MEASUREMENT AND ASSESSMENT OF UNEVENNESS ON MAJOR ROADS

by

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The views expressed in this Report are not necessarily those of the Department of Transport

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MEASUREMENT AND ASSESSMENT OF UNEVENNESS ON MAJOR ROADS

ABSTRACT

The report describes the derivation of evenness criteria for use on new and in-service roads. Separate criteria for the evaluation of ride over road subsidence and overlay ramps are also presented. The evenness criteria were developed by comparing the unevenness of new and in-service roads with the subjective assessments of road users. The application of the criteria using profile measurements made by the TRRL high-speed road monitor is described and examples are presented illustrating how the system might be used in practice.

1. INTRODUCTION

The road user perceives the quality of a road primarily through the riding quality of its surface. In extreme cases of unevenness this perception may also be influenced by safety considerations and concern about the effect of road roughness on vehicle maintenance costs. More usually deterioration of the surface profile merely reduces the comfort of the road user, at least initially. Although vehicle suspensions help to mitigate the effects of unevenness in road vehicles, effective maintenance management requires the definition of acceptable evenness of roads. For roads with traffic speeds less than 80 km/h, Jordan and Young (1980) have proposed evenness criteria, based on bump integrator measurements. However, because of limitations in wavelength response and operating speed the bump integrator is not well suited for use on major roads. In the present specification for road and bridge works used by the Department of Transport (1976) the evenness of new roads is evaluated by the rolling straight edge. This equipment has been described by Young (1977); it has a limited wavelength response, is very much slower than the bump integrator and is not suitable for use on in-service roads.

The surface profiles of major roads and motorways can now be measured, without interference with the normal traffic, using the high speed road monitor developed at the Laboratory and extensive research with the equipment has made it possible to propose new evenness criteria linked to the road user’s perception of quality of ride.

2. PROFILE MEASUREMENT

Plate 1 shows the high-speed road monitor, the development of which has been described by Dickerson and Mace (1976) and Still and Jordan (1979). It consists of a trailer supporting a rigid 4.5 metre beam to which four laser sensors, developed by Still and Winnett (1976), are fixed in a configuration designed to measure the longitudinal profile features that are of interest in riding quality research. The trailer is towed behind a Ford Transit van that houses a power supply, electronics, and computer system; the system is outlined in Figure 1. A suite of programs mounted on the computer provides control of the measurement process and also various types of analysis of the profile measurements.

The performance of the equipment has been thoroughly investigated by Still and Jordan (1979) and their results are summarised in Figure 2. Good amplitude response up to wavelengths greater than 100 metres is well above that required for riding quality evaluation. For profile features with a wavelength less than 3, 10 and 25 metres the accuracy is more than adequate for the assessment of ride, better than 1.5, 2.1 and 5.3 mm respectively.
To date the equipment has been used to measure in excess of 20,000 kilometres of longitudinal profile on roads and airfields in both the UK and continental Europe. It has operated successfully on both bituminous and concrete surfaces at speeds in the range 5 to 80 kilometres per hour. Only on wet, deeply textured surfaces does the number of 'dropouts' or lost sensor measurements reach a level that significantly affects the accuracy of measurement.

3. THE ANALYSIS OF PROFILE MEASUREMENTS

3.1 Moving-average datum

To evaluate the effect of surface unevenness on vibration in vehicles it is necessary to examine the unevenness associated with the range of wavelengths in the profile of the road that can interact with suspensions of vehicles operating at normal traffic speeds. A convenient method for presenting profile unevenness in this way is the use of a moving-average datum that smooths the observed profile: the method of calculating a moving-average datum is described in detail in Appendix 1. The deviations of the profile from this calculated datum are a measure of the amplitude of the profile up to a wavelength defined by the length of profile used to calculate the moving-average.

The longitudinal profile measured by the TRRL road monitor has been used to compare a moving-average datum derived from 3 metre lengths of profile with that obtained by simulating the passage of a 3 metre straight-edge over the same profile as shown in Figure 3. There is broad agreement between the two. That derived from a moving-average is smoother than the straightedge datum, because the latter, on moving forward to a new position, sometimes does not have a profile support point in common with its previous position; this results in discontinuities as shown in Figure 3. Profile amplitudes defined relative to the moving-average datum are thus a better representation of the observed profile than those defined relative to a straightedge datum.

3.2 Methods of evaluating unevenness

The degree of unevenness of a profile can be expressed in several ways to suit different applications using the profile amplitudes defined relative to a moving-average datum. For example, on newly constructed surfaces it may be necessary for contractual reasons, to locate precisely areas of unacceptable unevenness and for this purpose the counting of individual bumps is appropriate. On in-service roads, however, the statistical measure of unevenness given by the variance of the profile amplitudes relative to selected moving-averages over a considerable length of road is more useful for examining profile deterioration with time.

For certain types of problem it is important to know the levels of unevenness associated with particular wavelengths within the spectrum that makes up the road profile. An example is a road profile such as the one shown in Plate 2, which contains a persistent ripple. To provide this information the variance spectrum of the profile may be calculated as shown in Appendix 1. The variance spectrum illustrated in Figure 4 shows the contribution of each wavelength to the profile unevenness and the contribution of the ripple at 1.5 m wavelength may be seen clearly.

4. THE ASSESSMENT OF RIDE

4.1 Vibration in road vehicles

Vibration on the seat or on the floor of the vehicle is a good objective indicator of quality of ride. The excitation of vibration in a vehicle is related to unevenness through profile features and suspension dynamics;
vibration levels will vary with speed. A typical acceleration spectrum for vibration measured on the seat of a saloon car is shown in Figure 5. The peaks in the spectrum reflect the resonant responses of the different suspension components of the vehicle; above 15 Hz the acceleration level decreases with increasing frequency.

For major roads, the longest wavelength that excites suspensions into resonant vibration is less than 30 metres.

4.2 Subjective assessment of ride

In an extensive review of research on human response to vibration under controlled laboratory conditions Osborne (1976) has shown that humans are most sensitive to whole-body vibration at low frequencies, and in particular at the resonances of the human body i.e. in the range 3 to 8 Hz. These studies showed a large degree of variability in subjective assessments of the effect of vibration.

To allow for variability, Cooper and Young (1978 and 1980) used large samples representative of the motorizing public driving their own vehicles on selected sections of the public road network. In these experiments subjective assessment of ride was classified into four categories: Comfortable, Acceptable, Uncomfortable and Very Uncomfortable. The results from these field studies are presented in Figure 6 in terms of the proportion of the sample that rated the ride as 'Acceptable' or better for given levels of vibration, vibration being defined as the root mean square of the acceleration experienced by the test subjects over the frequency range 0.2 to 20 Hz. It will be noted that different curves are shown in Figure 6 for saloon cars, coaches and lorries. An rms acceleration level of 40 milli-g would give a quality of ride that 90 per cent of car occupants would rate as 'Acceptable' or better: this therefore seems to be a suitable quality of ride for newly surfaced roads.

5. EVENNESS AND RIDE

Given a vibration level that defines an acceptable ride it is then necessary to examine the relationship between unevenness and vibration and translate the critical vibration level into a profile criterion that may be more easily measured.

5.1 Newly surfaced roads

From the analysis described in Section 3 it follows that, for a particular moving-average datum, random profile unevenness can be described by the number of bumps that exceed a specified amplitude. Profiles from sections of road, 300 m long, were analysed in this way using a 3 and a 15 metre moving-average datum to define short and long-wave unevenness respectively. The same sections of road were ranked according to the vibration experienced by car occupants, in 10 milli-g bands. The range of bump counts exceeding a specified amplitude was determined for the test profiles associated with each acceleration band; the results are shown in Table 1.

For random profile unevenness a value of 5 mm was found to be the lowest peak to peak amplitude relative to a 3 metre moving-average datum that had a significant effect on acceleration level. This was established by examining the correlation between acceleration and the product of bump count and amplitude for bumps greater than a particular amplitude. The statistically significant correlation coefficient of 0.53 did not change significantly with deletion of bump amplitudes up to an amplitude of 5 mm.

Although the bump counts associated with a given acceleration band in Table 1 vary considerably within each bump amplitude level, the averages of the ranges of bump counts can be associated with the acceleration
band 30–40 milli-g that define an acceptable ride for random unevenness on major roads. The resulting criteria in Table 2 are for road test lengths of 300 metres.

### TABLE 1

Relationship between the number of bumps in the road profile and acceleration experienced by car occupants

<table>
<thead>
<tr>
<th>Length of moving average (m)</th>
<th>Minimum peak-to-peak amplitude of bumps (mm)</th>
<th>rms accelerations in bands of 10 milli-g</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>20 - 30</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>0 - 5</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0 - 1</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>10</td>
<td>0 - 1</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0</td>
</tr>
</tbody>
</table>

### TABLE 2

A proposed evenness standard for random unevenness on newly surfaced major roads (300 metre test length)

<table>
<thead>
<tr>
<th>MINIMUM PEAK-TO-PEAK AMPLITUDE h (mm)</th>
<th>ALLOWABLE NUMBER OF BUMPS RELATIVE TO A MOVING AVERAGE DATUM OF LENGTH:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 METRES</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>0</td>
</tr>
</tbody>
</table>

For road profiles containing a systematic component of unevenness such as the ripple shown in Plate 2 or the joints in a concrete road a further criterion is needed to ensure an acceptable ride. Observation has shown that systematic unevenness can affect riding quality even with bump amplitudes that are less than those associated with acceptable levels of random unevenness. Short-wave systematic unevenness can induce tactile vibration and intrusive noise in road vehicles and longer waves, because of their cumulative effect, can stimulate vehicle suspensions. As mentioned in Section 3, the variance spectrum provides a method of evaluating the significance, for riding quality, of systematic components in a road profile. From tests on the subjective perception of non-random components in vibration and noise spectra Burns (1978) has shown that the level of the spectrum peak relative to the background level determines the human response to this stimulus. This suggests therefore that the ratio of any peaks in the profile spectrum relative to the level in adjacent wavebands should be used to define the significance.
of the systematic components of a profile for ride purposes. From five test sites examined, four provided spectra with ratios in the range ten to twenty five and gave a ride ranging from uncomfortable to very uncomfortable; the remaining site gave a ratio of five and was judged to be comfortable. A ratio value of eight is therefore suggested to define the boundary between acceptable and uncomfortable. For an acceptable ride, peaks in the profile spectrum, up to a wavelength of 15 metres, should therefore not be greater than eight times the average of the spectrum level on either side of the peak. A procedure for evaluating systematic unevenness using the variance spectrum of a road profile is outlined in Table 3.

**TABLE 3**

A proposed evenness standard for systematic unevenness on major roads

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Deviations of the measured profile from a 15 metre moving-average datum should be computed over the length of the road to be examined (see Appendix 1).</td>
</tr>
<tr>
<td>2</td>
<td>For each consecutive 300 metre length the variance spectrum should be calculated. (See Appendix 1).</td>
</tr>
<tr>
<td>3</td>
<td>The calculated spectrum values should be examined and the ratio of any large peak value to the average of adjacent values computed. (Using a graphical presentation Figure 5 or a tabular presentation ten points from either side of the peak base should be used to compute the required average.</td>
</tr>
<tr>
<td>4</td>
<td>For an acceptable ride the computed ratio values should be less than 8 for all profile wavelengths less than 15 metres.</td>
</tr>
</tbody>
</table>

5.2 In-service roads

The profile of all roads gradually deteriorate because of the variability of their foundations and construction and the effects of traffic and climate. An analysis of the effects of profile deterioration on riding quality has been based on the ride investigations of Cooper and Young (1978 and 1980) referred to in Section 4. Figure 7 shows levels of unevenness found to correspond to a subjective assessment of ride as Comfortable/Acceptable, Acceptable/Uncomfortable and Uncomfortable/Very Uncomfortable as defined in Section 4.2. The boundary between Comfortable/Acceptable and Acceptable/Uncomfortable corresponds to the ride requirements defined in Table 2 for newly surfaced roads. Unevenness is defined in Figure 7 in terms of the variance of the profile amplitudes relative to selected moving-averages as described in Section 3 and Appendix 1.

5.3 Road subsidence

The subsidence of a road pavement may have a significant effect on ride and road safety. Examples of subsidence observed on major roads in the UK have ranged in length from 20 to 800 metres and in depth from 50 to 1000 mm. In general subsided sections of road have smooth transitions at entry and exit from the subsidence basin and the radii of curvature of the basin together with traffic speed determines the effect on ride. For subsidence longer than thirty metres, the longest feature likely to affect riding quality, a length of thirty metres centred at the deepest point of the subsidence will give a conservative estimate of the effect on ride. Combining the vertical radius of curvature over subsided lengths less than or equal to thirty metres and the traffic speed, the vertical acceleration experienced in road vehicles may be calculated as shown in Appendix 2.
Measurements by Cooper (1973) and by Cooper, Jordan and Young (1978) indicate that for discrete profile features an acceleration level of less than 0.6 m/s² peak-to-peak gives an acceptable or better ride; accelerations of greater than 1.5 m/s² gives an uncomfortable or very uncomfortable ride to the majority of road users. These levels may be used in calculations involving also the profile of the subsidence curvature to derive the criteria shown in Table 4 for assessing the effect of subsidence on ride as described in Appendix 2.

**TABLE 4**

Road subsidence criteria

<table>
<thead>
<tr>
<th>RIDING QUALITY</th>
<th>DEPTH OF SUBSIDENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMFORTABLE/ACCEPTABLE</td>
<td>(&lt;0.04 \frac{L^2}{V^2})</td>
</tr>
<tr>
<td>UNCOMFORTABLE/VERY UNCOMFORTABLE</td>
<td>(&gt;0.1 \frac{L^2}{V^2})</td>
</tr>
</tbody>
</table>

\(L = \) LENGTH OF SUBSIDENCE (\(<30m\))

\(V = \) MAX. TRAFFIC SPEED (m/s)

For example on a subsidence of length 20 metres with a traffic speed of 25 m/s the ride would be Uncomfortable/Very Uncomfortable if the depth of subsidence exceeded 64 mm.

5.4 Overlay ramps

The structural strengthening of roads by overlaying requires the use of properly constructed ramps between adjacent lengths of different overlay thickness to ensure both an acceptable ride and an economic use of materials. The acceleration normal to the ramp is determined by the ramp profile and traffic speed and, as for subsidence, an acceleration level of 0.6 m/s² defines an acceptable ride over the ramp. The ramp length required to achieve this quality of ride can be calculated by a method described in Appendix 2; the results are shown in Table 5.

**TABLE 5**

Overlay ramp criterion

<table>
<thead>
<tr>
<th>RIDING QUALITY</th>
<th>MINIMUM LENGTH OF RAMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMFORTABLE/ACCEPTABLE</td>
<td>(4.06V\sqrt{H})</td>
</tr>
</tbody>
</table>

\(V = \) MAX. TRAFFIC SPEED m/s

\(H = \) OVERLAY THICKNESS m

For a major road with a maximum permitted speed of 31.5 m/s (70 mph) and a difference in overlay thickness of 100 mm the ramp length should be greater than or equal to 40 metres with a gradual transition between the two levels to minimise the vertical acceleration.
6. EXAMPLES OF USE

6.1 Newly surfaced roads

The requirements defined in Section 5 for both new and in-service roads can be implemented using profile data collected by the profile measuring equipment described in Section 2. To achieve satisfactory accuracy, measurements should not be made on deeply textured surfaces that are wet; otherwise the dropout rate may exceed 40 per cent, the highest rate acceptable in making profile measurements for use with the ride criteria. The measurement should begin 50 metres before the section that is of interest and finish an equal length after the section. The additional length is needed to establish the moving-average and ensures that the first profile deviation from the moving-average datum can be made to coincide with the beginning of the section.

The measurements are stored on floppy disc and may be accessed directly using the computer system in the towing vehicle, or alternatively, transferred to a mainframe computer for analysis. For the evaluation of ride on newly surfaced roads a bump count analysis program gives the position and amplitude of bumps exceeding a set threshold value relative to a moving-average datum. A comparison of the number of bumps occurring between chainages that are 300 metres apart with the requirements of Table 2 shows whether or not the surface is acceptably even. An example of a bump count analysis applied to 1500 metres of a new concrete surface is shown in Table 6. For a 3 metre moving-average datum and using the criteria of Table 2, it can be seen that four out of the five 300 metre lengths may be judged acceptable; the fifth 300 metre length (2020 – 2320m) is shown not to be acceptable because of the 10 mm bump contained within this length. A similar bump count analysis on the same profile but using a 15 metre moving-average datum showed all of the 300 metre sections complying with the criteria given in Table 2. A variance spectrum analysis of each of the sections showed that the profile contained no significant systematic unevenness. Consequently after removal of the 10 mm bump in Section (2020 – 2320m) the profile should provide an acceptable ride. These observations show the importance of examining all of the criteria before accepting a new road surface.

6.2 In-service roads

For evaluating ride on in-service roads the variance of unevenness is used and programs are available to compute variance values for any selected moving-average datum. Figure 8 shows the improvement in profile achieved in an example of road reconstruction over several kilometres; alternatively Figure 8 may be interpreted as showing in a general sense the extent of deterioration that occurs over the lifetime of a road. Superimposed on the ride criteria curves from Figure 7 this approach allows the maintenance engineer to assess the quality of the ride offered by different roads in the network.

For profile surveys over hundreds of kilometres of road the variance relative to a given moving-average can be summarised to show the proportion of the survey falling into each of the bands of quality defined in Figure 7. An example of such a frequency plot is shown in Figure 9 where approximately eleven per cent of the length of road has a riding quality in the Uncomfortable/Very Uncomfortable category. Similar frequency plots can be produced for variances computed relative to other moving-averages, thus showing for each moving-average the proportion of a survey with unevenness greater than a specified level.

Deterioration of profile caused by subsidence can be detected using an analysis procedure whereby the depression beneath a 30 metre simulated straight edge is compared to the ride criteria given in Table 4.
TABLE 6
A typical bump count analysis

DISC 143 PROF 5
FROM 820 to 2320 METRES
MOVING—AVERAGE LENGTH = 3m
PEAK—PEAK AMPL. = 5mm

<table>
<thead>
<tr>
<th>CHAINAGE</th>
<th>PEAK-PEAK AMPLITUDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>START</td>
<td>END</td>
</tr>
<tr>
<td>m</td>
<td>m</td>
</tr>
<tr>
<td>852</td>
<td>855</td>
</tr>
<tr>
<td>868</td>
<td>870</td>
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<td>2166</td>
<td>2167</td>
</tr>
<tr>
<td>2230</td>
<td>2231</td>
</tr>
</tbody>
</table>

= 300 METRES; 5 BUMPS ≥ 5mm] ACCEPTABLE
= 300 METRES; 6 BUMPS ≥ 5mm] ACCEPTABLE
= 300 METRES; 1 BUMP > 8mm)
= 300 METRES; 11 BUMPS ≥ 5mm] ACCEPTABLE
= 300 METRES; 5 BUMPS ≥ 5mm] NOT
= 300 METRES; 3 BUMPS ≥ 8mm] ACCEPTABLE
= 300 METRES; 1 BUMP ≥ 10mm]
7. CONCLUSIONS

A proposal for the assessment of ride on new and in-service roads has been based on the results of research into the quality of ride. Evenness criteria have been suggested for:

(i) assessing the acceptability of surface unevenness on newly surfaced roads
(ii) assessing the effect on ride of profile deterioration on in-service roads
(iii) determining the effect of road subsidence on ride and
(iv) defining ramp dimensions between overlays of different thickness that should give an acceptable ride.

Examples are given of the way in which the system might be employed using the TRRL high-speed road monitor. The combination of analytical techniques and hardware promises an efficient method for evaluating profiles on new and in-service roads. Further trials will be needed to determine the extent to which the high-speed road monitor can be used in support of existing methods for testing compliance of new construction and to determine whether the evenness standards suggested in this report are appropriate.

8. ACKNOWLEDGEMENTS

The work described in this report was carried out in the Pavement Design and Maintenance Division (Head of Division: Mr J Porter). The author acknowledges the assistance of Mr. D R C Cooper and Mr J C Young in the collection and processing of the profile data.

9. REFERENCES


Fig. 1 Computer control and analysis facilities

Fig. 2 Amplitude and phase response and maximum measurement errors of amplitude
Fig. 4 Variance spectrum of road profile containing systematic unevenness ('ripple')

Profile spectrum

Profile 'ripple'
(see Plate 2)
Fig. 5 Typical acceleration spectrum on the seat of a saloon car
Fig. 6 Comfort characteristic curves for coaches, cars and heavy goods vehicles travelling on major roads.
Fig. 7 Surface unevenness and ride criteria for major in-service roads

Fig. 8 Example of profile deterioration that can occur over the life of a major road.

Profile variance (σ^2) vs. Length of moving-average (m)

- Surface quality – Good/acceptable
- Ride – Comfortable/acceptable
- Surface quality – Acceptable/poor
- Ride – Uncomfortable/uncomfortable
- Surface quality – Poor/very poor
- Ride – Uncomfortable/uncomfortable

Before reconstruction
After reconstruction
Plate 1 TRRL high-speed road monitor

Plate 2 Road surface ripple
Fig. 9 Cumulative frequency plot of variances computed over 100 metre lengths of profile in a survey of 10km of road

Fig. 10 Comparison of sinusoidal model of overlay ramps with constructed ramps on a major bituminous road
APPENDIX A

METHODS OF ANALYSING ROAD PROFILES

A1 Moving-average datum and bump count

Profiles measured by the high speed profilometer are computed at points nominally 0.1 metre apart: this distance, which is defined by the separation of the front two sensors of the high speed road monitor, is determined from the rotation of the wheels of the trailer. A moving-average datum may be calculated from m profile amplitudes (\(y\)) by averaging:

\[
\bar{Y}_k = \frac{1}{m} \sum_{j=i}^{i+m-1} Y_j \quad \text{for } i=1, 2, \ldots N - \frac{m-1}{2}
\]  

(1)

for convenience in the calculation, \(m\) is always an odd number.

The profile deviations (\(d\)) relative to the moving-average datum are given by:

\[
d_k = Y_k - \bar{Y}_k
\]

(2)

The deviation \(d_k\) defines the bump amplitude relative to the moving-average datum at point \(k\).

A2 Variance of profile amplitudes relative to a moving-average datum

Profile amplitudes relative to a moving-average datum, derived from a selected averaging length, are given by the values of \(d_k\) given by Equation 2 above. Still and Jordan (1980) observed that the measurements were influenced by systematic long-wave parabolic errors that gave the moving-average datum a constant offset, resulting in an asymmetry of the distribution of profile amplitudes about the datum. This offset may be estimated by averaging the computed profile deviations as follows:

\[
\bar{d} = \frac{1}{N-m} \sum_{k=1}^{N-m} d_k
\]

(3)

Allowing for this offset the variance of the corrected deviations is given by:

\[
\sigma_m^2 = \frac{1}{N-m} \sum_{k=1}^{N-m} (d_k - \bar{d})^2
\]

(4)

Variance is a measure of the unevenness associated with profile features that are \(m\) profile points or less in length. For increasing values of \(m\) in Equation 4 the unevenness associated with an increasing range of profile wavelengths will be included in the variance and the variance term will in general therefore increase. In exceptional cases, where certain profile wavelengths may have zero amplitudes the graph of variance against \(m\) may show a
plateau. The criteria curves in Figure 7 are derived from the relationship between variance and length of the moving-average used to compute the datum.

**A3 Variance spectrum calculation**

Variance from Equation 4 gives a measure of profile unevenness for wavelengths less than the length of the moving-average. As the averaging length increases the contribution from correspondingly greater wavelengths will be included. Consequently the variance spectrum, that is the variance associated with particular narrow bands of wavelength, cannot be determined directly. To calculate the variance spectrum Fourier analysis is used to fit a function of cosine and sine waves to the profile that is being analysed. The coefficient of each cosine and sine wave gives a measure of the contribution made by that wavelength to the unevenness of the profile. Fourier analysis of the measurements is based on a technique described by Bendat and Piersol (1966). It gives Fourier components $F(\Omega_i)$ at spatial frequency $\Omega_i$ as follows:

$$
F(\Omega_i) = \sum_{k=1}^{N-m} \Delta x \left( d_k - \bar{d} \right) e^{-j \frac{2\pi ik}{N-m}}
$$

where $e^{-j \frac{2\pi ik}{N-m}} = \cos \frac{2\pi ik}{N-m} - j \sin \frac{2\pi ik}{N-m}$

(5)

and $\Delta x$ is the distance between successive profile points.

The variance spectrum ordinates, $\sigma^2(\Omega_i)$, at spatial frequencies $\Omega_i$ are obtained by multiplying each Fourier component by its complex conjugate to form the scalar quantity $|F(\Omega_i)|^2$ which then gives the variance spectrum ordinates:

$$
\sigma^2(\Omega_i) = \frac{2\Delta x}{N-m} |F(\Omega_i)|^2 \text{ m}^3/\text{cycle}
$$

(6)

An estimation error is inherent in the computation but its effect may be reduced by averaging ordinates over adjacent frequencies to give a smoothed variance spectrum with improved accuracy but with a poorer frequency resolution.

The number, $n$, of ordinates needed to give an acceptable accuracy depends on the length of profile being analysed, the degree of randomness of the profile data, and the frequency resolution required from the analysis. The frequency resolution of the smoothed spectrum ordinates is given by:

$$
\text{Frequency resolution} = \frac{n}{N\Delta x} \text{ cycles/metre}
$$

(7)

Figure 4 shows a graph of variance spectrum ordinate against spatial frequency for profile amplitudes defined relative to a 25.1 metre moving-average datum over a profile length of 300 metres. The raw spectrum ordinates were smoothed by averaging over 9 adjacent ordinates to give a frequency resolution of 0.05 cycles/metre.
A4 References


APPENDIX B
OVERLAY RAMP AND SUBSIDENCE CRITERIA

B1 Overlay ramp

Figure 10 shows a comparison between ramps constructed on a major bituminous road and a sinusoidal model of the ramps. The agreement is good and shows that a constructed ramp of length, L, will approximate to a sinewave with a wavelength of twice the ramp length.

An overlay ramp may therefore be represented mathematically by a sinewave with its axis midway between the surfaces being linked by the ramp and an amplitude equal to half the thickness, H, of the overlay.

\[ A = \frac{H}{2} \sin \frac{\pi x}{2L} \]  
(1)

where x is the horizontal distance from the midpoint of the ramp and 2L is the wavelength of the sinewave.

For the sinusoidal ramp defined by Equation 1 the largest vertical curvatures, generating the greatest radial accelerations normal to the ramp surface will occur near to the entry and exit points and may be obtained by differentiating Equation 1 twice and substituting \( x = \pm L/2 \)

\[ \frac{d^2A}{dt^2} = \pm \frac{V^2 \pi^2 H}{2L^2} \]  
(2)

For a discrete profile feature such as the ramp the amplitude of acceleration below which the ride is acceptable was shown by Cooper (1973) to be 0.3 m/sec^2. Therefore from Equation 2 the ramp length, L, is:

\[ L = 4.06 \sqrt{\frac{V}{H^{0.5}}} \]  
(3)

For an overlay of thickness 0.1 metre and maximum permitted traffic speed of 31.6 m/sec (70 m/h) the minimum length L of ramp is 40 metres. The dominant frequency component of the acceleration generated by this ramp would occur at 0.40 Hz. As this frequency is below the lowest suspension resonant frequency of road vehicles the acceleration experienced by vehicle occupants would not exceed that predicted by Equation 3 for an unsprung mass and the ramp would therefore provide an acceptable ride.

Reduction in speed below the maximum permitted or increases in overlay thickness would decrease the characteristic frequency and the response of the vehicle suspension would be of lower amplitude. Thus ramps constructed to satisfy Equation 3 will not excite a resonant response in vehicle suspensions and will provide an acceptable ride at all permitted speeds.
B2 Subsidence

Road surface deformation caused by subsidence usually develops over a period of time with the greatest curvatures typically at the bottom of the subsidence; its shape on both bituminous and concrete roads can, for ride purposes, be approximated by the arc of a circle of radius, R, given by:

\[ R = \frac{L^2}{8H} \quad \text{for } H \ll L \]  

(4)

where \( H \) = depth of subsidence
\( L \) = length of subsidence

Deformation caused by subsidence, may excite a resonant response from vehicle suspensions and at resonance the profile input amplitude may be amplified by a factor of approximately two by the vehicle suspension. Thence, using Equation (4) the acceleration corresponding to the resonant response of a sprung mass is given by:

\[ a = \frac{16V^2H}{L^2} \]  

(5)

As described in Section 5.3 accelerations of 0.6 and 1.5 m/sec\(^2\) define the ride boundaries between comfortable/acceptable and uncomfortable/very uncomfortable. Thus from Equation (5) the ride categories are given by:

\[ H < \frac{0.6L^2}{16V^2} \text{ m : comfortable/acceptable} \]

\[ H > \frac{1.5L^2}{16V^2} \text{ m : uncomfortable/very uncomfortable} \]

B3 References

ABSTRACT

Measurement and assessment of unevenness on major roads: P G JORDAN: Department of Transport, TRRL Laboratory Report 1125: Crowthorne, 1984 (Transport and Road Research Laboratory). The report describes the derivation of evenness criteria for use on new and in-service roads. Separate criteria for the evaluation of ride over road subsidence and overlay ramps are also presented. The evenness criteria were developed by comparing the unevenness of new and in-service roads with the subjective assessments of road users. The application of the criteria using profile measurements made by the TRRL high-speed road monitor is described and examples are presented illustrating how the system might be used in practice.

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