The MERLIN road roughness machine: User Guide

by M A Cundill

TRL Report 229

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TRL REPORT 229

THE MERLIN ROAD ROUGHNESS MACHINE: USER GUIDE

by M A Cundill

Subsector:	Transport
Theme:	Reduce the costs of constructing, rehabilitating and maintaining road infrastructure and vehicle operations
Project title:	Transport Planning
Project reference:	R5591

This document is an output from a project funded by the UK Overseas Development Administration (ODA) for the benefit of developing countries. The views expressed are not necessarily those of the ODA.

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First Published 1996
ISSN 0968-4107

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EXECUTIVE SUMMARY

Road surface roughness is an important measure of road condition. The Merlin road roughness measurement machine was developed by the Transport Research Laboratory for use in developing countries. The machine is easily constructed, robust and straightforward to use. It can be used to either measure road surface roughness directly or to calibrate other instruments.

The Merlin consists of a metal frame with a wheel at the front and handles and a foot at the rear. The distance between the rear foot and the bottom of the wheel is 1.8 m long. Attached to the frame is a pivoted moveable arm which has a probe at one end which rests on the road surface half way between the wheel and the rear foot. At the other end of the arm is a pointer which moves over a prepared chart. The arm is pivoted close to the probe so that a vertical displacement of the probe of 1 mm will produce a displacement of the pointer of 1 cm.

The Merlin is used to measure the roughness of a stretch of road by taking repeated measurements at regular intervals along the road. For each measurement the machine is rested on the road with the wheel, the rear foot and probe in contact with the road surface. The position of the pointer on the chart is recorded with a cross. Each new measurement is taken by moving the Merlin forward to a new position on the road and recording the corresponding new position of the pointer on the chart so that a histogram distribution of crosses is gradually built up. Once two hundred measurements have been made the position between the tenth and eleventh crosses, counting in from one end of the distribution, is marked. The procedure is repeated for the other end of the distribution and the spacing between the two marks, D, is measured in millimetres.

For most road surfaces the road roughness can be determined using the equation

$$IRI = 0.593 + 0.0471\ D$$
$$(2.4 < IRI < 15.9)$$

where IRI is the roughness in terms of the International Roughness Index (in m/km) and D is measured from the Merlin chart (in mm).

The equation given above assumes a mechanical amplification of 10. In practice this will not be true because of small errors in manufacturing. However the Merlin can be simply calibrated. This is done by placing a calibration block (usually made from machined metal) of known thickness, T, under the probe and measuring the corresponding displacement, S.

The measurements on the chart should then be multiplied by the scaling factor:

$$\text{Scaling factor} = 10\ T\ /\ S$$

The report provides further information on the design and manufacture of the Merlin and on its method of use, alignment and adjustment. Advice is also given on safety considerations, the choice of test section and the problems associated with corrugations.

THE MERLIN ROAD ROUGHNESS MACHINE: USER GUIDE

(MERLIN: A Machine for Evaluating Roughness using Low-cost Instrumentation)

ABSTRACT

Road surface roughness is an important measure of road condition. This report provides a detailed description of the Merlin road roughness measurement machine and practical guidance on its use. The Merlin can be used for the direct measurement of road roughness or to help calibrate other instruments such as the vehicle mounted Bump Integrator.

1. INTRODUCTION

The purpose of this guide is to describe how to use a MERLIN to measure road roughness. The Merlin was designed by the Transport Research Laboratory for use in developing countries. Its advantages are:

- easily built - it can be made by local craftsmen from parts which are readily available. Drawings can be obtained from TRL
- robust - requires no special care in handling, though of course it should not be abused
- easily calibrated - using a simple procedure
- easily used - the measurement process is straightforward and an operator can be quickly trained
- easily maintained - one of its most important attributes.

The Merlin can be used either for direct measurement of roughness, or for the calibration of "response type" instruments such as the vehicle-mounted bump integrator.

Detailed information on how the machine works is given in an earlier TRL report (Cundill 1991) and further analyses of its operation and wavelength sensitivity are given in Cundill (1996). Guidelines for conducting and calibrating road roughness measurements are given by Sayers et al (1986).

2. GENERAL DESCRIPTION

2.1 PRINCIPLE OF OPERATION

See Figure 1. The Merlin has two feet, 1.8 metres apart, which rest on the road surface along the wheel track whose roughness is to be measured. A moveable probe is placed on the road surface mid-way between the two feet and the Merlin measures the vertical distance, y, between the road surface under the probe and the centre point of an imaginary line joining the bottom of the two feet. The result is recorded on a chart mounted on the machine. By taking repeat measurements along the wheel track, a histogram of values of y can be built up on the chart. The width of this histogram can be used to estimate road roughness on the IRI scale.

2.2 DESIGN

Figure 2 shows a sketch of the Merlin Mk1. It consists of:

- a horizontal metal beam about 2 metres long
- a bicycle wheel at the front attached to the beam by bicycle front forks. The bottom of the tyre acts as the front foot
- a vertical metal leg attached to the rear of the beam. A shaped piece of metal at the bottom of the leg acts as the rear foot
- a centre leg about halfway along the beam which reaches down close to the road surface
- a moving arm attached to the bottom of the centre leg by a pivot. The arm is stepped to avoid the risk of it touching the surface of very rough roads
- the probe, a piece of metal shaped like the rear foot, attached to the underside of the moving arm. It makes contact with the road mid-way between the front and rear feet
- a weight attached to one end of the moving arm which forces the probe downwards until it touches the road surface or the upper end of the arm reaches its end stop
- a pointer attached to the top end of the moving arm which moves over a chart holder. The dimensions are such that a movement of the probe of 1 mm will give rise to a pointer movement of 1 cm
- a prepared data chart taped to the chart holder. It consisting of columns each 5 mm wide and divided into boxes
- a stabiliser on one side of the rear leg which prevents the Merlin from falling over when taking measurements
- two handles at the end of the beam which permit the operator to raise the Merlin and wheel it along the road
- a marker on the wheel or tyre. When the marker is at the bottom, as in the Figure, the wheel is said to be in its "normal position".

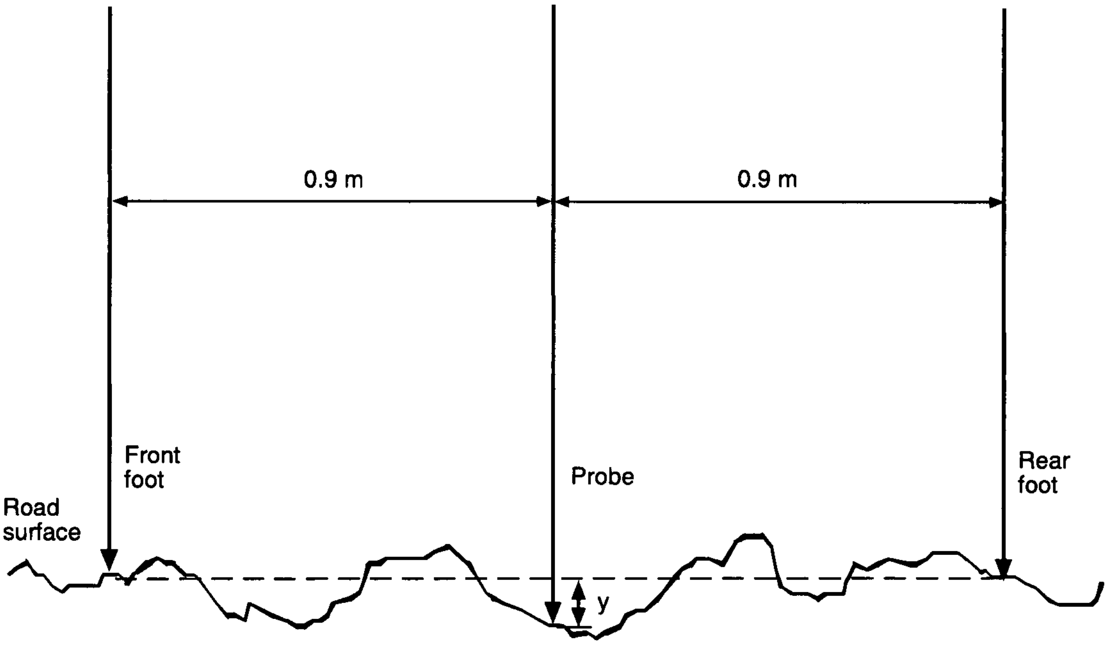


Fig. 1 Measurement of displacement, y

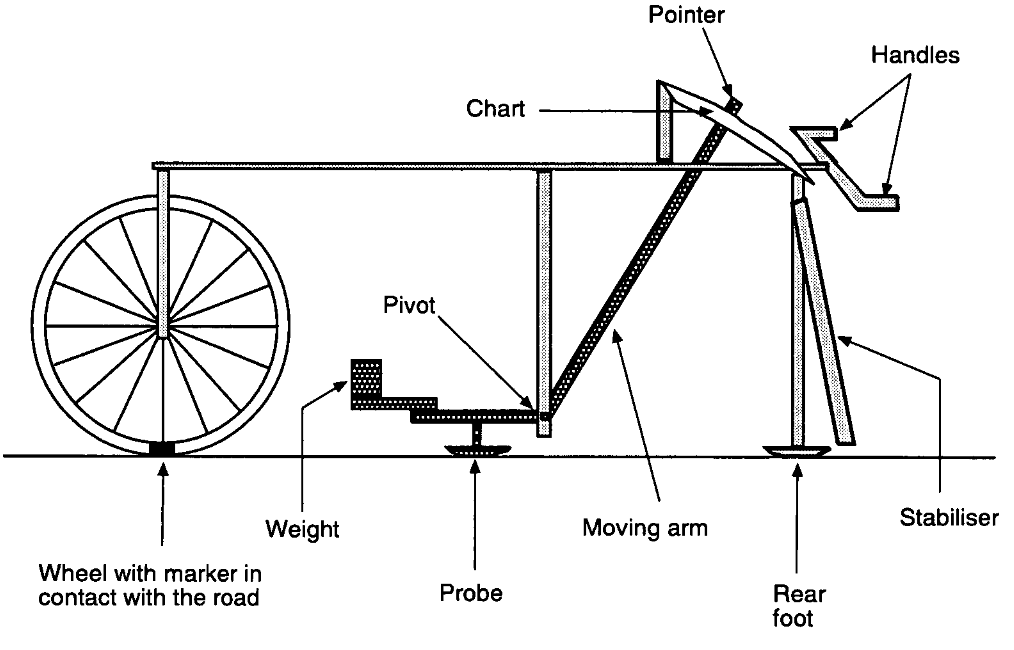


Fig. 2 MERLIN Mark 1

For ease of manufacture, the horizontal beam, the central and rear legs, the moving arm, the stabiliser and the handles are all made from steel tubing of square cross-section. Joints are welded where possible, though the stabiliser and handles are fixed by bolts so that they can be removed for easier transportation. To strengthen the joints between the main beam and the legs, additional struts are used which are not shown in the Figure but can be seen in Plate1.

The original Merlin design has now been improved and the Mk2 version is shown in Figure 3 and Plate 2. It is also built from steel tubing of square cross-section and uses a bicycle wheel. It operates in the same way as the Mk1 but the new design is more rugged and, although it looks more complicated, it should in practice be easier to make and more easily aligned. The main differences are:

- the horizontal beam has been replaced by two interconnected beams and lowered to be on a level with the wheel hub
- there are two centre legs, so that it is easier to attach the pivot
- the stabiliser is alongside the centre leg
- the machine can be assembled for left-handed or right-handed use.

2.3 METHOD OF USE

To determine the roughness of a section of road, 200 measurements are made at regular intervals. For each measurement, the machine is rested on the road with the wheel in its normal position and the rear foot, probe and stabiliser in contact with the road surface. The position of the pointer on the chart is then marked by a cross in the next box in line with the pointer and, to keep a count of the total number of measurements made, a cross is also put in the "tally box" on the chart (see Figure 4). The handles of the Merlin are then raised so that the probe, rear foot and stabiliser are clear of the road and the machine is wheeled forward to the next measuring position, where the process is repeated.

When the 200 measurements have been made, the chart is removed from the Merlin and turned on its side. The position mid-way between the tenth and the eleventh crosses, counting in from one end of the distribution, is marked on the chart below the columns. The procedure is repeated for the other end of the distribution. It may be necessary to allocate only a proportion of a column width, as shown by the lower mark in the example. Counting in from the lower end of the distribution, the tenth cross appears in a column containing 5 crosses. The mark is therefore made one fifth of the way in from the edge of the column. The spacing between the two marks, D, is then measured in millimetres and this can be used to derive roughness using the equations in Section 2.4.

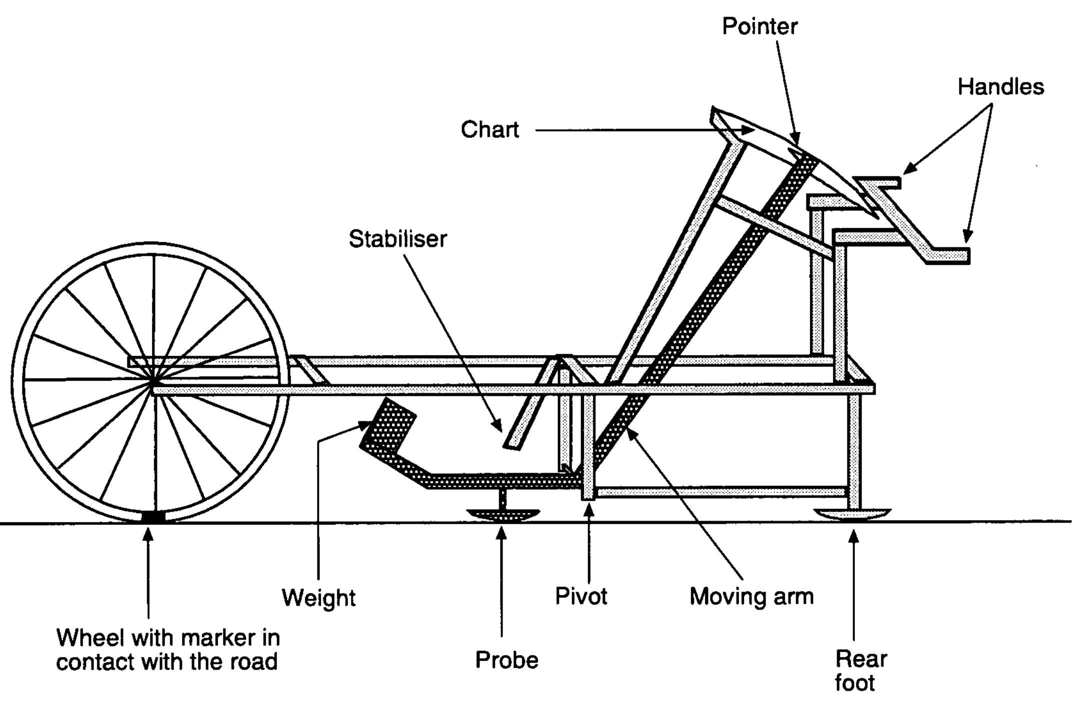


Fig. 3 MERLIN Mark 2

TEST SECTION C7

WHEEL PATH NS

DATE 12.6.90

OPERATOR G.Smith

TALLY BOX

1	2	3	4	5	6	7	8	9	10	
X	X	X	X	X	X	X	X	X	X	1
X	X	X	X	X	X	X	X	X	X	2
X	X	X	X	X	X	X	X	X	X	3
X	X	X	X	X	X	X	X	X	X	4
X	X	X	X	X	X	X	X	X	X	5
X	X	X	X	X	X	X	X	X	X	6
X	X	X	X	X	X	X	X	X	X	7
X	X	X	X	X	X	X	X	X	X	8
X	X	X	X	X	X	X	X	X	X	9
X	X	X	X	X	X	X	X	X	X	10
X	X	X	X	X	X	X	X	X	X	11
X	X	X	X	X	X	X	X	X	X	12
X	X	X	X	X	X	X	X	X	X	13
X	X	X	X	X	X	X	X	X	X	14
X	X	X	X	X	X	X	X	X	X	15
X	X	X	X	X	X	X	X	X	X	16
X	X	X	X	X	X	X	X	X	X	17
X	X	X	X	X	X	X	X	X	X	18
X	X	X	X	X	X	X	X	X	X	19
X	X	X	X	X	X	X	X	X	X	20

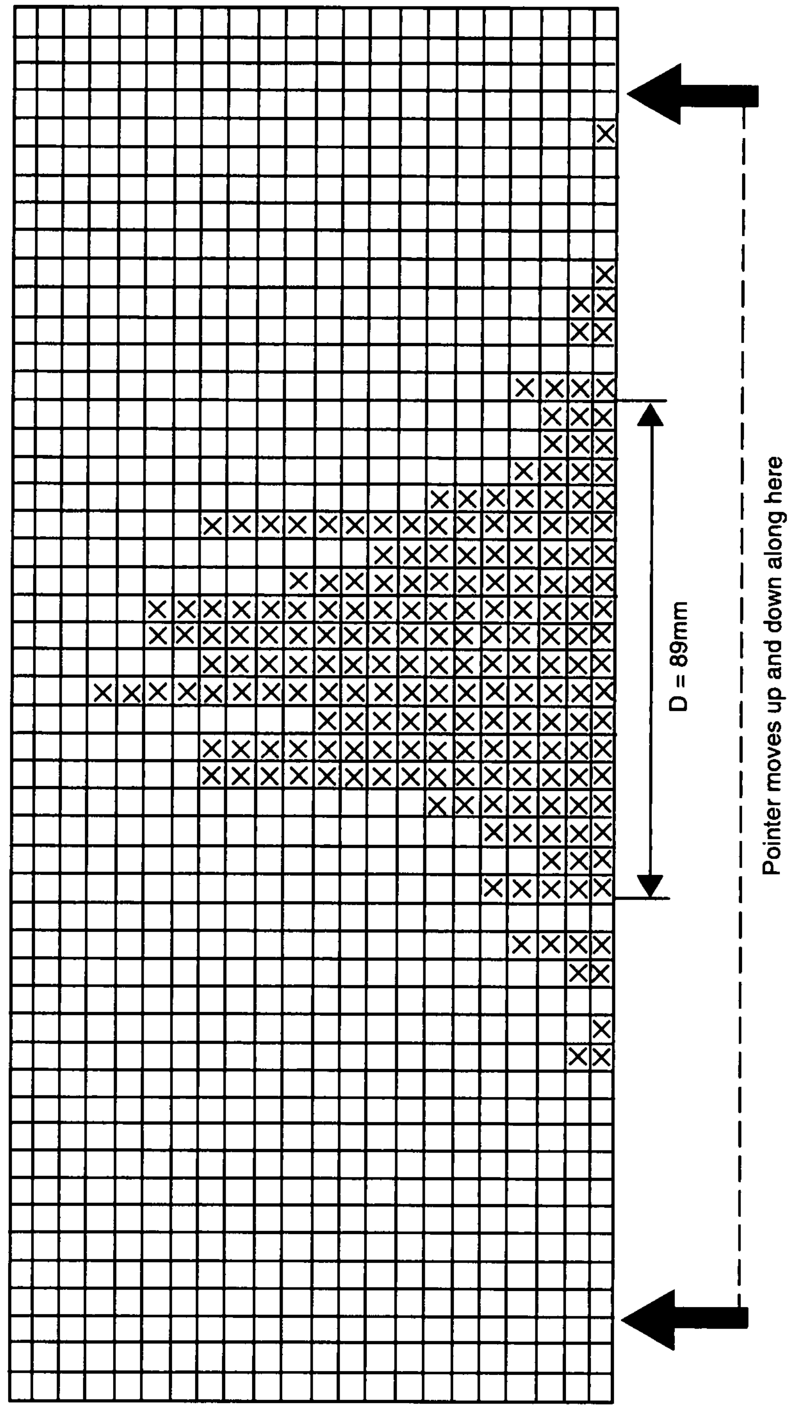


Fig. 4 Typical completed chart

Neg. No. R114690/4

Plate 1 Merlin Mk1

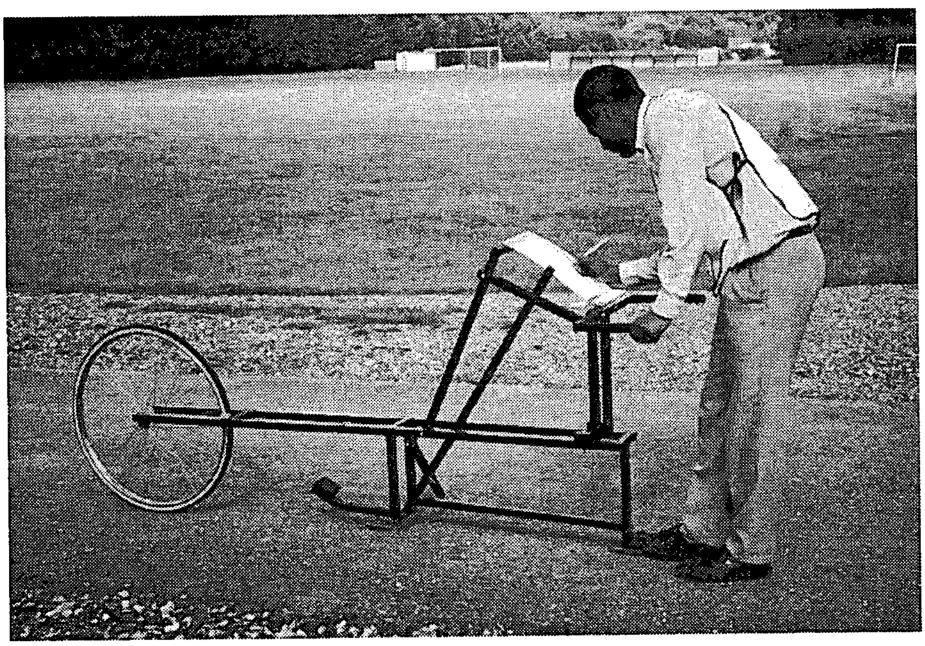


Plate 2 Merlin Mk2

2.4 ROUGHNESS EQUATIONS

For earth, gravel, surface dressed or asphaltic concrete roads, roughness can be determined using the equation

$$IRI = 0.593 + 0.0471\,D \qquad (1)$$

$$(2.4 < IRI < 15.9)$$

where IRI is the roughness in terms of the International Roughness Index (in m/km) and D is measured from the Merlin chart (in mm). The equation was derived over the range of IRI values shown and should be extrapolated with caution. Measurement of IRI values below 3 is not usually important because at this level, roughness has little effect on vehicle operating costs.

The standard error of the estimated IRI will be about 10%. If the measurement is repeated to give a second estimate of IRI (making sure that the feet are not placed in exactly the same positions), then the error of the mean will be around 8%.

The undulations in a road's surface consists of as a mixture of surface waves of different wavelengths. The sensitivity of the IRI scale varies with wavelength and it is highest for waves of around two metres. The sensitivity of the Merlin is also high at these wavelengths and that is why it gives a good estimate of IRI. However, at other wavelengths there are differences, the Merlin being more sensitive than the IRI to short waves and less sensitive to long waves.

Because of the different wavelength sensitivities, it is important to calibrate the bump integrator on a range of test sections whose surfaces are typical of the surfaces which the bump integrator is going to measure.

Some hand-laid surfaces have a much higher proportion of long waves and so they have a different relationship between IRI and D. A study in Indonesia gave the following equation for hand-laid penetration Macadam:

$$IRI = 1.913 + 0.0490\,D \qquad (2)$$

$$(6.7 < IRI < 11.3)$$

Section 6 describes how to convert between the BI and IRI scales.

3. FURTHER DESCRIPTION OF THE MACHINE

3.1 DESIGN DETAILS AND ASSEMBLY CONSIDERATIONS

A number of other design details should be noted:

- It is important to ensure that the feet and the probe are sufficiently well aligned that the lateral adjustment described in Section 3.2 can be carried out. If there is a problem with alignment, check to see if it can be rectified by adjusting the position of the wheel hub nuts. Failing that, it may be necessary to bend or twist the structure slightly to get it back into shape.

- The front tyre should have a smooth tread pattern. Any variation in the radius of the wheel plus tyre could affect the measurements and to overcome this, all measurements should be made with the wheel in the "normal position". The radius of the wheel plus tyre should be checked by spinning the wheel and carefully watching its circumference as it passes a fixed point. The marker should be positioned to avoid any sections where there are fluctuations in radius (tyre thickness often changes near the valve).

- To reduce sensitivity to road surface micro-texture, the probe and the rear foot are both 12 mm wide and rounded in the plane of the wheel track to a radius of 100 mm. The rounding also tends to keep the point of contact of the probe with the road in the same vertical line. The edge of the rear foot can be quite sharp and to prevent the user from accidentally catching his shins, a protective piece is fitted to the rear leg to shield the back of the rear foot.

- A metal guide is fitted near the chart to restrict the arm so that it can only move in a vertical plane over the wheel track. This protects the pivot by preventing the arm from being accidentally knocked sideways. It is important to check that the arm is free and not rubbing against the guide. A piece of rubber is fitted in one end of the guide to act as the end stop for the moving arm when the Merlin is lifted by the handles.

- Only one stabiliser should be used. If stabilisers are fitted on both sides of the Merlin, there is a danger that on very rough surfaces, especially with deep wheel ruts, the Merlin may rest on its stabilisers with one of the feet clear of the ground.

3.2 ALIGNMENT

Before the Merlin can be used, the position of the probe has to be vertically and laterally adjusted so that it is correctly aligned with the front and rear feet. The probe mounting is designed so that these adjustments can be carried out. The probe is fixed to a threaded rod which passes through a hole in the moving arm and is held in position by two nuts, one on each side of the hole. The vertical position of the probe can be adjusted by altering the position of the nuts. Lateral adjustment can be made at the same time because the hole is elongated transversely.

To carry out the alignment:

- turn the Merlin upside down and prop it up so that the moving arm is free
- stretch a piece of string tightly between the bottom of the tyre and the bottom of the rear foot
- pull the pointer end of the moving arm gently downwards. This will make the probe slowly rise towards the string.

Then check the two alignments (see Figure 5):

- Vertical alignment. When properly adjusted, the bottom of the probe will just touch the string when the pointer is at the centre of the chart. If correct, the histograms will be central on the chart.
- Lateral alignment. When properly adjusted, the string will run along the centre of the bottom of the probe. If correct, leaning the Merlin from side-to-side when making a measurement, for example to rest on the stabiliser, will have little effect on the pointer position.

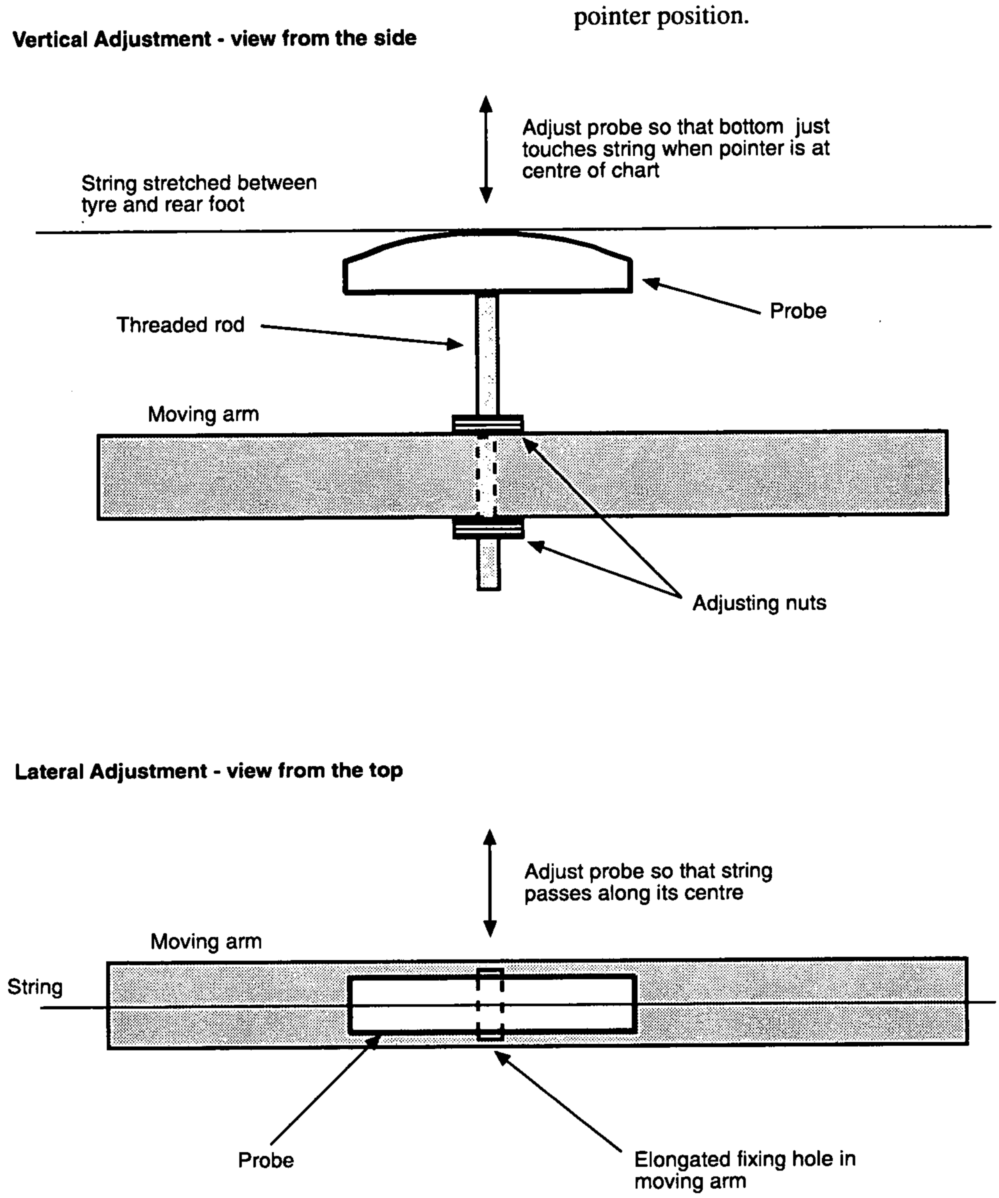


Fig. 5 Aligning the probe

3.3 AMPLIFICATION OF THE MOVING ARM

Normally, the moving arm has a mechanical amplification of about 10. As surface roughness increases, the scatter of points on the chart will increase. Points will start to collect in the columns at either end of the chart which correspond to the two limits of the arm movement. (See Figure 6). If the pointer is able to move off the end of the chart, then any points falling there should be plotted in the end column. If the number of points at each limit is 10 or less, D can still be measured in the normal way but if the number at either limit exceeds 10, then the chart cannot be used.

To overcome the problem, the probe can be moved to an alternative position on the moving arm which is twice as far from the pivot (Figure 7). This reduces the mechanical amplification of the arm to 5 and halves the width of the

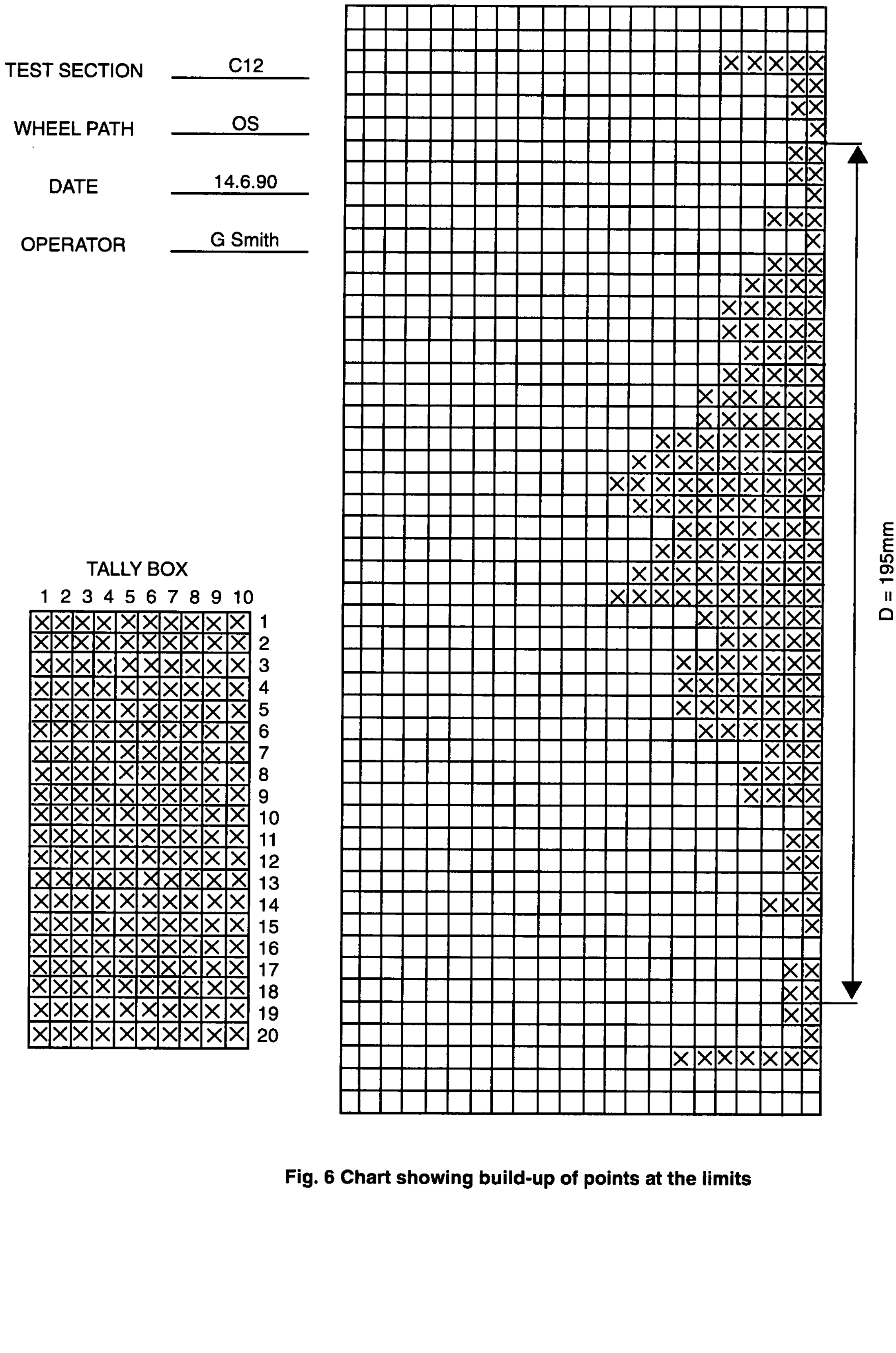
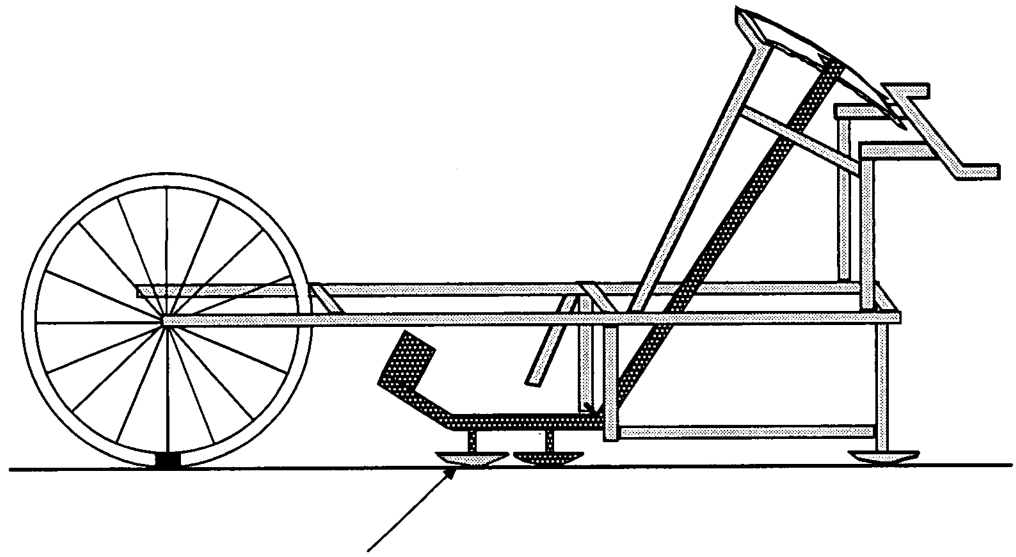


Fig. 6 Chart showing build-up of points at the limits



Alternative probe position for use on very rough roads. Reduces amplification of moving arm from 10 to 5

Fig. 7 Alternative probe position

distribution. With a mechanical amplification of 10, the maximum roughness that can be measured is around 10 on the IRI scale; with a mechanical amplification of 5, the Merlin should be able to deal with the highest roughness values normally encountered. When the probe is in its alternative position, it is no longer exactly midway between the front and rear feet. However, the errors introduced by this are small and can be ignored.

3.4 CALIBRATION

Equations 1 and 2 assume that D was derived using a mechanical amplification of 10. In practice this will not be true because of small errors in manufacturing and because the amplification of the arm might be set to 5. Before it can be used, therefore, the amplification has to be checked and the value of D adjusted. To do this, the Merlin is rested with the probe on a smooth surface and the position of the pointer on the chart is carefully marked by a line. The probe is raised and a calibration block of known thickness, made from machined metal, and measuring approximately 50 mm long, 25 mm wide and 6 mm thick is placed under the probe which is then lowered onto it.

The new position of the pointer is marked. The process should be repeated to check that the values are consistent. If the space between the two marks is S and the thickness of the block is T, then measurements made on the chart should be multiplied by the scaling factor :

$$\text{Scaling factor} = \frac{10\,T}{S} \qquad (3)$$

4. CHOICE OF TEST SECTION

4.1 LENGTH

If 200 measurements are taken, using a 26 inch bicycle wheel, one at each wheel revolution, then the length of the surveyed section is 415 metres. For shorter or longer test sections, a different measuring procedure will be required. The guiding principles are:

- make the test sections at least 200 metres long
- take about 200 readings per chart. With less readings, accuracy will fall; with more readings, the chart will become cluttered. If the number of readings differs from 200, then the number of crosses counted in from each end of the distribution will have to change accordingly; 180 readings will mean counting in 9 crosses, 220 readings will mean counting in 11 crosses, etc.
- always take measurements with the wheel in its normal position. This not only prevents errors due to variations in radius but it also avoids operator bias - when asked to take measurements at random, Merlin operators often tend to avoid taking measurements where the ground is uneven
- take regularly-spaced measurements over the full length of the test section. This gives the most representative result

- if taking repeat measurements along a section, try to avoid taking readings at the same points on the different passes - start the second series of measurements half a metre after the point where the first series started.

Three examples are given below:

- for a test section 210 metres long, take the measurements in two passes, taking one reading every wheel revolution
- for a test section 280 metres long, take the measurements in two passes, taking one reading every wheel revolution on the first pass and one reading every two revolutions on the second.
- for a test section 500 metres long, take the measurements in one pass, taking one measurement every wheel revolution and skipping every fifth measurement

  or

- rather than skip readings, enlarge the tally box and take all 240 measurements. Measure the limits on the chart by counting in 12 rather than 10 points.

4.2 UNIFORMITY AND CORRUGATIONS

Test sections should have a fairly uniform roughness. If there are very large variations, the Merlin will tend to overestimate as it will be disproportionately affected by the roughest parts. One way to check on this is to use letters rather than crosses on the chart to identify where the measurements come from. For example, if the test section is being measured using 200 readings in a single pass, then mark the first 10 results with an "A" on both the histogram and the tally box, the next 10 results with a "B", etc. Then check that the extreme results are not coming just from one particular part of the test section.

Test sections containing major corrugations can also give rise to errors and should be avoided. There are three main problems with corrugated surfaces:

- the Merlin could give a poor estimate of IRI
- the vehicle-mounted bump integrator could give a poor estimate of IRI
- estimates of vehicle operating costs could be inaccurate.

4.3 IDENTIFICATION OF WHEEL TRACKS

The Merlin measures roughness along one wheel track at a time, and the roughness of a lane is taken as the average of the two separate wheel tracks. The difference between the wheel tracks is usually less than 20 per cent with the offside track having the higher value. However, the difference can be much higher, especially on gravel roads, and the nearside track can be rougher, especially on surface dressed roads. To measure the roughness of a multi-lane road, it will be necessary to measure the roughness of each lane separately.

When using the Merlin to measure the roughness of a test section for calibrating a vehicle-mounted bump integrator, it is important to ensure that both measuring devices are working in the same wheel tracks. Also, it is better to avoid sections where the wheel tracks have very different roughnesses. When using the Merlin on its own to measure roughness, the positions of the wheel tracks used by normal road traffic need to be identified. They may be evident from ruts or it may be necessary to watch traffic behaviour.

If IRI is derived as the mean roughness of n different wheel tracks, then the error will be $10/\sqrt{(n)}$ per cent.

5. PRACTICAL CONSIDERATIONS

5.1 NUMBER OF OPERATORS

The most convenient way of using the Merlin is to share the work between two operators, one wheeling the machine and the other taking the readings. The second operator, standing to one side, is better able to see if there are any problems with the probe or moving arm and can check that the machine is following the correct wheel path. By switching jobs, the two operators can keep working for much longer.

5.2 SAFETY

To protect the Merlin operators from traffic, a number of safety measures should be considered:

- place signs to warn traffic approaching the test section
- take measurements with the Merlin facing oncoming traffic
- ensure the operators wear fluorescent safety vests
- on busy sites, segregate the test section with traffic cones (cones are also useful for marking the ends of the wheel tracks).

5.3 ZERO CHECK

To check that there has been no unwanted movement in the Merlin, for example by the probe or pivot coming loose during a measuring session, it is recommended that, if possible, "zero checks" should be carried out.

To do this:

- securely tape a piece of paper to the chart holder. It remains there, under the charts, during the measuring session
- set up the Merlin on a smooth section of road with the wheel in the normal position
- mark with chalk the places where the wheel and the rear foot touch the road
- mark the position of the pointer on the paper
- from time to time during the session, return the Merlin to the chalk marks and, with the wheel in the normal position, check that the position of the pointer has not changed.

6. CONVERSION BETWEEN THE IRI AND BI SCALES

To convert from roughness measured on the BI scale (towed fifth wheel Bump Integrator travelling at 50 km/hr) to roughness on the IRI scale, the following simple equation is recommended:

$$IRI = 1 + 1.05\,(BI/1000) \qquad (4)$$

To convert from BI to IRI

1. Express the BI measurement in m/km rather than mm/km (i.e. divide by 1000)
2. Add 5 per cent
3. Add 1.

Although the equation does not pass through the origin, this will only cause problems at very low roughness values.

A more accurate conversion for individual machine-laid surface types is given in Table 1. The Table also shows the range of BI values over which the equations have been established.

7. ACKNOWLEDGEMENTS

The work presented in this Report was carried out in the Overseas Centre of the Transport Research Laboratory (Programme Director: John Rolt) under the Technology Development Research Programme of the Engineering Division, Overseas Development Administration.

TABLE 1

Roughness Conversion Equations
IRI = A0 + A1 (BI/1000)

Surface type	A0	A1	BI (min)	BI (max)
Asphaltic concrete	0.32	1.45	1,270	5,370
Surface dressed	-0.05	1.25	2,145	4,920
Gravel	1.25	1.13	2,010	12,225
Earth	1.47	0.92	2,935	16,750

8. REFERENCES

CUNDILL, M A (1991). The Merlin low-cost road roughness measuring machine. TRL Research Report 301. Transport Research Laboratory, Crowthorne.

CUNDILL, M A (1996). The Merlin road roughness machine: further analysis of performance. TRL Project Report PR/OSC/107/96. Transport Research Laboratory, Crowthorne. Unpublished.

SAYERS,W S et al (1986). Guidelines for conducting and calibrating road roughness measurements. World Bank Technical Paper Number 46. The World Bank, Washington D.C.