rather short wavelength with high resolution. No surface damage.
DISADVANTAGES:	Very slow
COMMENTS	High resolution scanning on electrically conductible prints of the road surface. Laboratory analysis only.
CONTACT:	

EQUIPMENT: Drainoroute
OPERATION: Continuously measures the horizontal drainability of road surface by measuring the water outflow under a metal pad skidding on the pavement.
PARTS: Water tank, flow meter, and metal pad mounted on a trailer towed by a car.
OUTPUT: Drainoroute Coefficient (O to 100%)
MEASURE: Flow (100% = max flow without contact with the surface)
SPEED: 30 km/h
NO.OPERATORS: 1 or 2
RESOLUTION: <1%
RATE: Continuous measurement. Standard average value each 5m or 10m of road.
METHOD: One or two lanes of measurement (100 m to 5 km)
USERS: France
OPERATIONS:
COST: 200,000 FF (equipment and trailer without car)
ADVANTAGES: Very high resolution and sensitivity. Results are independent of speed.
DISADVANTAGES: Low speed requires measurement during low traffic periods or under traffic control
COMMENTS:
CONTACT: LCPC (Laboratoire Central des Ponts et Chaussées, National Road Research Laboratory)
Pavement Maintenance Management Division
Centre de Nantes
BP 19 - Route de Pornic
44340 BOUGUENAIS (FRANCE)
Phone: 40 84 58 37; Fax: 40 84 59 98; Telex: 710 805 F

EQUIPMENT: FHWA Texture Equipment
OPERATION: Light sectioning. Vertical light projection, 45° camera angle. 100 mm transverse macrotexture profile.
PARTS: Strobe and lens system, video camera, supporting frame
OUTPUT: Digital data, statistical profile information
MEASURE: 2 dimensional image on videotape
SPEED: 90 km/h
NO.OPERATORS: 2
RESOLUTION: At 90 km/h 0.25 mm; at 60 km/h 0.12 mm
RATE: 10 Hz, 100 mm long. sections of 2% of the pavement at 90 km/h or 3% of the pavement at 60 km/h
METHOD: Computer post-processing to calculate profile statistics
USERS:
OPERATIONS: None
COST:
ADVANTAGES: Iterative operator interaction is reduced to a minimum
DISADVANTAGES: Limited resolution
COMMENTS: Still in the development stage, but some tests have shown that it can perform very well
CONTACT: R R Hegmon
FHWA, HNR-20
6300 Georgetown Pike
McLean, VA 22101, USA

EQUIPMENT: High Speed Road Monitor
OPERATION: Laser sensor measures texture depth
PARTS: Towing vehicle, laser sensor and computer to process measurements
OUTPUT: RMS texture depth
MEASURE: Texture depth
SPEED: 0-100 km/h
NO. OPERATORS: 2
RESOLUTION: 0.01 mm vertical
RATE. 4 kHz
METHOD: Real time sorting and RMS calculation
USERS: UK, Germany
OPERATIONS: Profile, rut depth, video, curvature, gradient, crossfall
COST:
ADVANTAGES: Suitable for fast extensive surveys at normal traffic speeds
DISADVANTAGES: Not accurate in wet conditions
COMMENTS: Available commercially in UK: output correlates well with HSTM, MTM and sand patch
CONTACT: D R Cooper
Transport and Road Research Laboratory
Old Wokingham Road
Crowthorne, Berkshire
ENGLAND RG 11 6AU

EQUIPMENT: Laser RST
OPERATION: Uses lasers to record the texture height of the pavement
PARTS: Laser unit, on-board computer
OUTPUT: Distribution of texture in 10 amplitude ranges
MEASURE: Digital on-board processing to give height of texture
SPEED: 8-90 km/h
NO. OPERATORS: 2
RESOLUTION: 0.025% of measurement range
RATE: 32 kHz
METHOD: Real-time sorting and RMS of texture height calculation
USERS: Australia, Denmark, Saudi Arabia, Spain, Sweden, SA
OPERATIONS: Crack, rut depth, longitudinal profile
COST:
ADVANTAGES: Has little environment restriction. Real-time data processing.
DISADVANTAGES: Operational with full accuracy only on dry surfaces
COMMENTS: The laser has a very small light spot
CONTACT: Leif Sjbgren
Swedish Road and Traffic Research Institute
S-581 01 Linköping
SWEDEN
Phone: +46 - 13204359; Fax: +46 - 13141436

EQUIPMENT: Mechanical Needle Profilometer
OPERATION: A needle is stepped over the surface and a displacement sensor gives an electrical output
PARTS: Needle displacement sensor, stepping device
OUTPUT: Electrical signal proportional to vertical displacement
MEASURE: Digital output of vertical displacement
SPEED: Very slow
NO. OPERATORS: 1
RESOLUTION: +0.005 mm vertical, 0.0125 mm horizontal
RATE:
METHOD: Texture spectra
USERS: Austria
OPERATIONS: Profile
COST:
ADVANTAGES: Enables texture spectral analysis down to rather short wavelength with high resolution
DISADVANTAGES: Slow; for laboratory use only. Needle pressure may damage surface texture.
COMMENTS: There are several profilometers of this type in European laboratories
CONTACT: Dr Harald Augustin
Bundesversuchs und Forschungsanstalt Arsenal
Geotechnisches Institut
Faradaygasse 3, PF 8
A-1031 WIEN, AUSTRIA

EQUIPMENT: Outflow Meter
OPERATION: Measure the time required for a specific volume of water to flow out of the bottom of the meter through the gaps formed by the rubber annulus and the road surface texture
PARTS: Open ended tube with rubber gasket on one end face, timer, water volume measure
OUTPUT: Outflow rate
MEASURE: Manual timing of volume flow rate
SPEED: Stationary
NO.OPERATORS: 1
RESOLUTION:
RATE: One per 10 minutes approximately
METHOD: Volume flow rate cc/min
USERS: Australia, Germany
OPERATIONS: None
COST:
ADVANTAGES:
DISADVANTAGES: Repeatability is poor
COMMENTS:
CONTACT: Dr J J Henry, Director
Pennsylvania Transportation Institute
The Pennsylvania State University
Research Building B
University Park, PA 16802, USA
Phone: 814-863-1888; Fax: 814-865-3039

EQUIPMENT: Outflowmeter for Pervious Pavement
OPERATION: A circular rubber pad with a large hole in the center is applied on the road surface. A given volume of water is stored in a small tank on the pad, while the hole is closed. Measurement gives the time delay for the given volume of water to flow, after opening the hole, into the road surface or between the macrotexture of the road and the rubber pad.
PARTS: Water tank, rubber pad, chronometer, load on rubber pad, apparatus to suddenly open or close the hole.
OUTPUT: Time delay for a given volume of water.
MEASURE:
SPEED: Static
NO. OPERATORS: 1
RESOLUTION: 0.1 second for a volume of water of 5 litres
RATE.
METHOD:
USERS: French Public Road Research Laboratories and Road Agencies
OPERATIONS:
COST: 50,000 FF (without car)
ADVANTAGES: Large range of ability. The large outer and internal diameter of the pad allow the main outflow through the pervious pavement and not on the texture itself. The same apparatus is used by road agencies and research laboratories.
DISADVANTAGES: Needs a car (van) to apply a sufficient load on the rubber pad.
COMMENTS:
CONTACT: LCPC (Laboratoire Central des Ponts et Chaussées,
National Road Research Laboratory)
Pavement Maintenance Management Division
Centre de Nantes
BP 19 - Route de Pornic
44340 BOUGUENAIS (FRANCE)
Phone: 40 84 58 37; Fax: 40 84 59 98; Telex: 710 805 F

EQUIPMENT: Paviameter
OPERATION: Measures the relative displacement of road texture with respect to the vehicle body in order to detect the depth of the joint between consecutive pavings
PARTS: Laser sensor, processing unit, and two computers mounted in a car
OUTPUT: Classification of paving maintenance priority in five classes, one value each 10 m of road
MEASURE: Digital on-board processing to give joint depth
SPEED: 0-12 km/h
NO.OPERATORS: 2
RESOLUTION: Depends on laser: with 0-15°/32 kHz sensor 0.05 mm vertical, 2 mm horizontal
RATE: Profile is not recorded. One quality index of paving joint given each 10 m.
METHOD:
USERS: France
OPERATIONS:
COST: 200,000 FF (without car)
ADVANTAGES: Specific survey of paving roads. Able to perform at very low speed (useful on urban roads).
DISADVANTAGES: Maximum speed not high enough
COMMENTS: Used on paved roads only, and in urban area mainly
CONTACT: LCPC (Laboratoire Central des Ponts et Chaussées,
National Road Research Laboratory)
Pavement Maintenance Management Division
Centre de Nantes
BP 19 - Route de Pornic
44340 BOUGUENAIS (FRANCE)
Phone: 40 84 58 37; Fax: 40 84 59 98; Telex: 710 805 F

EQUIPMENT: Profile Tracer
OPERATION: A stylus is moved across the pavement and the vertical motion of the stylus is measured
PARTS: Stylus traversing apparatus, amplifier, recorder
OUTPUT: Texture height
MEASURE: Chart trace of vertical displacement against distance
SPEED: Spot test
NO.OPERATORS: 1
RESOLUTION: 0.025
RATE. Macro 3.8 mm/s; Micro 0.25 mm/s
METHOD: Post processing can give average texture depth
USERS:
OPERATIONS: Profile
COST:
ADVANTAGES: High sensitivity and good linearity (± 1%)
DISADVANTAGES: Measurement is slow; needle may bend around some microtexture peaks
COMMENTS: Measurement speed is too slow. Not convenient for regular field use
CONTACT: Dr J J Henry, Director
Pennsylvania Transportation Institute
The Pennsylvania State University
Research Building B
University Park, PA 16802, USA
Phone: 814-863-1888; Fax: 814-865-3039

EQUIPMENT: Profilon
OPERATION: Measures the vertical height versus horizontal displacement between a frame on the surface and the surface texture
PARTS: Distance and laser sensor (0-15°), PC computer, specific software "TRMIDIM"
OUTPUT: Texture profiles, macrotexture criteria Ra, Rq, SK, EK, Abbott curve, and PSD curve
MEASURE:
SPEED: static
NO.OPERATORS: 1
RESOLUTION: 0.25 mm longitudinal determined by laser sensor
RATE. Moved manually to any spot location
METHOD: Macrotexture criteria based on a distance of 2 m
USERS: France
OPERATIONS: Profile
COST: 300,000 FF
ADVANTAGES: Accurate
DISADVANTAGES: Static and slow; requires traffic control when operating on an in-service road
COMMENTS: Research apparatus, since 1983 called 'Macroprofilographe' upgraded in 1991 and called 'Profilon'
CONTACT: LCPC (Laboratoire Central des Ponts et Chaussées,
National Road Research Laboratory),
Pavement Maintenance Management Division, Centre de Nantes,
BP 19 - Route de Pornic, 44340 BOUGUENAIS (FRANCE)
Phone: 40 84 58 37; Fax: 40 84 59 98; Telex: 710 805 F

EQUIPMENT: Road Surface Digitalizer
OPERATION: Measures vertical height over a matrix of 256 x 256 spots; distance between spots is variable from 0.01 to 1.00 mm
PARTS: Cross-moving table, sensor laser (0-15°), PC computer, specific software 'TRIDIM'
OUTPUT: Texture criteria Ra, Rq, SK, EK, Abbott curve, PSD curve, for two or three dimensions (3-D surface representation)
MEASURE:
SPEED: Static
NO.OPERATORS: 1
RESOLUTION: Determined by laser, now 0.25 mm spot diameter
RATE:
METHOD: Texture criteria (limited to macro with current laser)
USERS: France
OPERATIONS: Surface (or profile)
COST. 350,000 FF
ADVANTAGES: Accurate: time for calculations (on digital values) is short.
DISADVANTAGES: Numerisation is rather long (1 to 3 hours)
COMMENTS: Research apparatus: has been completely upgraded in 1990
CONTACT: LCPC (Laboratoire Central des Ponts et Chaussées,
National Road Research Laboratory)
Pavement Maintenance Management Division, Centre de Nantes,
BP 19 - Route de Pornic, 44340 BOUGUENAIS (FRANCE)
Phone: 40 84 58 37; Fax: 40 84 59 98; Telex: 710 805 F

EQUIPMENT:	ROSAN (Road Surface Analyzer)
OPERATION:	Laser measures macro texture; rubber slider measures friction.
PARTS:	Precimeter laser, force transducer in rubber slider, microprocessor, water system
OUTPUT:	RMS macrotexture depth, low speed friction, estimate of high friction
MEASURE:	Texture depth and friction
SPEED:	2 mph
NO.OPERATORS:	1
RESOLUTION:	0.006 mm. vertical
RATE.	1000/samples/second
METHOD:	Micro processor computes RMS texture, low speed friction
USERS:	FHWA
OPERATIONS:	Friction and macrotexture
COST:	US$15,000
ADVANTAGES:	Fast texture measurement and estimate of high speed friction from a 2 to 4 m section
DISADVANTAGES:	High cost of laser
COMMENTS:	First prototype is ready for field testing. Good laboratory performance.
CONTACT:	R R Hegmon FHWA, HNR-20 6300 Georgetown Pike McLean, VA 22101, USA

EQUIPMENT:	Rugolaser
OPERATION:	Measures the relative displacement of road texture with respect to the vehicle body, along a longitudinal profile generally located in the right wheelpath of the lane
PARTS:	Laser sensor (45°-45° made in UK until 1990, 0-15° made in Sweden since 1991), distance and speed sensors, PC computer
OUTPUT:	RMS macrotexture depth
MEASURE:	Digital on-board processing to give texture depth
SPEED:	20-100 km/h
NO.OPERATORS:	1 or 2
RESOLUTION:	Better than 0.1 mm vertical, 0.625 mm horizontal at 72 km/h
RATE:	Sensor sampling = 32 kHz; texture depth is sensed over 120 mm each 250 mm
METHOD:	RMS and average macrotexture depth calculated over 10 or 20 m
USERS:	France
OPERATIONS:	Longitudinal profile
COST:	400,000 FF (without car)
ADVANTAGES:	Fast and easy to operate. Good resolution and repeatability. Low drop-out rate using 0-15° laser.
DISADVANTAGES:	Not operational in wet conditions; does not (yet) include texture under 50 mm wavelengths. Drop-out rate is high with 45-45° laser.
COMMENTS:	Used in three configurations (in France): –Mounted alone on a specific car or van. –Mounted on SCRIM vehicle to measure SFC skidding resistance simultaneously. –Integrated in the new multifunctional French device "SIRANO" (System for Inspection of Roads and Highways by Analysis of Numerical and Optical data).
CONTACT:	LCPC (see p.70 for address)

EQUIPMENT: Stereophotography ASTM E-770-80
OPERATION: Pairs of stereophotographs are taken
PARTS: Frame for mounting camera at two locations, 35 mm single lens camera, flash source, stereoscope
OUTPUT: Texture code number consists of 6 texture parameters
MEASURE: Pairs of photographs
SPEED: Stationary
NO.OPERATORS: 1
RESOLUTION: 0.25 mm
RATE: Photos cover 210 cm^2; maximum 150 m interval between photo pairs is recommended
METHOD: Visual stereoscopic interpretation for code numbers. Average for ten random centimetre squares
USERS: Ontario, Canada
OPERATIONS:
COST:
ADVANTAGES: Can get 3-D image
DISADVANTAGES: Considerable training is required for operators and interpreters
COMMENTS: Post processing of data is too complex and time consuming
CONTACT: Dr J J Henry, Director
Pennsylvania Transportation Institute
The Pennsylvania State University
Research Building B
University Park, PA 16802, USA
Phone: 814-863-1888; Fax: 814-865-3039

EQUIPMENT: TRRL Mini Texture Meter (MTM)
OPERATION: Measures the relative displacement of road texture with respect to a two-wheeled frame. A non-contact laser sensor is used to measure texture depth.
PARTS: Laser unit, sensor, microprocessor
OUTPUT: RMS texture depth
MEASURE: Digital on-board processing to give average texture depth, relative displacement
SPEED: Walking, 3-6 km/h
NO. OPERATORS: 1
RESOLUTION: 0.01 mm vertically
RATE: 50 Hz
METHOD: Real time sorting and RMS calculation of texture depth
USERS: UK, France, New Zealand, Hong Kong, China, Australia
OPERATIONS: None
COST: US$13,000
ADVANTAGES: Gives average texture depth value. Easy to operate and transport.
DISADVANTAGES: Does not cover shortest macrotexture wavelengths. Not operational in wet weather; high drop-out rate. Walking speed influences measurement result.
COMMENTS: Gives inaccurate (too high) value for smooth surface. Designed for compliance checking of new work and investigation of accident locations.
CONTACT Mr G West
Transport and Road Research Laboratory (TRRL)
Crowthorne, Berkshire
ENGLAND RG 11 6AU

EQUIPMENT:	TRRL High Speed Texture Meter (HSTM)
OPERATION:	Measures the relative displacement of road texture with respect to the trailer body. Non-contact laser sensor used to compute texture depth.
PARTS:	Laser unit, sensor, distance meter, visual display unit, computer
OUTPUT:	RMS texture depth
MEASURE:	Digital on-board processing to give average texture depth
SPEED:	Up to 110 km/h
NO OPERATORS:	2
RESOLUTION:	0.01 mm vertical, horizontal 6 mm between each sample at 80 km/h
RATE:	4 kHz
METHOD:	Real time sorting and RMS of texture depth calculation
USERS:	UK, France, Italy
OPERATIONS:	None
COST:	US$60,000
ADVANTAGES:	Suitable for fast and extensive surveys; 300 km per day survey capacity
DISADVANTAGES:	Does not cover shortest macrotexture wavelengths. Not operational in wet weather, high drop-out rate.
COMMENTS:	Correlates well with MTM and sand patch method. This system also used in TRRL high speed road monitor.
CONTACT:	Mr G West Transport and Road Research Laboratory (TRRL) Crowthorne, Berkshire ENGLAND RG 11 6AU

EQUIPMENT:	Volumetric Methods
OPERATION:	Sand patch method: spread a known volume of sand or glass spheres and measure the diameter of the circular patch produced
PARTS:	Sand, volume measure, spreader, ruler
OUTPUT:	Mean texture depth
MEASURE:	Diameter
SPEED:	Stationary
NO.OPERATORS:	1
RESOLUTION:	
RATE:	Spot test: one per 10 minutes approximately
METHOD:	Hand calculation of average texture depth from diameter of patch and known volume
USERS:	Many
OPERATIONS:	None
COST.	Negligible
ADVANTAGES:	Inexpensive
DISADVANTAGES:	There are many error sources. Measurement is slow.
COMMENTS:	Glass spheres used in ASTM standard method E-965-87, grease and putty also have been used. Not a convenient method for routine large database field tests.
CONTACT:	Chairman E17.23 ASTM 1916 Race Street Philadelphia, PA 19103, USA

EQUIPMENT:	VTI Mobile Laser Profilometer
OPERATION:	Measures the relative displacement of the road texture with respect to the vehicle body
PARTS:	Laser unit, signal processing unit, spectrum analyzer, computer
OUTPUT:	Profile calculation in bands of megatexture and macrotexture, profile spectra
MEASURE:	Digital and analog on-board processing to give relative height
SPEED:	36 km/h
NO.OPERATORS:	1 or 2
RESOLUTION:	0.01 mm RMS vertical, 2 mm texture wavelength longitudinal
RATE:	One track per run. Probe movable laterally over entire car width.
METHOD:	Real time spectrum analysis and RMS of texture height calculation. Also simulated sand patch texture depth calculation.
USERS:	VTI Sweden
OPERATIONS:	Profile
COST:	
ADVANTAGES:	Gives a comprehensive quantification of road macrotexture and megatexture. Suitable for research as well as surveys.
DISADVANTAGES:	Can operate only in dry weather. Does not cover the wavelengths of macrotexture between 0.5 and 2 mm. Doesn't measure microtexture.
COMMENTS:	Only prototype version available. Normal operating speed is slow. May be increased to 90 km/h at the expense of horizontal resolution.
CONTACT:	Dr Ulf Sandberg Swedish Road and Traffic Research Institute 2-581 01 Linköping, SWEDEN Phone: +46 13204131; Fax: +46 13141436

EQUIPMENT:	VTI Stationary Laser Profilometer
OPERATION:	Measures the relative displacement of the road texture with respect to a 1.2 m long beam placed on a tripod
PARTS:	Laser unit, signal processing unit, beam, motor, tachometer generator, tape recorder, spectrum analyzer, computer
OUTPUT:	Profile spectrum, texture depth
MEASURE:	Digital and analog output of relative height
SPEED:	Stationary
NO. OPERATORS:	1
RESOLUTION	0.01 mm RMS vert, 2 mm wavelength 0.003 mm RMS vertical, 0.2 mm wavelength
RATE:	Maximum 1 m/10 s; Minimum 1 m/50 s
METHOD:	RMS of texture height. Also simulated sand patch texture depth calculation. Spectrum analysis.
USERS:	VTI Sweden
OPERATIONS:	Profile
COST:	
ADVANTAGES:	Gives a comprehensive quantification of road macrotexture and megatexture and approaches the microtexture range. Suitable for research.
DISADVANTAGES:	Operates only in dry weather. Operates slowly. The 'micro' probe is still impractical and not very accurate.
COMMENTS	Only a prototype version available. Not suitable for routine field use.
CONTACT:	Dr Ulf Sandberg Swedish Road and Traffic Research Institute (VTI) (see above for address)

EQUIPMENT: Yandell-Mee Texture Friction Meter
OPERATION: Light sectioning. Light and camera 45 °C to surface. Records 100 mm profile to ±4 micro-metres.
PARTS: Knife of light lenses and small video camera driven by laptop computer
OUTPUT: Total texture plus its four components, texture depth and friction prediction
MEASURE: Floppy disk or printer
SPEED: Stationary
NO. OPERATORS: 1
RESOLUTION: 4 mm on 100 mm profile
RATE: One set per minute (50 Hz)
METHOD: Pascal program in laptop computer
USERS: Dynatest and RTA, Australia
OPERATION: Texture profile its components and texture depth
COST: US$30,000
ADVANTAGES: Faster than sand patch. Contains statistical analysis routines.
DISADVANTAGES: Slower than some other methods
COMMENTS: Its main use is for instantaneous tyre-road friction prediction. The texture depth capability is incidental.
CONTACT: W Yandell
School of Civil Engineering
P 0 Box 1
Kensington 2033
AUSTRALIA

APPENDIX 2

PIARC INTERNATIONAL EXPERIMENT TO COMPARE AND HARMONISE TEXTURE AND SKID RESISTANCE MEASUREMENTS

APPENDIX 2. PIARC INTERNATIONAL EXPERIMENT TO COMPARE AND HARMONISE TEXTURE AND SKID RESISTANCE MEASUREMENTS

A2.1 Objectives of the Experiment

The overall objectives of the experiment as stated in the project plan (PIARC 1991) is reproduced below:

"The purpose of this experiment is to provide a means of comparing the results of measurements made by different countries throughout the world. The results of this experiment will be invaluable in realising consistent pavement management practices across national boundaries. Furthermore, it is necessary that the measurement methods be harmonised in order to standardise the specifications for paving materials.

"The overall objective of the experiment is to compare the many different pavement friction measurement methods used in different countries around the world, and to give recommendations for harmonising them. To this end it will be necessary to accomplish the following objectives:

- *Quantify relationships between standard measures of friction obtained with various devices under specified conditions to facilitate interchanges and harmonisation of technical information. This will require the development of models that may include texture measures.*
- *Develop and evaluate relationships between friction and texture measurements obtained with various measurement devices under varying physical test conditions including texture, speed, slip angle, test tyre, climate and materials.*
- *Quantify repeatability and measurement errors associated with the various devices. Sampling rate and/or sample size required by the various methods to achieve decimal accuracy will be evaluated.*
- *Evaluate the methods for their suitability for project or network level data collection."*

A2.2 Outline of the Experiment

The experiment (reported in PIARC 1995b) was divided into two parts - one carried out in Belgium and one in Spain. In Belgium, 22 test sites on public roads subjected to normal traffic were included. In addition, six sites on an airport and a race car track were included for run-in and training purposes before the main tests started. In Spain, after run-in on a track closed to road traffic, 18 test sites on public roads subjected to normal traffic were utilised. All 150 m long test sites were divided into two sections, each 75 m long, on which separate measurements were made.

The US$705,000 experiment started in Belgium on 14-16 September 1992 and took two months to complete.

All tests included the following types of measurements or studies:

- friction measured by the locked wheel principle (or close to locking) (wet)
- friction measured by the side force principle (wet)
- friction measured by the optimum slip principle (peak friction) (wet)
- friction coefficient versus slip (curve plotted) (wet)
- friction coefficient versus slip (curve plotted) (dry)
- friction coefficient measured by special portable sliders/disks (wet)
- friction coefficient measured by the British Pendulum (BPN number) (wet): this was considered to give a measure of microtexture
- stereo photographs
- conventional photographs
- road surface and air temperatures
- macro and megatexture profile curves measured by mobile and stationary profilometers
- macro and megatexture spectra measured by mobile and stationary profilometers
- macrotexture depth measured by the volumetric method ("sand patch")
- macrotexture depth measured by laser based sensors (mobile).

Several of the tests above were conducted with more than one type of device. Most devices took part in the experiments in both Belgium and Spain, but a few participated only in one country. The mobile friction measurements were generally made at 30, 60 and 90 km/h. However, some devices tested only at one speed, normally 60 km/h.

All devices were grouped into one of four groups. Tests were run for all types of devices in one group during the same period of the day (morning or afternoon). However, devices within each group requiring dry surface finished testing before devices requiring wet surface started. When one group had finished another group took over. Mostly, two sites were tested in one day for each type of equipment.

Traffic was re-routed on all test sites so that there was no interference with other traffic.

A2.3 Equipment

Equipment participating in the experiment included friction measuring devices, photographic equipment and texture measuring devices. Of particular interest to this report are the texture measuring devices, which are listed in Table A2.1 below. This list includes all major measuring systems/methods existing today and useful for field testing. The only exception would be the Mini Texture Meter (MTM) developed originally by the Transport and Road Research Laboratory (TRRL) in the UK. However, one could see equipment No. D5 as a high speed version of this meter, so the measurement principle as such was represented anyway. There are also some systems under development in Germany but they are more or less similar to the laser profilometers in the list. In total, this means that the experiment in practice included virtually all techniques available today.

Table A2.1. The texture measuring equipment evaluated in the experiment.

No.	Name	Origin	Type	Notes
A1	FHWA texture measuring system	US	Light slit ≈ 100 mm, video system	Measures texture depth (lateral profile curve). Mobile
A2	VTI mobile laser profilometer	S	Laser spot, linear sensor	Measured longitudinal profile curve + spectrum. Mobile
A3B	ARAN (in Belgium only)	CAN	Laser spot, linear sensor	Measures texture depth. Mobile. Part of bigger system
A3E	RST (in Spain only)	E	Laser spot, linear sensor	Measures texture depth. Mobile. Part of bigger system
A4	CRR mobile laser profilometer	B	Laser spot, linear sensor	Measures longitudinal profile curve + spectrum. Mobile
A5	CRR static profilometer	B	Laser spot, linear sensor	Measures profile curve + spectrum. Stationary
A8	Volumetric method (ASTM E965)	US	"Sand patch" but glass beads instead of sand	Measures mean texture depth only. Manual method
A12	ROSAN	US	Laser spot, linear sensor	Measures texture depth, at walking speed. Includes also friction measurement (by slider)
D1	SCRIM+SRM+texture (only in Spain)	D	Laser spot, linear sensor	Measures texture depth. Mobile. Part of bigger system, main part is friction measurement system
D3	SCRIM	F	Laser spot	Measures texture depth. Mobile. Part of bigger system, main part is friction measurement system
D4	SCRIM-SUMMS	I	Laser spot	Measures texture depth. Mobile. Part of bigger system, main part is friction measurement system
D5	SCRIMTEXT	UK	Laser spot, diode array sensor	Measures texture depth. Mobile. Part of bigger system, main part is friction measurement system

* Abbreviation for country of origin:

B = Belgium
CAN = Canada
D = Germany
E = Spain
F = France
I = Italy
S = Sweden
UK = United Kingdom
US = United States of America

A2.4 Description of Test Sites

A site pre-selection was made that included 19 road sections in the vicinity of Valencia, Alicante and Murcia, Spain, and 28 road sections in Belgium. All sites were selected to provide desired levels of macro- and microtexture and are by no means representative of the road surfaces of the country.

The sites include a range of surfaces potentially encompassing all combinations of high, medium and low values of microtexture and macrotexture. Generally megatexture was intended to be low. However, several sites were chosen where a site having low megatexture is followed by a site with high megatexture and both have the same micro- and macrotexture.

The test sites included in the test programmes in Spain and Belgium are listed in Tables A2.2 and A2.3 respectively.

Table A2.2 The road surfaces in Spain used for the PIARC experiment.

No.	Type	Maximum chip size	Condition	Special features and notes
E00	Asphalt concrete	≈10 mm	Good	Airport runway
E01	Asphalt concrete	≈12 mm	Rather unpolished	Smooth textured
E02	Asphalt concrete	≈15 mm	Somewhat polished	
E03	Asphalt concrete (cold)	≈8 mm	Highly polished	Rather smooth
E06	Asphalt concrete	≈15 mm	Some tracks visible	Uneven
E07	Surface dressing	≈12 mm	Rather poor	Cracks, uneven
E08	Asphalt concrete	≈30 mm	Inhomogeneous	Includes 4 mm chippings. Some parts rather rough
E09	Asphalt concrete	≈10 mm		Pronounced aggregate 2-4 mm
E10	Asphalt concrete	≈16 mm		Pronounced aggregate 2-4 mm
E11	Cement concrete	NA		Longitudinal shallow, wavy grooves. Deep unfilled joints (which we put tape over)
E12	Surface dressing	≈10 mm	Old and polished	Similar to E13
E13	Surface dressing	≈10 mm	Old and polished	Pronounced bump on section A
E14	Asphalt concrete (cold)	≈12 mm	Very poor, repaired, inhomogeneous	Uneven. Section A was worse than B
E15	Asphalt concrete	≈12 mm		Rather dark
E16	Asphalt concrete	≈12 mm		Pronounced aggregate 2-4 mm
E17	Cement concrete	NA	Good	Longitudinal, deep, wavy grooves. Deep unfilled joints
E18	Asphalt concrete	≈10 mm		Pronounced aggregate 2-6 mm
E19	Cement concrete	NA		Longitudinal, shallow grooves. Deep unfilled joints
E20	Porous asphalt concrete	≈15 mm	Rather new	Rough textured, like new surface dressing

Table A2.3 The road surfaces in Belgium used for the PIARC experiment.

No.	Type	Maximum chip size	Condition	Special Features and Notes
B01	Surface dressing	≈15 mm	Unpolished	Rough textured
B02	Chip, asphalt concrete	≈18 mm	Highly polished	Very low microtexture expected
B03	Chip, asphalt concrete	≈15 mm	Bumps between A and B	Smooth. Large spacing between chippings. "Positive" texture
B04	Chip, asphalt concrete	≈15 mm	Old	Rather similar to site B02
B06	Asphalt concrete	≈10 mm	Polished	
B08	Asphalt concrete	≈8 mm	Inhomogeneous	Measurement made somewhat to the right of the right wheeltrack. "Negative" texture
B09	Surface dressing	≈14 mm	Unpolished	In right wheeltrack. Leaves fallen on road
B10	Surface dressing	≈20 mm	Severe chip losses (mostly on section B)	Rough textured
B11	Surface dressing	≈15 mm		Medium textured
B12	Surface dressing	≈10 mm	Absolutely new	Loose chippings. Rather rough textured
B13	Surface dressing	≈15 mm	Laterally inhomogeneous	Very rough textured, mostly on section B
B15	Surface dressing	≈18 mm	Unpolished	Chippings closely spaced
B17	Surface dressing	≈12 mm	Bleedings on section A and first half of B	Partly very smooth due to bleedings, but originally rough textured
B18	Strip cement concrete	≈15 mm	Unpolished	Large spacing between chippings
B19	Chip cement concrete	≈30 mm		Very rough texture, uneven, partly humid
B21	Strip cement concrete	≈25 mm	Rather unpolished	Uneven at end of section B. Clay at beginning of A
B24	Strip cement concrete	≈20 mm		Relatively smooth. Exposed aggregate
B26A	Asphalt concrete	≈12 mm	Like new	Airport runway. Smooth, "negative" texture
B26B	Porous asphalt concrete	≈15 mm		Airport runway. Rough, "negative" texture
B32	Strip cement concrete	≈40 mm		Very rough texture. Some clay at beginning of A
B33A	Asphalt concrete	≈12 mm		Race track surface
B33B	Asphalt concrete	≈12 mm		Race track surface
B33C	Asphalt concrete	≈12 mm		Race track surface
B33D	Asphalt concrete	≈12 mm		Race track surface
B34	Resinous slurry	≈4 mm	Good condition	Sandpaper-like surface, on bridge
B40	Strip cement concrete	≈20 mm		Medium texture. Exposed aggregate
B41	Porous asphalt concrete	≈13 mm	New	Dark surface hard to measure. "Negative" texture
B42	Slurry seal	≈10 mm		Smooth. Somewhat humid during measurement

A2.5 Experiment Status

A draft report has been prepared and is presently undergoing editorial and peer review. Conclusions have been drawn from an analysis of over 15,000 measurements. The principal investigators were Drs John Henry and James Wambold from the Pennsylvania Transportation Institute at Pennsylvania State University. Topics covered in the report include:

- Correlations between texture measuring devices;
- Correlations between friction measuring devices;
- Relationships between friction and texture according to different empirical and semi-empirical models;
- Repeatability of each device;
- Reproducibility between devices based on similar measurement principles;
- Proposal of a universal standard for measuring and characterising anti-skid performance of roads and airfield surfaces.

To obtain PIARC publications related to this experiment, the appropriate contact is:

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