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Department of Transport

The MERLIN low-cost road roughness measuring machine

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Digest of Research Report 301 **1991**

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INTRODUCTION

The longitudinal unevenness of a road's surface (normally termed its roughness) is an important measure of road condition and a key factor in determining vehicle operating costs on poor quality surfaces. A number of instruments have therefore been developed for measuring roughness but many of them are expensive, slow in use or require regular calibration.

The report describes a simple machine which has been designed especially for use in developing countries. It is called **MERLIN** - A **M**achine for **E**valuating **R**oughness using **L**ow-cost **IN**strumentation. It was designed using a computer simulation of its operation on road profiles measured in the International Road Roughness Experiment in Brazil. The device can be used either for direct measurement or for calibrating other instruments such as the vehicle-mounted Bump Integrator. Merlins are in use in a number of developing countries and can usually be made locally at a current cost of typically 250$ US.

PRINCIPLE OF OPERATION

The device has two feet and a probe which rest on the road surface along the wheel-track whose roughness is to be measured. The feet are 1.8 metres apart and the probe lies mid-way between them. The Merlin measures the vertical displacement between the road surface under the probe and the centre point of an imaginary line joining the two points where the road surface is in contact with the two feet. If measurements are taken at successive intervals along a road, then the rougher the surface, the greater the variability of the displacements. By plotting the displacements as a histogram on a chart mounted on the instrument, it is possible to measure their spread and the simulations have shown that this correlates well with road roughness, as measured on standard roughness scales.

Figure 2 shows a sketch of the Merlin. For ease of operation, a wheel is used as the front leg, while the rear leg is a rigid metal rod. On one side of the rear leg is a shorter stabilising leg which prevents the device from falling over when taking a reading. Projecting behind the main rear leg are two handles, so that the device looks in some ways like a very long and slender wheelbarrow. The probe is attached to a moving arm which is weighted so that the probe moves downwards, either until it reaches the road surface or the arm reaches the limit of its traverse. At the other end of the arm is attached a pointer which moves over the prepared data chart. The arm has a mechanical amplification of ten, so that a movement of the probe of one millimetre will produce a movement of the pointer of one centimetre. The chart consists of a series of columns, each 5 mm wide, and divided into boxes.

The recommended procedure to determine the roughness of a stretch of road is to take 200 measurements at regular intervals, say once every wheel revolution. At each measuring point, the machine is rested on the road with the wheel, rear foot, probe, and stabiliser all in contact with the road surface. The operator then records the position of the pointer on the chart with a cross in the appropriate column and, to keep a record of the total number of observations, makes a cross in the 'tally box' on the chart. The handles of the Merlin are then raised so that only the wheel remains in contact with the road and the machine is moved forward to the next measuring point where the process is repeated. Figure 3 shows a typical completed chart.

When the 200 observations have been made, the chart is removed from the Merlin. The positions mid-way between the tenth and the eleventh crosses, counting in from each end of the distribution, are marked on the chart below the columns. It may be necessary to interpolate between column boundaries, as shown by the lower mark of the example. The spacing between the two marks, D, is then measured in millimetres and this is the roughness on the Merlin scale. Road roughness, in terms of the International Roughness Index or as measured by a towed fifth wheel bump integrator, can then be determined using one of the equations given in the report.

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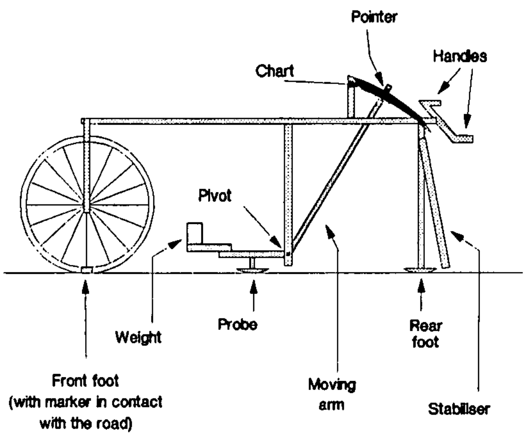

Figure 2 Sketch of the Merlin

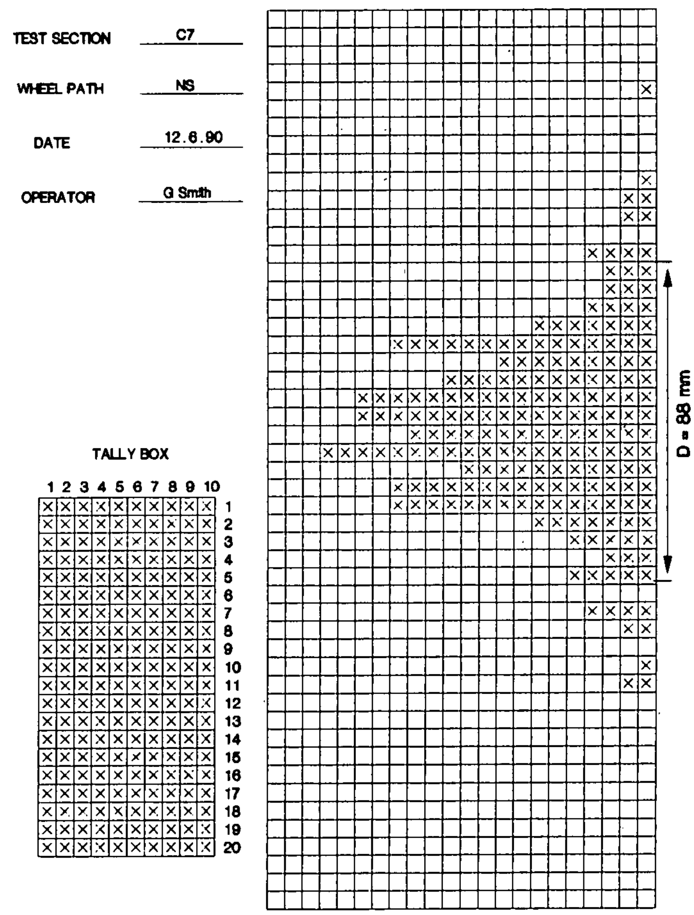

Figure 3 Typical completed chart

The work described in this Digest forms part of the programme carried out by the Overseas Unit (Unit Head: Mr J S Yerrell) of TRRL for the Overseas Development Administration, but the views expressed are not necessarily those of the Administration.

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TRANSPORT AND ROAD RESEARCH LABORATORY
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THE MERLIN LOW-COST ROAD ROUGHNESS MEASURING MACHINE

ABSTRACT

The roughness of a road's surface is an important measure of road condition and a key factor in determining vehicle operating costs on poor quality surfaces. This report describes a simple roughness measuring machine which has been designed especially for use in developing countries. It is called MERLIN - a Machine for Evaluating Roughness using Low-cost INstrumentation. The device can be used either for direct measurement or for calibrating response type instruments such as the vehicle-mounted bump integrator. It consists of a metal frame 1.8 metres long with a wheel at the front, a foot at the rear and a probe mid-way between them which rests on the road surface. The probe is attached to a moving arm, at the other end of which is a pointer which moves over a chart. The machine is wheeled along the road and at regular intervals the position of the pointer is recorded on the chart to build up a histogram. The width of this histogram can be used to give a good estimate of roughness in terms of the International Roughness Index. Calibration of the device was carried out using computer simulations of its operation on road profiles measured in the 1982 International Road Roughness Experiment. Merlins are in use in a number of developing countries. They can usually be made locally at a current cost of typically 250$ US.

1. INTRODUCTION

The longitudinal unevenness of a road's surface (normally termed its roughness) is both a good measure of the road's condition and an important determinant of vehicle operating costs and ride quality. Within developing countries, there is particular interest in the effect on vehicle operating costs. A number of studies (Hide et al 1975, Hide 1982, CRRI 1982, Chesher & Harrison 1987) have shown how roughness can influence the cost of vehicle maintenance, the extent of tyre damage and vehicle running speeds (and hence vehicle productivity).

Reliable measurement of road roughness is therefore seen as an important activity in road network management. Several different road roughness scales have been established and a variety of roughness measuring machines have been developed. However, it was felt that there was a need, particularly within developing countries, for a new simple type of measuring instrument which could be used either directly to measure roughness over a limited part of the road network or for calibrating other roughness measuring equipment, particularly the very widely used vehicle-mounted bump integrator.

2. ROUGHNESS MEASURING INSTRUMENTS

Roughness measuring instruments can be grouped into three different classes. The simplest in concept are the static road profile measuring devices such as the rod and level, which measure surface undulations at regular intervals. Unfortunately, these devices are very slow in use and there can be a considerable amount of calculation involved in deriving roughness levels from the measurements taken.

Two recent devices which work on a similar principle but are semi-automated are the TRRL Abay beam (Abaynayaka 1984) and the modified 'Dipstick profiler' (Face Company). With both of these instruments, the surface undulations are measured from a static reference and data is fed directly into a microprocessor to do the necessary calculations. They produce high quality results, but they are relatively slow in operation and expensive.

The second class of instrument is the dynamic profile measuring device, such as the TRRL high-speed profilometer (Still and Jordan 1980). In these instruments, surface undulations are measured with respect to a moving platform equipped with some means of compensating for platform movement, so that the true road profile can be derived. This is then converted to roughness indices by automatic data processing. These devices can operate at high speeds and give good quality results, but they are very expensive, they are not usually suitable for very rough roads and they have to be carefully maintained.

Finally, there are the response-type road roughness measuring systems (RTRRMS). These measure the cumulative vertical movements of a wheel or axle with respect to the chassis of a vehicle as it travels along the road. In the case of a standard device such as the towed fifth wheel bump integrator (BI) (Jordan and Young 1980), the response is used directly as a roughness index. In other non-standard devices, such as the vehicle-mounted BI, the response is converted to a standard roughness measure by calibration. The towed fifth wheel BI is expensive and needs careful operation. The vehicle-mounted BI, however, is much cheaper and can perform well as long as it is correctly used and is calibrated regularly.

The standard roughness scale which has been used for many years by the Overseas Unit of TRRL in its studies on vehicle operating costs and pavement deterioration is the output of the fifth wheel BI towed at 32 km/h. However, another scale which is now being widely used is the International Roughness Index (Sayers et al 1986a). This scale, which is derived from road profile data by a fairly complex mathematical procedure, represents the vertical movement of a wheel with respect to a chassis in an idealised suspension system, when travelling along the road at 80 km/h. As with the BI scale, it is measured in terms of units of vertical movement of the wheel per unit length of road, and is normally quoted in metres per kilometre. Traditionally, the BI scale is normally quoted in millimetres per kilometre.

3. THE MERLIN

The new instrument which has been developed is a variation of the static profile measuring device. It is a manually operated instrument which is wheeled along the road and measures surface undulations at regular intervals. Readings are easily taken and there is a graphical procedure for data analysis so that road roughness can be measured on a standard roughness scale without the need for complex calculation. Its particular attractions for use in the developing world are that it is robust, inexpensive, simple to operate, and easy to make and maintain.

The device is called **MERLIN**, which is an acronym for a **M**achine for **E**valuating **R**oughness using **L**ow-cost **IN**strumentation. It was designed on the basis of a computer simulation of its operation on road profiles measured in the International Road Roughness Experiment (Sayers et al 1986a). Details of this simulation are given in Appendix A.

3.1 PRINCIPLE OF OPERATION

The principle of operation is as follows. The device has two feet and a probe which rest on the road surface along the wheel-track whose roughness is to be measured. The feet are 1.8 metres apart and the probe lies mid-way between them (see Figure 1). The device measures the vertical displacement between the road surface under the probe and the centre point of an imaginary line joining the two points where the road surface is in contact with the two feet. This displacement is known as the 'mid-chord deviation'.

If measurements are taken at successive intervals along a road, then the rougher the road surface, the greater the variability of the displacements. By plotting the displacements as a histogram on a chart mounted on the instrument, it is possible to measure their spread and this has been found to correlate well with road roughness, as measured on standard roughness scales.

The concept of using the spread of mid-chord deviations as a means of assessing road roughness is not new. For example, two roughness indices, QI_r and MO, have been proposed by other researchers and are described by Sayers et al (1986a). They are each based on the root

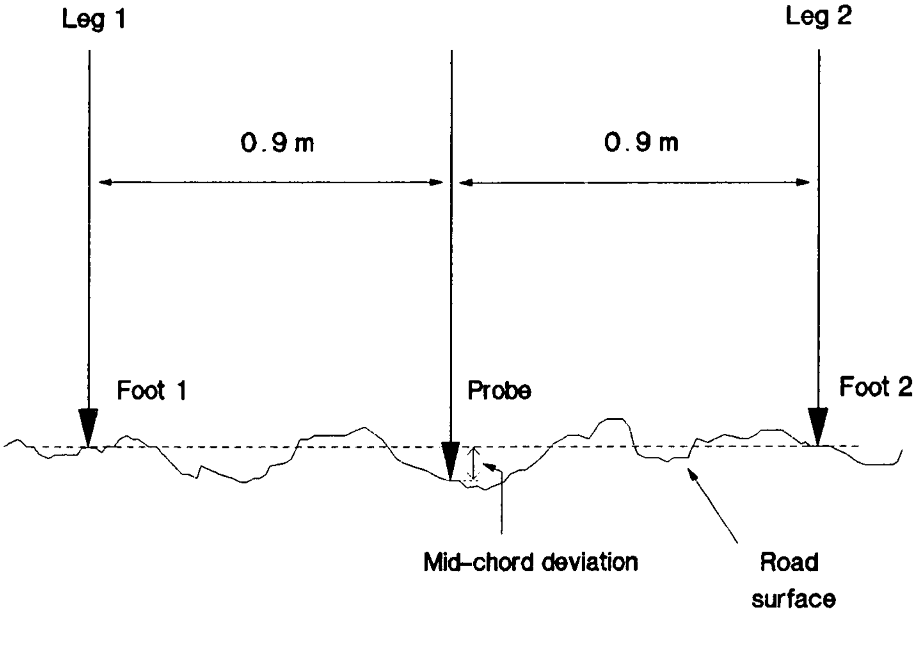

Figure 1. Measurement of mid-chord deviation

mean square values of two mid-chord deviations with different base lengths and have been suggested as standards which can be calculated relatively easily from road profiles measured by rod and level.

However, the Merlin operates by using just one base length, the machine measures mid-chord deviations without the need for rod and level, the variability of the mid-chord deviations is determined graphically and very little calculation is involved to determine roughness.

3.2 GENERAL DESCRIPTION

Figure 2 shows a sketch of the Merlin. For ease of operation, a wheel is used as the front leg, while the rear leg is a rigid metal rod. On one side of the rear leg is a shorter stabilising leg which prevents the device from falling over when taking a reading. Projecting behind the main rear leg are two handles, so that the device looks in some ways like a very long and slender wheelbarrow.

The probe is attached to a moving arm which is weighted so that the probe moves downwards, either until it reaches the road surface or the arm reaches the limit of its traverse. At the other end of the arm is attached a pointer which moves over the prepared data chart. The arm has a mechanical amplification of ten, so that a movement of the probe of one millimetre will produce a movement of the pointer of one centimetre. The chart consists of a series of columns, each 5 mm wide, and divided into boxes.

If the radius of the wheel is not uniform, there will be a variation in the length of the front leg from one measurement to the next and this will give rise to inaccuracy in the Merlin's results. To overcome this, a mark is painted on the rim of the wheel and all measurements are taken with the mark at its closest proximity to the road. The wheel is then said to be in its 'normal position'.

3.3 METHOD OF USE

The recommended procedure to determine the roughness of a stretch of road is to take 200 measurements at regular intervals, say once every wheel revolution. At each measuring point, 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 operator then records the position of the pointer on the chart with a cross in the appropriate column and, to keep a record of the total number of observations, makes a cross in the 'tally box' on the chart.

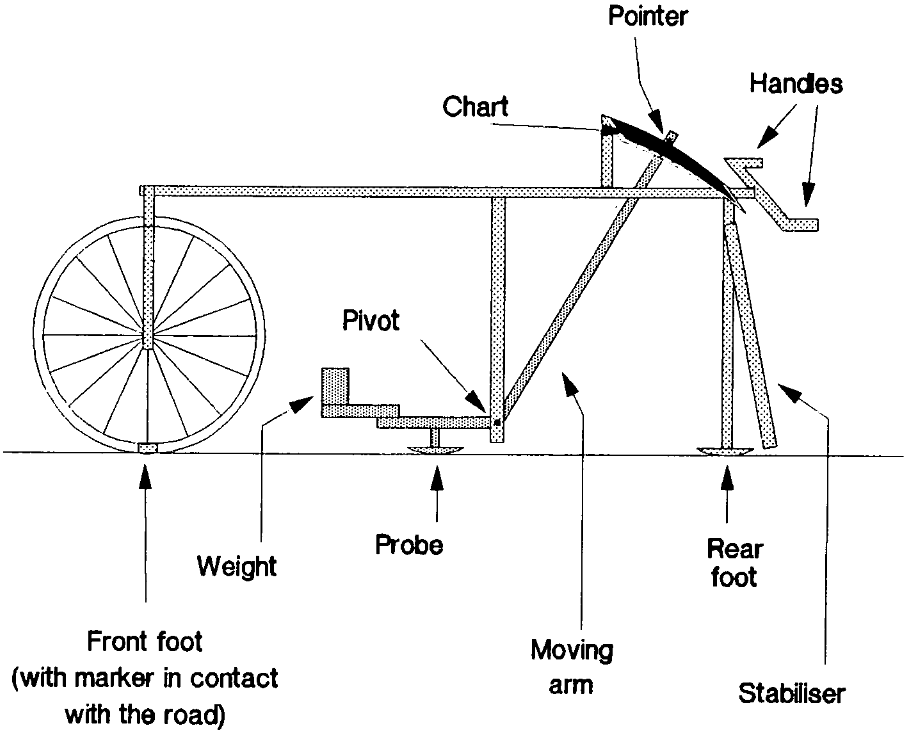

Figure 2. Sketch of the Merlin

The handles of the Merlin are then raised so that only the wheel remains in contact with the road and the machine is moved forward to the next measuring point where the process is repeated. The spacing between the measuring points does not matter, as long as the readings are always taken with the wheel in the normal position. Taking measurements at regular intervals should both produce a good average sample over the whole length of the section and reduce the risk of bias due to the operator tending to avoid particularly bad sections of road. Figure 3 shows a typical completed chart.

When the 200 observations have been made, the chart is removed from the Merlin. The positions mid-way between the tenth and the eleventh crosses, counting in from each end of the distribution, are marked on the chart below the columns. It may be necessary to interpolate between column boundaries, as shown by the lower mark of the example. The spacing between the two marks, D, is then measured in millimetres and this is the roughness on the Merlin scale. Road roughness, in terms of the International Roughness Index or as measured by a towed fifth wheel bump integrator, can then be determined using one of the equations given in Section 4.

3.4 PRACTICAL DETAILS

Plates 1 and 2 show the Merlin. For ease of manufacture, the main beam, the central and rear legs, the moving arm, the stabiliser and the handles are all made from steel tubing of square cross-section, 25 x 25 mm with wall thickness of 1.5 mm. 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. The wheel can be

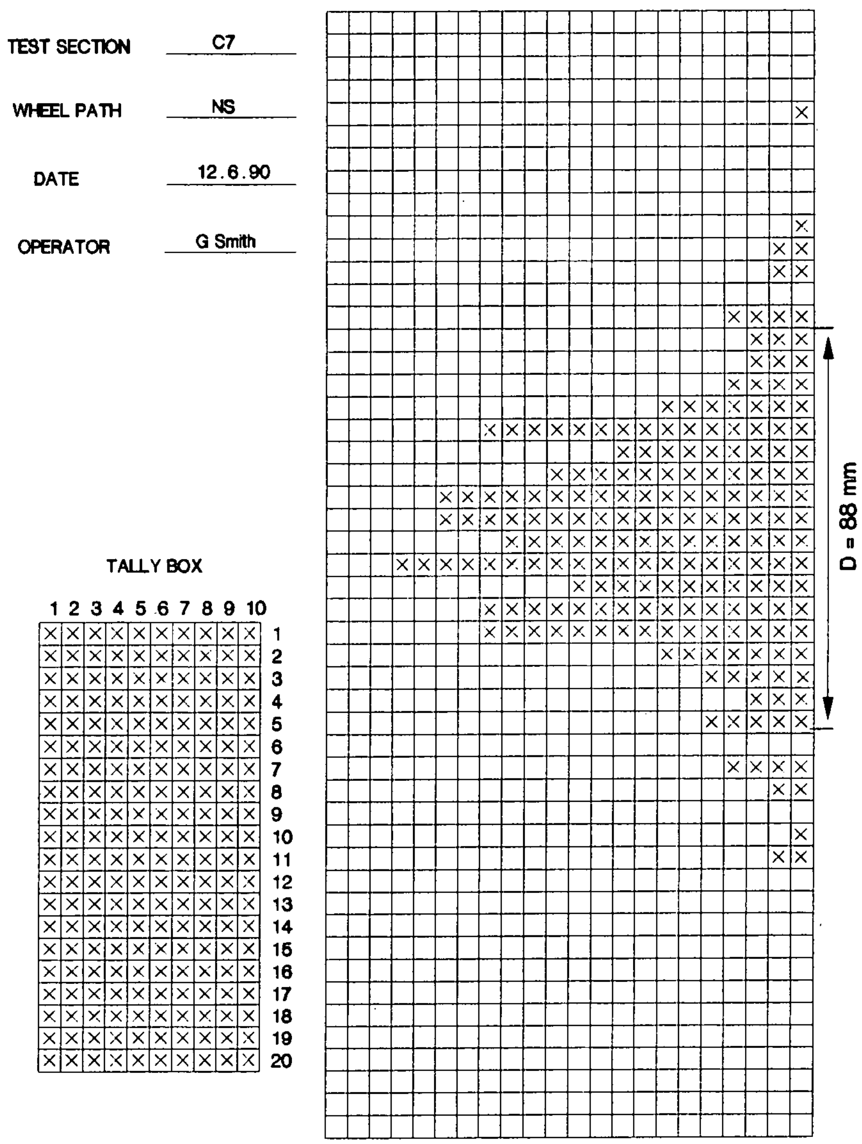

Figure 3. Typical completed chart

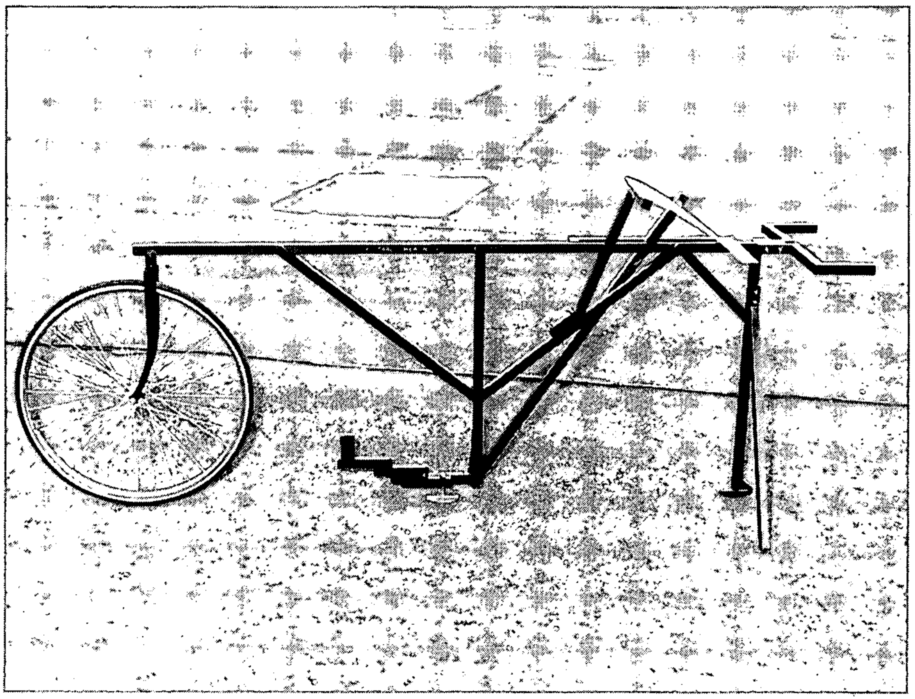

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Plate 1 General view

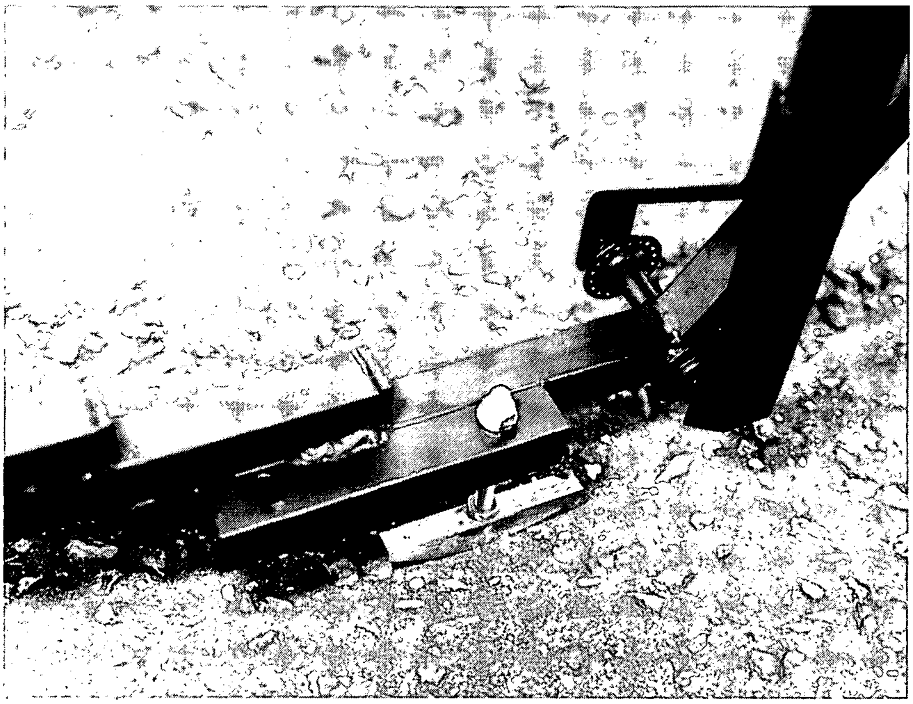

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Plate 2 Close-up of probe and moving arm

any type of common bicycle wheel mounted in a pair of front forks and with a tyre which has a fairly smooth tread pattern.

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 pivot is made from a bicycle wheel hub and the arm between the pivot and the weight is stepped to avoid grounding on very rough roads.

The chart holder is made from metal sheet and is curved so that the chart is close to the pointer over its range of movement. To protect the arm from unwanted sideways movement, a guide is fixed to the side of the main beam, retaining the arm close to the beam. One end of this guide acts as a stop when the machine is raised by its handles.

The probe is attached to the moving arm by a threaded rod passing through an elongated hole: a system which allows both vertical and lateral adjustment. The vertical position of the probe must be set so that the pointer is close to the middle of the chart when the probe displacement is zero, or the histogram will not be central. The lateral position of the probe has to be adjusted so that its traverse passes centrally through the line joining the bottom of the tyre and the rear foot. If not, it will be found that when the machine is tilted from side to side, the pointer moves. When correctly adjusted, leaning the machine over to one side so that the stabiliser rests on the road has little effect on the position of the pointer.

Before use, the mechanical amplification of the arm should be checked using a small calibration block, typically 6 mm thick. Insertion of the block under the probe should move the pointer by 60 mm and any discrepancy has to be allowed for. For example, if the pointer moved by only 57 mm, then the value of D measured on the chart should be increased by a factor of 60/57.

It is also recommended that a check is carried out before and after each set of measurements to ensure that there has been no unwanted movement of critical parts such as the rear foot or the probe mounting. The check is carried out by returning the machine to a precisely defined position along the road and making sure that the same pointer reading is obtained.

If, when making measurements on a very rough road, more than 10 readings are at either limit of the histogram, the probe should be removed and attached to the alternative fixing point which is provided. This is twice as far from the pivot and reduces the mechanical amplification of the arm to 5, halving the width of the distribution. Values of D read from the chart are scaled using the calibration procedure described earlier. Although the spacing between the probe and the two feet is no longer 0.9 metres in this case, the errors introduced are small and can be ignored.

4. CALIBRATION EQUATIONS

The relationships between the Merlin scale and the BI and IRI scales are given below.

For all road surfaces:

$$IRI = 0.593 + .0471\ D \qquad (1)$$

$$42 > D > 312\ (2.4 > IRI > 15.9)$$

where IRI is the roughness in terms of the International Roughness Index and is measured in metres per kilometre and D is the roughness in terms of the Merlin scale and is measured in millimetres.

$$BI = -983 + 47.5\ D \qquad (2)$$

$$42 > D > 312\ (1{,}270 > BI > 16{,}750)$$

where BI is the roughness as measured by a fifth wheel bump integrator towed at 32 km/h and is measured in millimetres per kilometre.

When measuring on the BI scale, greater accuracy can be achieved by using the following relationships for different surface types.

Asphaltic concrete

$$BI = 574 + 29.9\ D \qquad (3)$$

$$42 < D < 177\ (1{,}270 < BI < 5{,}370)$$

Surface treated

$$BI = 132 + 37.8\ D \qquad (4)$$

$$57 < D < 124\ (2{,}250 < BI < 4{,}920)$$

Gravel

$$BI = -1{,}134 + 44.0\ D \qquad (5)$$

$$77 < D < 290\ (2{,}010 < BI < 12{,}230)$$

Earth

$$BI = -2{,}230 + 59.4\ D \qquad (6)$$

$$84 < D < 312\ (2{,}940 < BI < 16{,}750)$$

These relationships are shown in graphical form in Figures 4 and 5. The equations were derived over the range of roughnesses shown and care should be used if extrapolating outside these ranges.

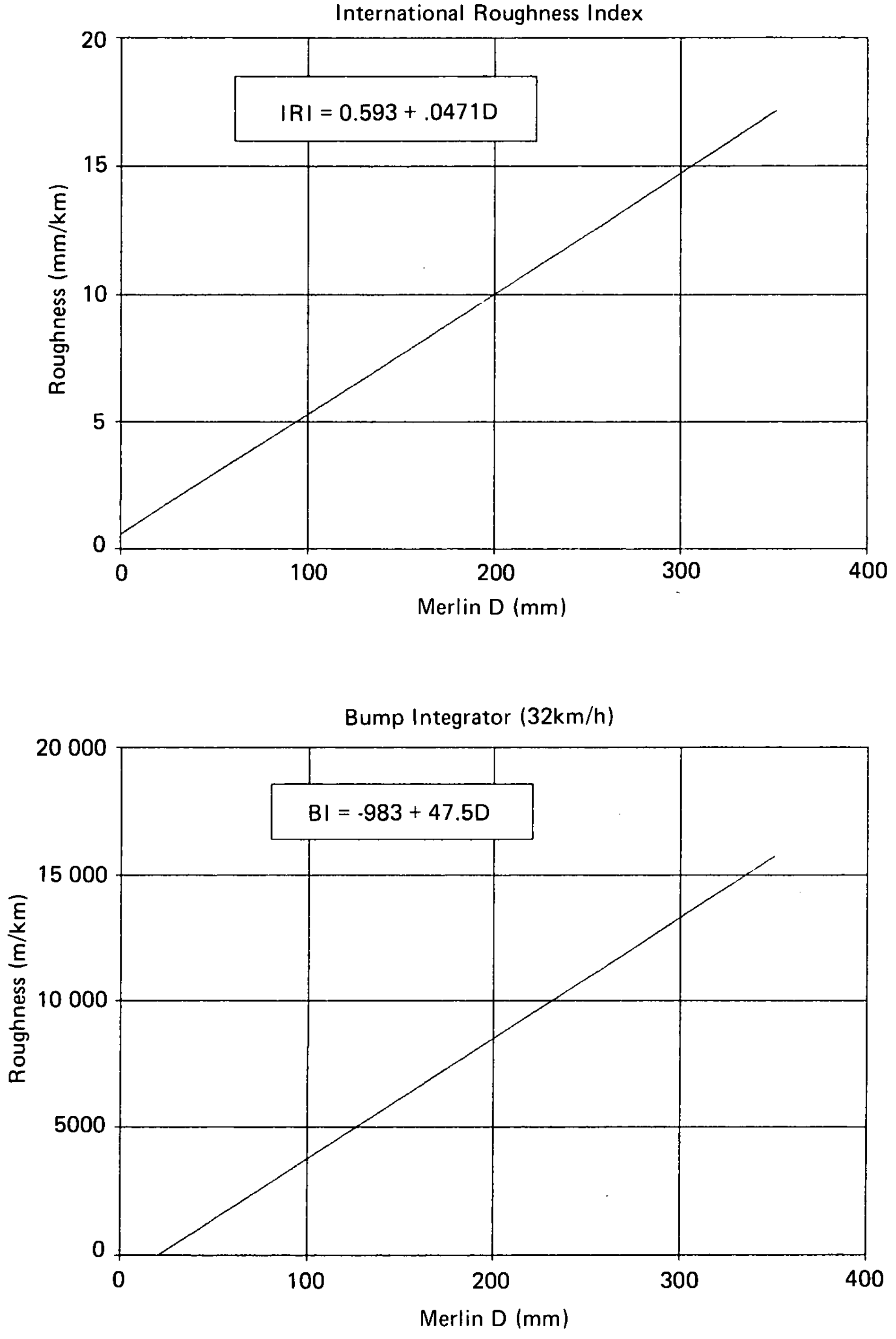

Figure 4. Calibration relationships

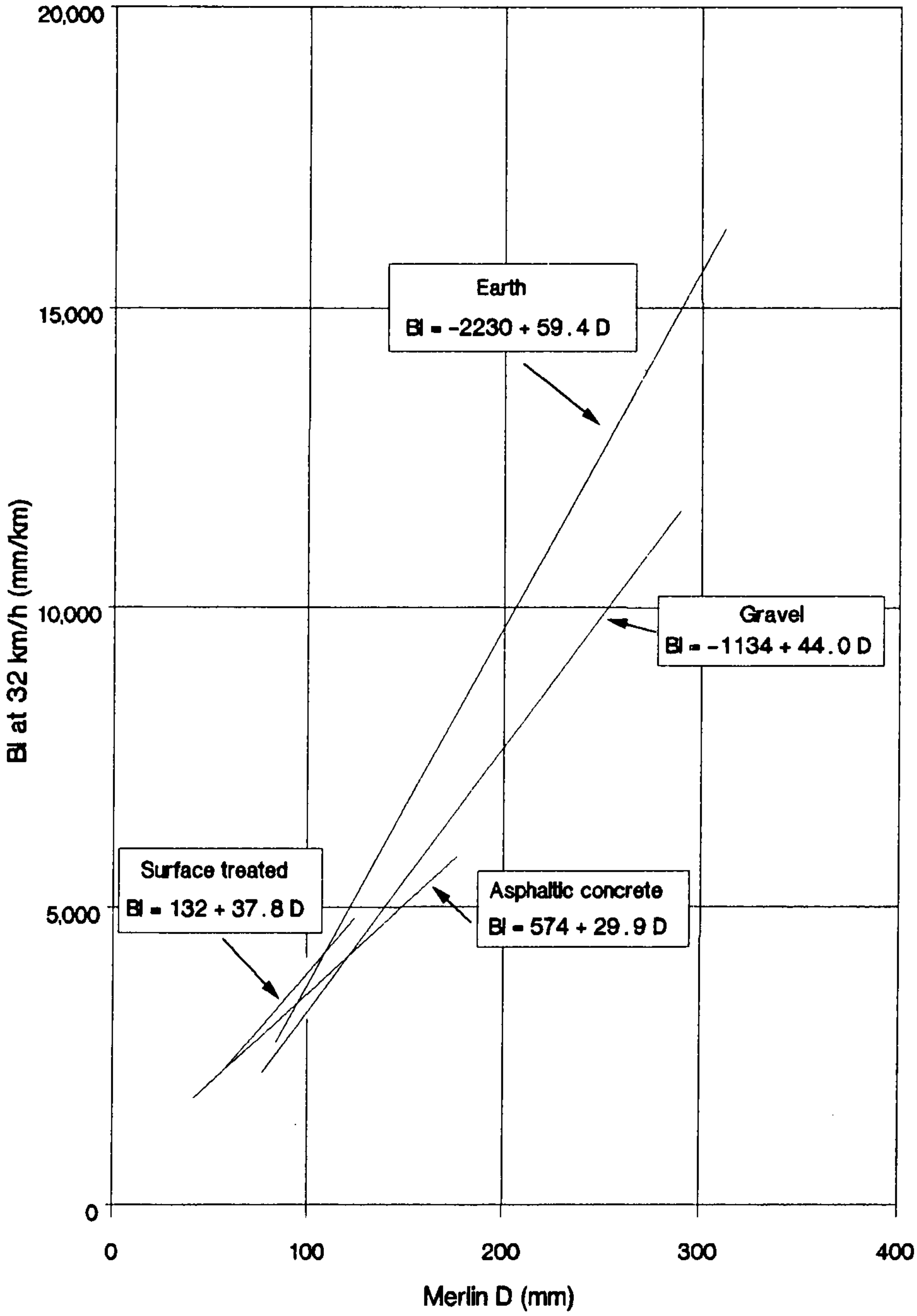

Figure 5. Calibration relationships for BI
- different surface types

5. ACCURACY OF MEASUREMENT

When using the Merlin to measure roughness, two considerations about accuracy have to be borne in mind. The first is that the Merlin measurement for a road section is derived from a sample of observations and so is subject to a random sampling error. This can be reduced by repeat observations on the same section. The second is that there are systematic differences between the roughness scales which can only be reduced by repeat observations on different road sections.

Undulations in a road's surface can be considered as surface waves with a spectrum of spatial frequencies (spectral signature). The IRI, BI and Merlin scales and any RTRRMS device being calibrated, all have different sensitivities to different spatial frequencies and so they correspond uniquely with each other only for surfaces with the same spectral signature. In practice, individual road sections have different spectral signatures, though there are broad similarities, especially between sections with the same surface type. Hence the relationship between the scales is not unique and this gives rise to the systematic differences mentioned above.

The relationships between the Merlin and the IRI scales are very similar for all the surface types examined whereas the relationships between the Merlin and the BI scales (and the IRI and BI scales) are clearly different for each surface type. This implies that the effective spectral sensitivity of the Merlin is closer to that of the IRI scale than the BI scale. It is interesting to note that the coefficients and constants in equations (3) to (6) follow a steady progression as the surfaces vary from asphaltic concrete to earth, presumably reflecting a progressive change in spectral signature.When the random error is greater than the systematic error, significant improvements can be made by repeat measurements on the same road section. If the systematic error increases, the benefit of repeat measurements on the same section decreases. Table 1, which was derived from the computer simulation, shows the mean residual error in roughness level for estimates based on one and four runs of the Merlin.

If roughness is being measured directly on the Merlin scale, then there are no systematic errors to contend with and the error falls with the reciprocal of the square root of the number of observations. As Table 1 shows, a single measurement gave a root mean square (RMS) residual error of 8 per cent while taking the mean of four observations halved the error to 4 per cent.

If measuring roughness on the IRI scale, taking four measurements gave an RMS residual error of 7 per cent, compared with 10 per cent when using single measure-

TABLE 1

Residual errors

Roughness scale	Surface type (*)	RMS residual error (%) *One observation*	*Four observations*
Merlin (mm)	All	8	4
IRI (m/km)	All	10	7
BI (mm/km)	All	21	19
BI (mm/km)	AC	15	13
BI (mm/km)	ST	9	4
BI (mm/km)	GR	14	11
BI (mm/km)	EA	12	11

* AC = Asphaltic concrete
ST = Surface treated
GR = Gravel
EA = Earth

ments. If working to the BI scale and using a single relationship for all surface types, systematic errors are much larger. The RMS residual error for single measurements was 21 per cent and this reduced only slightly to 19 per cent for four measurements.

The benefits of multiple measurements are greater when using separate BI relationships for each surface type: the RMS residual errors ranged from 9 to 15 per cent for single measurements compared with 4 to 13 per cent for multiple measurements. The relatively large error for asphaltic concrete compared to surface treated roads could well reflect the more limited roughness range for the latter and that the true relationships are non-linear.

When estimating roughness for a vehicle, the normal procedure is to assume that the combined roughness for the two wheel tracks can be equated to the mean of the individual tracks, although this does give rise to a small error. Hence, in practice, a minimum of two sets of Merlin observations are required. The roughness of the individual wheel tracks can differ considerably.

Bearing in mind the above limitations, it is normally better to calibrate an RTRRMS device at a larger number of sites than make many repeat measurements at the same site. Moreover, particularly if working on the BI scale, these sites should have similar surfaces to those on which the RTRRMS is to be used. A number of other practical points should be considered when measuring roughness or calibrating an RTRRMS and a useful guide is provided by Sayers et al (1986b).

As a simple cross-check on performance, roughness values on the Merlin scale were measured for a series of asphaltic concrete test sections on the TRRL experimental track. Four measurements were taken on each section and the mean values are shown plotted in Figure 6 against the roughness of each section on the BI scale as measured with the Abay beam (Abaynayaka 1984). The Figure also shows the Merlin-BI calibration line for asphaltic concrete roads as given in equation 3. As can be seen, the points lie very close to the calibration line and while the check is by no means comprehensive, it does lend strong support to the results derived from the simulation.

6. DISCUSSION

The reason for designing the Merlin was to provide a device which is easy to use and reasonably accurate and yet can be manufactured and maintained with the limited resources available within developing countries. Experience indicates that it has been successful in meeting these objectives. A number of the machines have been made at TRRL and shipped overseas, while other units have been made overseas from drawings provided by the Laboratory. To date, Merlins have been used in 11 developing countries in South America, Africa and Asia; in six of these, the equipment was made locally at current prices of typically 250 US dollars.

One inconvenience of the Merlin is that, because of its length, it is not easily transported within a vehicle. A shorter machine could be used but, as is shown in the Appendix, this will lead to some reduction in correlation with the IRI scale. Alternatively, a more portable design could be considered using a structure which folds or dismantles. While this is a possibility, it has been avoided because of the need to retain rigidity. Although its design is very simple, the Merlin is able to measure displacements to less than a millimetre and this ability could easily be compromised by unwanted flexing of the structure.

In recent years, there has been a move towards reducing the number of different roughness scales in use and standardising on the International Roughness Index. However, the Merlin scale does have the advantage of being easy to visualise and although Merlin readings can be converted easily to IRI values, in some cases this conversion is unnecessary and direct use of the Merlin scale should be considered.

7. ACKNOWLEDGEMENTS

This work forms part of the programme of research of the Overseas Unit (Head: J S Yerrell) of the Transport and Road Research Laboratory, UK.

8. REFERENCES

ABAYNAYAKA, S W (1984). Calibrating and standardising road roughness measurements made with response type instruments. In: ENPC. International Conference on Roads and Development, Paris, May 1984, pp13 - 18. Presses de l'ecole nationale des ponts et chaussees, Paris.

CHESHER, A and HARRISON, R (1987). Vehicle operating costs: evidence from developing countries. John Hopkins University Press, Baltimore and London.

CRRI (1982). Road user cost study in India: final report Central Road Research Institute, New Delhi.

FACE COMPANY. The Edward W. Face Company Inc, Norfolk,Virginia.

GILLESPIE, T D (1986). Developments in road roughness measurement and calibration procedures. In: ARRB. Proc. 13th ARRB - 5th REAAA Conf. 13(1), pp 91 - 112. Australian Road Research Board, Vermont South.

HIDE, H (1982). Vehicle operating costs in the Caribbean: results of a survey of vehicle operators. TRRL Laboratory Report 1031: Transport and Road Research Laboratory, Crowthorne.

HIDE, H et al (1975). The Kenya road transport cost study: research on vehicle operating costs. TRRL Laboratory Report 672: Transport and Road Research Laboratory, Crowthorne.

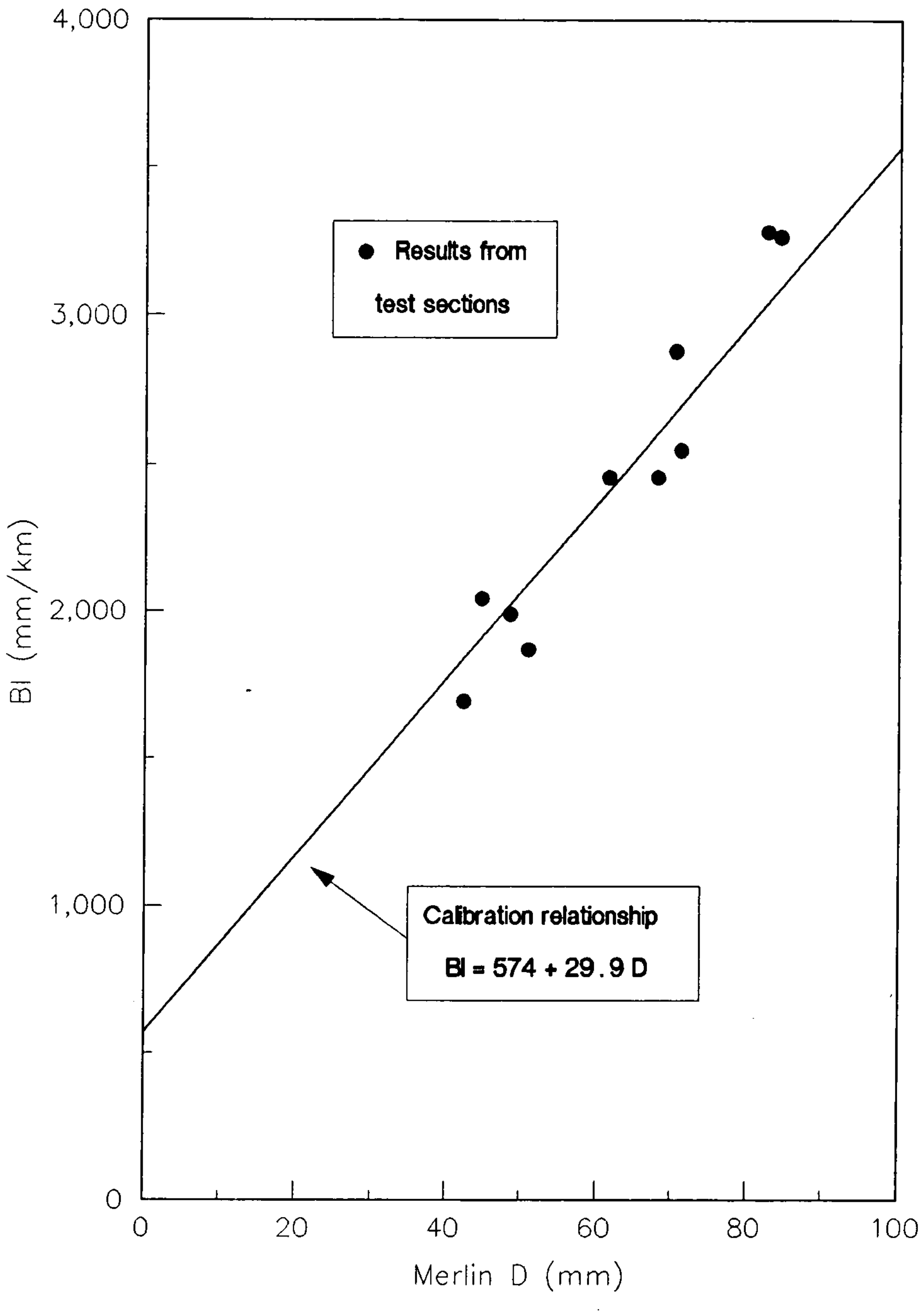

Figure 6. Calibration check on asphaltic concrete

JORDAN, P G and YOUNG, J C (1980). Developments in the calibration and use of the Bump-Integrator for ride assessment. TRRL Supplementary Report 604: Transport and Road Research Laboratory, Crowthorne.

SAYERS, W S et al (1986a). The International Road Roughness Experiment: establishing correlation and a calibration standard for measurements. World Bank Technical Paper Number 45. The World Bank, Washington D.C.

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

STILL, P B and JORDAN, P G (1980). Evaluation of the TRRL high-speed profilometer. TRRL Laboratory Report 922: Transport and Road Research Laboratory, Crowthorne.

APPENDIX A: SIMULATION OF PERFORMANCE

A.1 THE INTERNATIONAL ROAD ROUGHNESS EXPERIMENT

In 1982, a major study, the International Road Roughness Experiment (IRRE), was carried out in Brasilia (Sayers et al 1986a) to compare the performance of a number of different road roughness measuring machines and to calibrate their measures to a common scale. As part of this study, the machines were run over a series of test sections 320 metres long, for four types of road surface - asphaltic concrete, surface treated, gravel and earth. One of the instruments used in the study was an early version of the TRRL Abay Beam. This employed an aluminium beam, 3 metres in length, supported at each end by adjustable tripods which were used for levelling. Running along the beam was a sliding carriage which had at its lower end a wheel of 250 mm diameter which was in contact with the road surface. A linear transducer inside the carriage measured the distance between the bottom of the wheel and the beam to the nearest millimetre and this was recorded at 100 mm intervals along the road. By successively relocating the beam along the length of the road section and repeatedly levelling the beam, the recordings provided a continuous sampling of the road profile.

Data from the Abay beam were available for 27 of the test wheel paths. These are listed in Table A1 together with roughness on the IRI scale as computed from the beam road profile data and roughness on the BI scale as measured by a fifth wheel bump integrator towed at 32 km/h. As can be seen, there are eight paths on asphaltic concrete roads, five on surface treated roads, seven on gravel surfaces and seven on earth surfaces. Roughnesses range from 2.44 m/km on the IRI scale (1,270 mm/km on the BI scale) for the best asphaltic concrete surface to 15.91 m/km (16,750 mm/km on the BI scale) for the worst earth surface.

Figure A1 shows, as an example, the road profile as measured by the Abay Beam along 50 metres of two of the test sections. The first is an asphaltic concrete road in relatively good condition, while the second is a gravel surface in fair condition. As might be expected, compared to the asphaltic concrete, the gravel surface shows a much greater presence of short wavelength undulations. To help visualise the Merlin's response, the Figure also shows the machine's length, 1.8 metres, on the same scale.

A.2 SIMULATION RESULTS

Given these road profiles, it was possible to carry out a computer simulation of the performance of a Merlin. Neglecting the small effects due to the fact that the Merlin is not operated in a horizontal position, if it is assumed that the rear foot is placed at a horizontal distance of X metres from the start of the section, then the probe would be at a distance of (X + 0.9) metres from the start and the front foot at a distance of (X + 1.8) metres. If the corresponding vertical distances at these points are Y_0, Y_1 and Y_2, then the pointer on the Merlin will be displaced from the zero position by an amount d, given by

$$d = M \times (Y_1 - 0.5 \times (Y_2 + Y_0)) \quad (1)$$

where M is the mechanical amplification provided by the moving arm, usually close to 10.

Placing the Merlin at successive positions along the road is simulated by using successively increasing values of X. Tabulating the values of d into different 5 mm ranges corresponds to making crosses in the columns of the chart, and once 200 observations have been made, D can be deduced from the tabulation, using the process of counting in ten observations from each end of the distribution and interpolating where necessary.

For each of the test sections, four simulation runs were carried out. In each run, a Merlin reading was taken every 1.5 metres, so that the observations covered almost the entire test section. In the first run, the starting point was at the beginning of the test section. Subsequent runs started at 0.4, 0.8 and 1.2 metres from the beginning.

Table A2 shows the results of these simulations. Values of D for each of the four runs per section are denoted as D_1, D_2, D_3 and D_4. The Merlin's operation is essentially a statistical sampling of the road profile and the values of D show a statistical scatter with an average coefficient of variation of eight per cent. To reduce the effects of this scatter, mean values of the four simulation runs are used in the analyses.

A plot of roughness on the IRI scale against D for each of the test sections is shown in Figure A2. As can be seen, the points are a good fit to a linear regression passing close to, but not through, the origin. Table A3 gives the

TABLE A1

Test Sections

Sectn no.	Surface type(1)	Section code (2)	Wheel track (3)	IRI (m/km)	BI (mm/km)
1	AC	04	NS	4.76	3095
2	AC	04	OS	5.80	3465
3	AC	05	NS	5.68	4050
4	AC	05	OS	6.53	4390
5	AC	06	NS	6.96	4685
6	AC	06	OS	8.29	5370
7	AC	10	NS	3.29	1850
8	AC	12	OS	2.44	1270
9	ST	01	OS	4.51	3280
10	ST	04	OS	5.27	3705
11	ST	05	OS	7.00	4920
12	ST	06	NS	3.11	2250
13	ST	06	OS	3.41	2725
14	GR	01	NS	3.83	2010
15	GR	05	NS	8.50	5875
16	GR	05	OS	9.92	8095
17	GR	07	NS	4.11	2910
18	GR	07	OS	7.04	5025
19	GR	12	NS	11.65	8545
20	GR	12	OS	14.31	12225
21	EA	01	NS	4.39	2935
22	EA	01	OS	4.72	3865
23	EA	03	NS	6.03	4315
24	EA	03	OS	8.03	8385
25	EA	06	NS	15.91	16750
26	EA	11	NS	7.78	6855
27	EA	11	OS	10.78	10055

1. AC = Asphaltic concrete
   ST = Surface treated
   GR = Gravel
   EA = Earth

2. As used in the IRRE

3. NS = Nearside = Right
   OS = Off side = Left

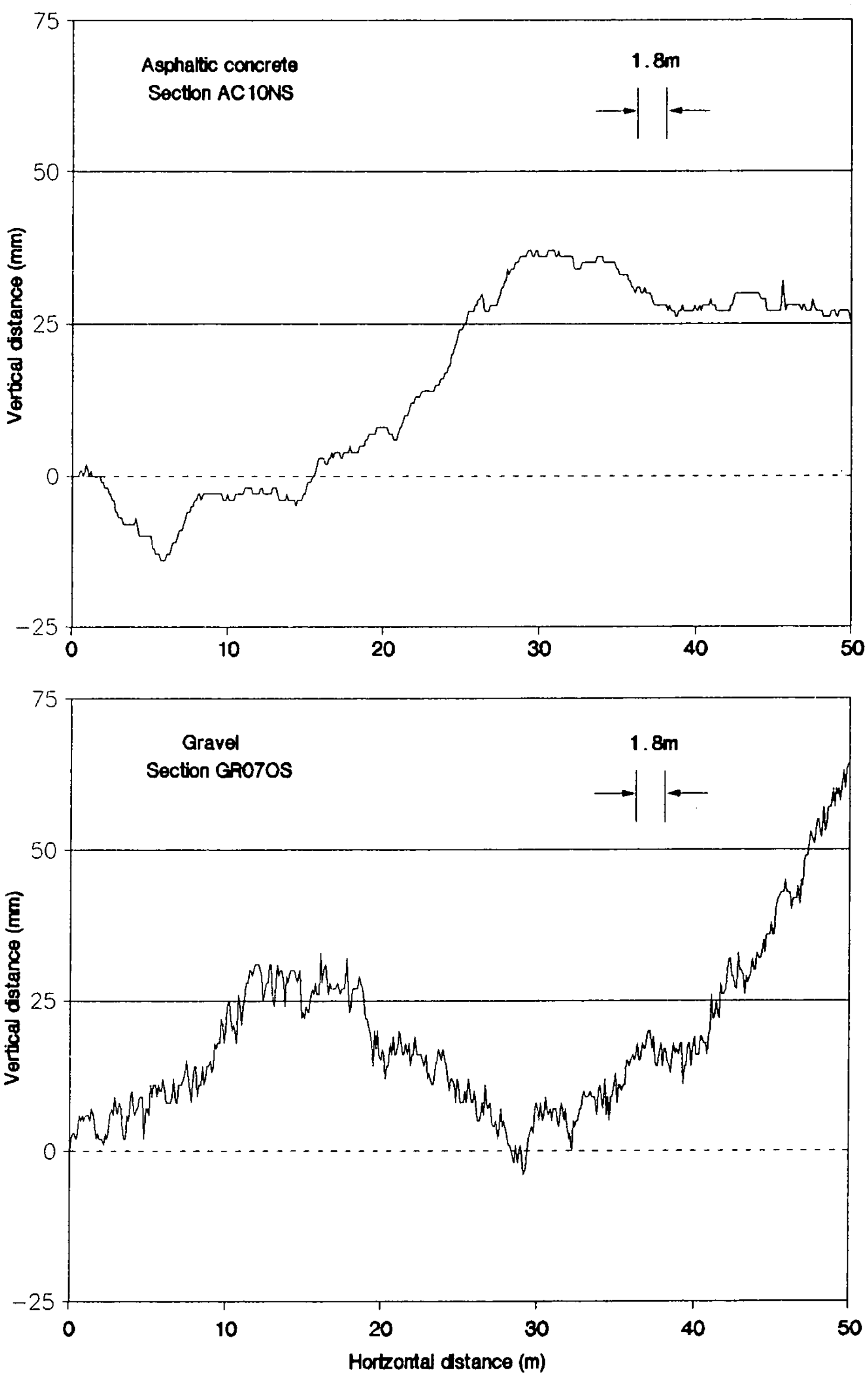

Fig.A1 Examples of test section profiles

TABLE A2

Simulation Results

Sectn no	Surface type (1)	IRI (m/km)	BI (mm/km)	D (mm) D_1	D_2	D_3	D_4	*Mean*
1	AC	4.76	3095	70.5	78.3	80.0	76.0	76.2
2	AC	5.80	3465	91.3	97.5	104.4	95.0	97.0
3	AC	5.68	4050	97.5	85.0	91.0	94.6	92.0
4	AC	6.53	4390	116.7	128.8	112.5	128.0	121.5
5	AC	6.96	46.85	117.1	118.0	181.3	123.0	134.8
6	AC	8.29	5370	185.0	190.0	162.5	168.3	176.5
7	AC	3.29	1850	45.0	57.0	53.4	40.6	49.0
8	AC	2.44	1270	40.8	52.3	42.7	30.3	41.5
9	ST	4.51	3280	75.0	84.8	92.5	79.3	82.9
10	ST	5.27	3705	100.6	107.5	94.4	95.1	99.4
11	ST	7.00	4920	115.0	137.0	132.5	111.9	124.1
12	ST	3.11	2250	50.4	63.6	59.2	53.6	56.7
13	ST	3.41	2725	65.0	64.7	73.1	61.5	66.1
14	GR	3.83	2010	74.2	78.3	77.9	75.5	76.5
15	GR	8.50	5875	141.3	169.2	152.5	162.5	156.4
16	GR	9.92	8095	205.0	180.0	204.2	184.2	193.3
17	GR	4.11	2910	85.7	81.3	102.5	75.0	86.1
18	GR	7.04	5025	137.5	140.8	150.0	155.0	145.8
19	GR	11.65	8545	215.0	232.5	285.0	255.0	246.9
20	GR	14.31	12225	295.0	277.5	272.5	315.0	290.0
21	EA	4.39	2935	80.0	88.3	85.4	81.7	83.8
22	EA	4.72	3865	85.8	100.0	96.7	87.5	92.5
23	EA	6.03	4315	122.0	134.2	123.3	105.0	121.1
24	EA	8.03	8385	157.0	165.8	150.0	170.8	160.9
25	EA	15.91	16750	287.5	330.0	320.0	310.0	311.9
26	EA	7.78	6855	178.8	175.0	163.8	171.7	172.3
27	EA	10.78	10055	215.0	222.5	217.5	203.3	214.6

1. AC = Asphaltic concrete
   ST = Surface treated
   GR = Gravel
   EA = Earth

regression coefficients together with their standard errors. The coefficient of determination (R^2) is over 0.98. Hence it appears that the Merlin can be used as a fairly accurate means of measuring roughness on the IRI scale.

Figure A3 shows a similar plot for roughness on the BI scale. Once again, the points can be fitted to a linear regression passing close to the origin. However, the fit to the line is not as good as for the IRI scale and the coefficient of determination is lower at just under 0.92. In part, this was to be expected since the BI value was determined independently using a dynamic measuring device whereas the IRI and Merlin values were both computed from the same static profile data. However, this is not the full explanation and better correlation can be achieved with a Merlin of different length as described in Section A.3.1.

Upon closer examination of Figure A3, it can be seen that there are consistent differences between the results for the different surface types. The analysis can therefore be improved by considering the different surface types separately and the result of doing so is shown in Figure A4. Table A3 lists the regression coefficients. The coefficient of determination ranges from 0.914 on asphaltic concrete surfaces to 0.987 on surface treated sections.

A.3 ALTERNATIVE PROCEDURES AND DESIGNS

The simulations described so far have used one sampling procedure, a Merlin of one particular size and one method of data analysis. In fact, the choice of these was based on other considerations and the results of other simulations.

The Merlin samples the road surface at a number of points, and the accuracy with which roughness can be deduced clearly depends upon the quality and size of the sample. It was felt that the best way of ensuring an unbiased result was to have a systematic sample with recordings taken at regular intervals. The sample size

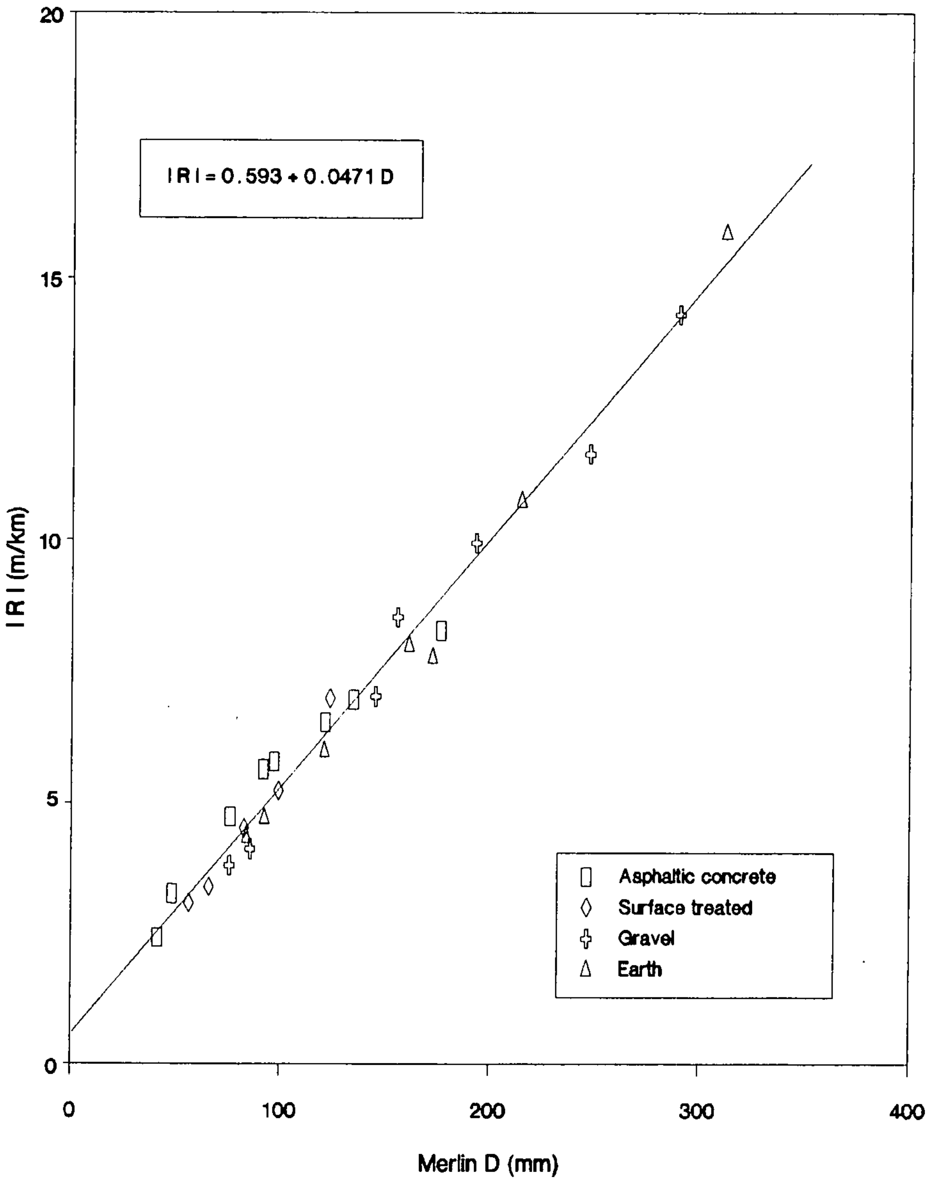

Fig.A2 Relationship between I R I and D

TABLE A3

Results of the Regression Analyses. (Roughness = $A_O + A_1.D$)

Roughness scale	Surface type (1)	A_O (2)	A_1 (2)	R^2	Number of sections
IRI (m/km)	All	0.593 (0.185)	0.0471 (0.0012)	0.983	27
BI (mm/km)	All	-983 (423)	47.5 (2.8)	0.918	27
BI (mm/km)	AC	574 (401)	29.9 (3.7)	0.914	8
BI (mm/km)	ST	132 (220)	37.8 (2.5)	0.987	5
BI (mm/km)	GR	-1134 (676)	44.0 (3.6)	0.967	7
BI (mm/km)	EA	-2230 (797)	59.4 (4.4)	0.973	7

1. AC = Asphaltic concrete
   ST = Surface treated
   GR = Gravel
   EA = Earth
2. Bracketed values are one standard error

(200 observations) was chosen as a practical upper limit from the point of view of managing the data handling and limiting the length of time taken to measure D.

A.3.1 Choice of machine length

The choice of machine length was examined by simulating Merlins of lengths ranging from 0.6 to 3 metres. Using the same procedure as that described above, and not distinguishing between the different types of surface, linear regressions were derived relating the value of roughness on the two measuring scales to D for each Merlin length.

Figure A5 shows the R^2 values for these regressions. On the IRI scale, the best correlations are between 1.4 and 2.6 metres. The highest value occurs at around 1.8 metres and so this was chosen as the standard Merlin length. Reducing the length below 1.4 metres causes a sharp decrease in correlation.

Turning to the results for the BI scale, the answer is quite different. Here the best correlation is more sharply defined and occurs at a Merlin length of one metre. The degree of correlation is not as good as the best IRI value, but this is to some extent explained by the fact that the BI value was determined by independent measurement.

The use of a one-metre Merlin is an attractive concept, since it would be considerably more portable than the 1.8 metre version. However, it would be a much poorer predictor of IRI and in practice it would be necessary to distinguish between the different surface types to reduce some of the uncertainty.

The underlying reason for the results of this analysis can be explained by considering the frequency sensitivities of the Merlin and the IRI and BI scales. The Merlin has a fundamental frequency response to surface waves of wavelength equal to its own base length, while the IRI and BI scales are particularly sensitive to surface waves which would stimulate the natural vibrations of a vehicle wheel (at about 10 Hz) and a chassis (at about 1 Hz).

At 80 km/h, the speed used for the IRI scale, the natural vibration of the wheel would be stimulated by surface waves of around 2.2 metres and the chassis by waves of around 22 metres. At 32 km/h, the speed used for the BI scale, the equivalent surface wavelengths are 0.9 metres and 9 metres respectively. Hence it appears that the correlation analysis has selected Merlin lengths such that the wavelength of the fundamental frequency is close to the wavelength of the surface waves which would stimulate the natural vibration of the wheel.

A.3.2 Measurement of data spread

Finally, the choice of method for determining the data spread should be described. Measuring the limits for a certain central percentage of the data points is an

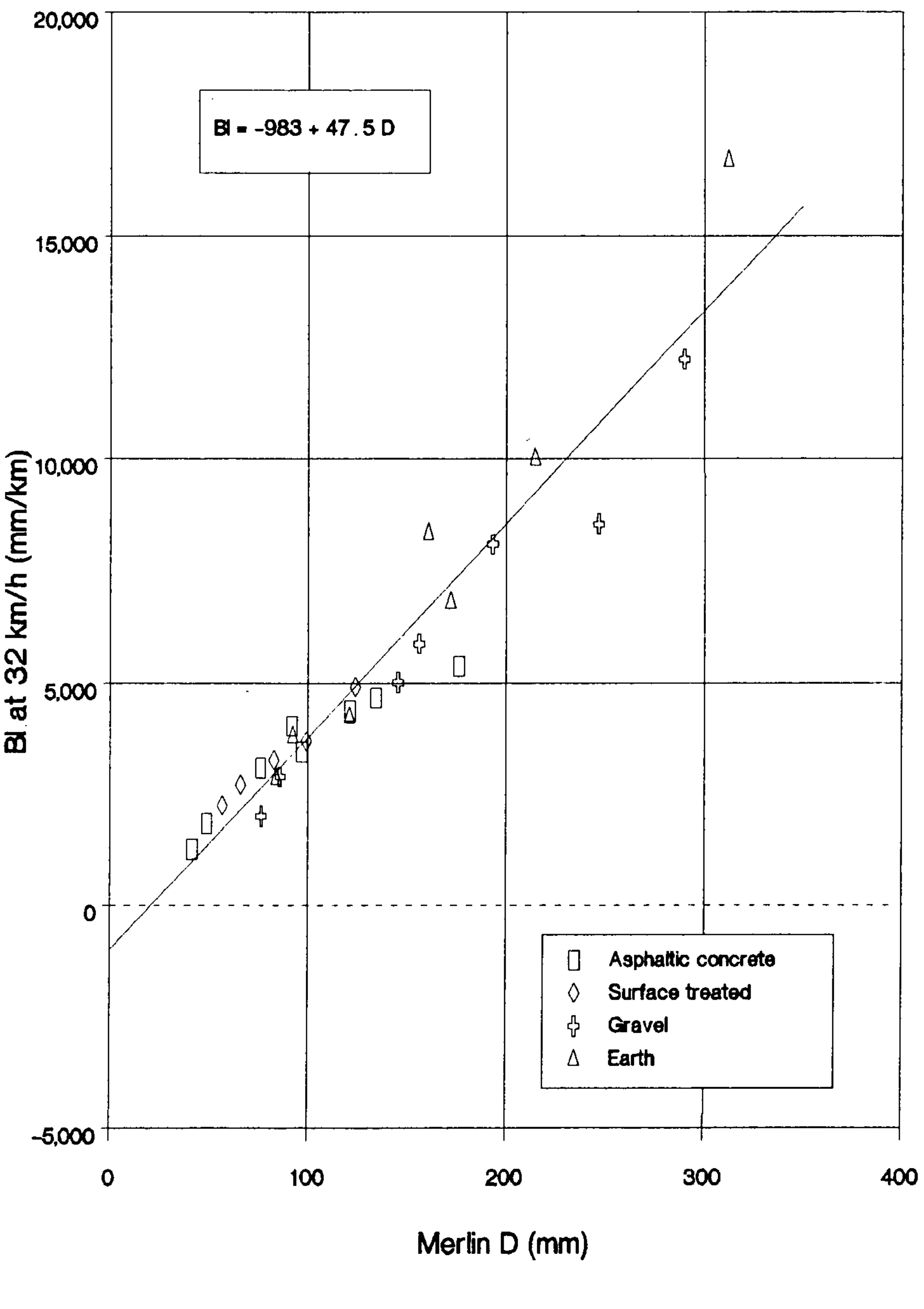

Figure A3. Relationship between BI and D

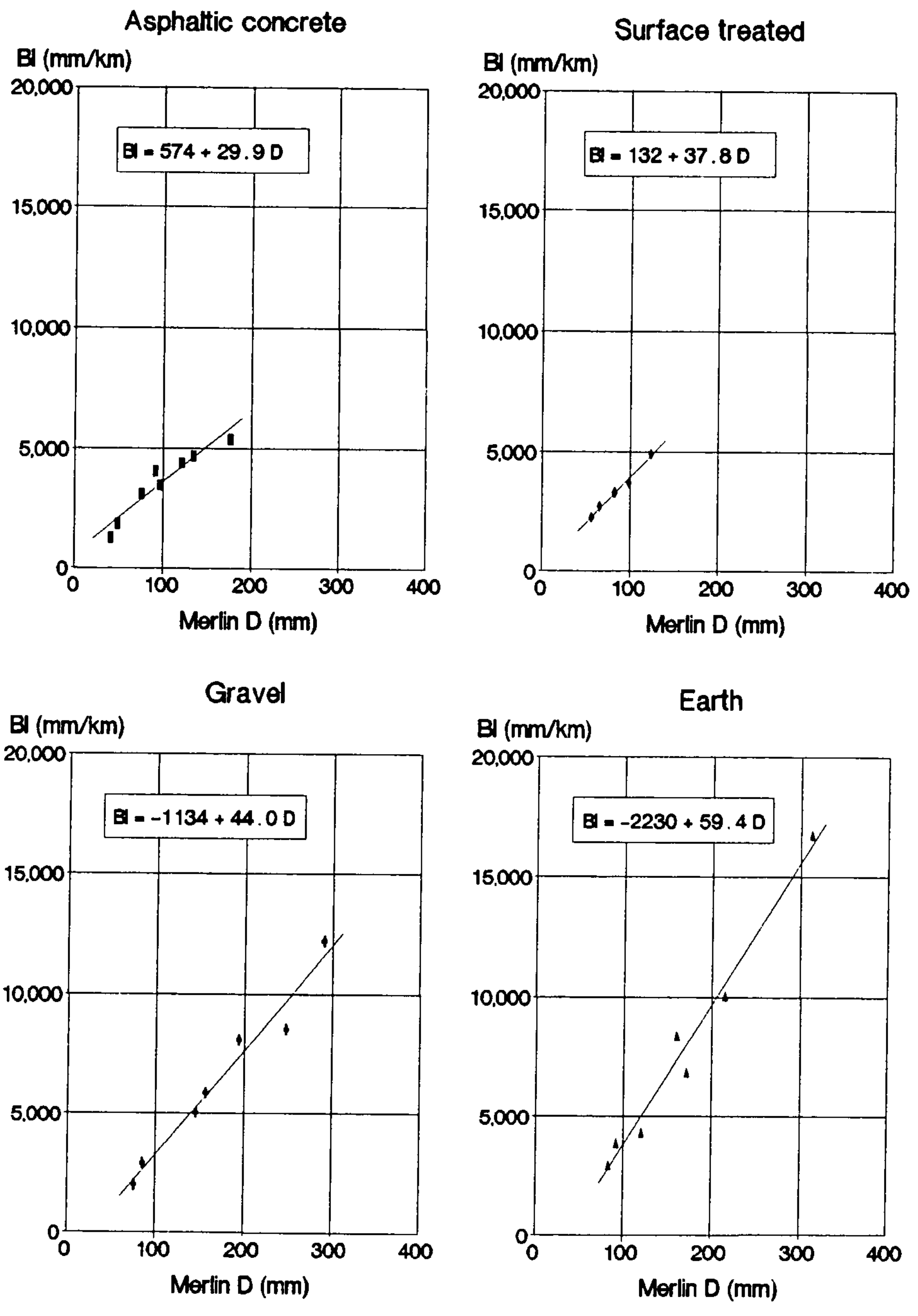

Figure A4. Relationship between BI and D for different surfaces

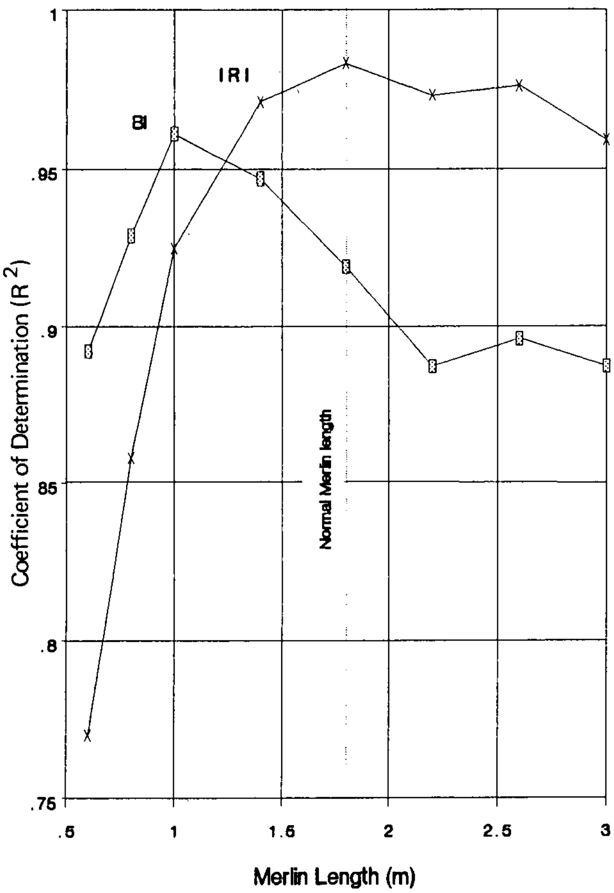

Figure A5. Roughness measuring accuracy for Merlins of different length

attractively simple procedure in the field and requires a minimum of calculation. To decide what percentage would give the best answers, the performance of a Merlin over the test sections was again simulated. This time, the machine length was fixed at 1.8 metres and the roughness was measured on the IRI scale.

Linear regressions were carried out between D values, derived using different data percentages, and roughness. Table A4 shows the resulting values of R^2, from which it can be seen that, of the values tested, 90 per cent, which corresponds to counting in 10 crosses from each end of the distribution, appeared to be the best choice.

TABLE A4

Effect of Data Limits on Correlation

Percentage of data	Count from edge of distribution	R^2
95	5	0.932
90	10	0.983
85	15	0.966
80	20	0.923

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