DEVELOPMENTS IN THE CALIBRATION AND USE OF THE
BUMP-INTEGRATOR FOR RIDE ASSESSMENT

by

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<table>
<thead>
<tr>
<th>CONTENTS</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>1</td>
</tr>
<tr>
<td>1. Introduction</td>
<td>1</td>
</tr>
<tr>
<td>2. Description and performance</td>
<td>1</td>
</tr>
<tr>
<td>2.1 Description</td>
<td>1</td>
</tr>
<tr>
<td>2.2 Performance</td>
<td>2</td>
</tr>
<tr>
<td>3. Effect of operating speed on index measurements</td>
<td>2</td>
</tr>
<tr>
<td>4. Calibration</td>
<td>3</td>
</tr>
<tr>
<td>5. Operation and maintenance</td>
<td>5</td>
</tr>
<tr>
<td>5.1 Operation</td>
<td>5</td>
</tr>
<tr>
<td>5.2 Maintenance</td>
<td>5</td>
</tr>
<tr>
<td>6. Improvements to the BI</td>
<td>5</td>
</tr>
<tr>
<td>7. Riding quality and the index r</td>
<td>6</td>
</tr>
<tr>
<td>8. Conclusions</td>
<td>7</td>
</tr>
<tr>
<td>9. Acknowledgements</td>
<td>8</td>
</tr>
<tr>
<td>10. References</td>
<td>8</td>
</tr>
<tr>
<td>11. Appendix: Effect of BI operating speed on the index r</td>
<td>15</td>
</tr>
</tbody>
</table>

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DEVELOPMENTS IN THE CALIBRATION AND USE OF THE BUMP-INTEGRATOR FOR RIDE ASSESSMENT

ABSTRACT

For roads, other than those where speeds of over about 50 mph (80 km/h) can be maintained, the Bump-integrator provides a suitable means of monitoring riding quality. The ride index measurement of the Bump-integrator is determined by the machine’s dynamic response to the unevenness of a road profile.

This Report describes an investigation of the machine’s dynamic characteristics and of their effect on ride measurements. New calibration and speed correction procedures are presented and the relationship between ride assessment and the ride index measured by the machine is investigated. Ride criteria, which are related to traffic speed, are defined for newly resurfaced roads where nominal speeds are below 80 km/h. A new microprocessor-based integrating unit is under development that will improve the accuracy of measurement and the flexibility of use of the Bump-integrator.

1. INTRODUCTION

Motorists judge the quality of a road primarily in terms of the safety and riding comfort provided by the road surface. The degree of evenness required of a road surface, to ensure adequate safety and riding comfort, depends on many variables but traffic speed\(^1,2,3\) is probably the most important. In general, the greater the traffic speed the more stringent the surface evenness requirements need to be to ensure an acceptable ride.

For roads where nominal traffic speeds are below about 50 mph (80 km/h) the Bump-integrator\(^4\) (BI) provides a suitable tool for monitoring riding quality. The more stringent requirements for motorways and other high-speed roads are best assessed using the new TRRL high-speed profilometer\(^5,6\).

Although up to thirty BI machines are in use throughout the UK, mostly by Local Authorities, little or no information has been published on the dynamic characteristics of the machine or on the manner in which they affect the ride index measurement. The relationship of the index measurement to ride assessment has also received little detailed attention.

The report describes recently developed speed correction and calibration procedures for the BI and defines ride criteria for newly resurfaced roads.

2. DESCRIPTION AND PERFORMANCE

2.1 Description

Details of the construction of the BI have been described elsewhere\(^7\); it consists of a single-wheeled trailer that is towed along the road at a constant speed, usually in the UK at 32 km/h. A general view is given in Plate 1.

The trailer, a heavy rectangular chassis, is supported on one wheel by two single-leaf springs positioned one to each side of the wheel. Two dashpot assemblies fixed between the chassis frame and wheel axle provide viscous damping.
In operation, the downward movement of the wheel relative to the chassis is summed by a mechanical integrator unit fitted to the chassis. The unevenness index \( r \) is given by the integrated vertical movements divided by the distance travelled. The mechanical integrator unit used in existing machines reads only in inches/mile (1 in/mile = 1.58 cm/km).

2.2 Performance

The essential features of the BI are shown in Figure 1, in which the wheel-tyre system is represented by a suitable mass-spring-dashpot assembly. The dynamic response of this mechanical system to oscillatory inputs is well known\(^8\) and for an idealised BI the dominant modes of vibration occur at the resonant frequencies of the tyre and of the chassis — leaf spring and dashpot. In practice, the BI construction deviates from the ideal and during operation rotational effects, caused by non-uniformity of the wheel-tyre assembly, influence the dynamic response of the machine.

Figure 2 shows a frequency analysis of the motion of the BI wheel relative to the chassis, generated during a test run on a relatively even road. From the figure the principle resonant responses are apparent at 2 and 12 Hz approximately but, in addition, a further peak, caused by the rotational effects of the wheel, is shown to occur at 4 Hz. Unlike the resonant frequencies of the BI, which are fixed, the frequency of the response produced by the rotational effects of the wheel varies with the operating speed of the machine. Provided the operating speed is maintained such that the frequency of the wheel's rotational response does not coincide with the resonant frequencies of the BI, then the contribution of the rotational response to the measured index \( r \) is essentially constant.

Tests using smooth steel rollers to drive the wheel of the BI have shown that, for a wheel-tyre assembly that complies with the calibration requirements described in Section 4 below, the magnitude of this contribution is essentially constant at 30 inches/mile within the range of operating speeds 20–65 km/h. Provided the BI is operated at speeds within this range, the index \( r \) measured by the machine will include a constant contribution of 30 inches/mile irrespective of the evenness of the road surface.

3. EFFECT OF OPERATING SPEED ON INDEX MEASUREMENTS

The upper abscissa in Figure 2 shows the range of profile wavelengths that excite the dynamic response of the BI when it is operated at the standard speed of 32 km/h (20 mph). The profile wavelengths \( \lambda \) are related to the frequencies \( f \) of the dynamic response of the BI through the operating speed \( V \) by the following expression:

\[
V = f\lambda
\]  \hspace{1cm} (1)

The wavelengths that excite the resonant responses of the BI increase with its speed of operation. Because profile amplitudes tend to increase with increase in wavelength, the amplitudes input to the BI increase with operating speed. However, the time taken to traverse a fixed length of profile decreases with increase in speed and consequently the number of resonant oscillations of the axle relation to the chassis also decreases. The outcome of these two conflicting effects of the increase in operating speed on the measured index \( r \) is examined in the Appendix and the results shown in Figure 3. Here the variation with speed of the index, obtained theoretically in the Appendix, is compared with test measurements obtained from some twenty test sites where the Bump-integrator was operated at
selected speeds within the range 20–65 km/h. To provide a common scale of index values the predicted and measured values of the quantity, \( r_V - K \), have been normalised to its value, \( r_{32} - K \), for the standard operating speed of 32 km/h. The figure shows that, for uneven profiles with a standard index of \( r_{32} \geq 100 \) inches/mile, the index decreases with operating speed according to the inverse square-root of the speed for speeds within the range 20–65 km/h. The same trend is obtained for even surfaces with values of \( r_{32} < 100 \) inches/mile for speeds within the range 20–32 km/h, but for speeds in the range 32–65 km/h the trend changes to one where the index decreases according to the inverse of the speed. In the Appendix the following equations have been derived that permit index values, \( r_V \), obtained using non-standard operating speeds, \( V \), to be corrected to give the standard index, \( r_{32} \), corresponding to the standard speed of 32 km/h:

\[
\begin{align*}
\text{For uneven surfaces and operating speeds 20–65 km/h} & \quad r_{32} = \sqrt{\frac{V}{32}} (r_V - 30) + 30 \text{ inches/mile} \\
\text{for even surfaces and operating speeds 32–65 km/h} & \quad r_{32} = \frac{V}{32} (r_V - 30) + 30 \text{ inches/mile}
\end{align*}
\]

In practice, Equation 2 would be applicable in the great majority of cases where speed corrections would be needed. For operating speeds that deviate from the standard speed by less than 10 km/h, the accuracy of estimation of the index \( r_{32} \) using Equation 2 or 3 is within 10 per cent of the true value. The accuracy reduces to within 20 per cent for a deviation of 30 km/h; the correction procedures are only applicable within the speed range 20–65 km/h. In the practical operation of the BI, maintaining a constant speed is often difficult and the correction procedures given above then improve the flexibility of use of the machine.

4. CALIBRATION

Sections 2 and 3 above have shown the importance of the resonant responses of the machine and of the rotational effects of the wheel in determining the magnitude of the unevenness index \( r \). To ensure that measurements of unevenness made by different machines can be validly compared, it is essential that the resonant responses of all machines should be the same. The wheel-tyre assembly should comply with the following requirements:

(i) radii of the inflated tyre (pressure 30 lb/inch\(^2\)) should not differ by more than 0.03 inches (0.75 mm). Measurement of the tyre’s radii should be made at 15 to 20 points around the circumference of the tyre.
(ii) the complete wheel assembly should be in-balance on both static and dynamic tests.
(iii) the tyre should not be more than 3 years old; it has been observed that the dynamic performance of the tyre changes significantly with age after 3 years.

Provided tyres of a standard construction are used that comply with the requirements above, the differences in their dynamic performance will have a negligible effect on the magnitude of the index \( r \).
To define the important resonant response of the chassis-leaf spring and dashpot system it is sufficient to know the system's resonant frequency and damping factor. Machines having the same resonant frequency and damping factor, will, when operated at the constant speed, produce the same resonant response to a given road profile. A simple 'drop' test has been developed at the Laboratory to determine the resonant frequency and damping factor of the chassis-leaf spring-dashpot system. In the test, the chassis is displaced from its rest position vertically through 35 mm by means of a hoist attached to the chassis frame directly above the wheel axle. When the BI is suddenly dropped from the hoist a linear transducer fixed vertically between the wheel axle and the cross member of the chassis senses the displacement of the axle relative to the chassis. The transducer movement is recorded onto a graph; Figure 4 shows a typical plot obtained from a 'drop' test. The resonant frequency and damping factor are easily calculated from the oscillatory trace in the manner shown in Figure 4.

Because the integrator unit affects the damping of the relative movement between the axle and the chassis, the drop test is first performed with the unit disconnected and then repeated with the unit connected to the wheel axle. Resonant frequency and damping factor values together with tolerances derived from tests on the 'standard' TRRL BI are shown in Table 1.

<table>
<thead>
<tr>
<th>Test</th>
<th>Parameter measured</th>
<th>Calibration requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tyre out-of-roundness</td>
<td>Maximum difference between measured radii</td>
<td>&gt; 0.03 inches (0.75 mm)</td>
</tr>
<tr>
<td>Wheel balance</td>
<td>Static and dynamic balance</td>
<td>In-balance</td>
</tr>
<tr>
<td>'Drop' test with integrator unit disconnected</td>
<td>Resonant frequency</td>
<td>2.1 ± 0.1 Hz</td>
</tr>
<tr>
<td></td>
<td>Damping factor</td>
<td>2.0 ± 0.15</td>
</tr>
<tr>
<td>'Drop' test with integrator unit connected</td>
<td>Resonant frequency</td>
<td>2.1 ± 0.1 Hz</td>
</tr>
<tr>
<td></td>
<td>Damping factor</td>
<td>2.5 ± 0.15</td>
</tr>
<tr>
<td>Centre of percussion</td>
<td>Time for one complete swing - average of 5/6 swings</td>
<td>2.5 ± 0.1 sec</td>
</tr>
</tbody>
</table>

A test is carried out to ensure that the centre of percussion of the BI, relative to the towing hitch, is coincident with the position of the wheel axle so that no significant axle/chassis motion is generated by the motion of the towing vehicle. The test, which is carried out by the manufacturer on all new machines, is performed by suspending the BI trailer, less the wheel assembly, from a stable support by means of a block and knife-edge fixed to the towing-hitch end of the trailer. When safely suspended the bottom of the frame is displaced, from its rest position through approximately 35 cm (14 inches) and then released. The time to complete five to six oscillations is measured using a stop watch and the calculated average time for a single oscillation should lie within the tolerances given in Table 1.

With the exception of the centre of percussion test, it is recommended that the calibration of the BI should be checked at least once every year. Because the centre of percussion test is carried out on all new machines by the manufacturer and because it does not change with use of the BI it is not necessary to check this calibration requirement on in-service machines.
5. OPERATION AND MAINTENANCE

5.1 Operation

Before commencing a test run the operator should ensure that the tyre pressure is at 206 kN/m² (30 lb/in²) and that the integrator and wheel revolution counters, which are housed in the towing vehicle, are set to zero. A test measurement consists of towing the machine at as near to a fixed speed of 32 km/h as possible over the nearside wheelpath of the road surface being tested.

At the beginning of the test the counters and the timer are switched on and, on completion of a length of at least 400 metres, the counters are switched off and the time taken to traverse the length noted. The measured time and distance, the latter obtained from the number of wheel revolutions, give the average operating speed during the measurement. The integrated vertical movement of the axle relative to the chassis divided by the distance gives the index r: the values are given to the nearest inch.

Where the operating speed has deviated from the standard speed of 32 km/h, Equation 2 or 3 of Section 3 should be used to obtain the index r corresponding the standard speed on in-service roads. For measurements on in-service roads Equation 2 would be used.

If consecutive test lengths are to be measured, a change-over switch is operated that switches off the counters in use and simultaneously starts a parallel set of counters to continue the measurements over the new test length.

5.2 Maintenance

Table 2 summarises the maintenance checks that should be made on the component parts of the Bump-integrator and indicates the action to be taken if the test results fail to comply with the calibration requirements. The test procedures are, with the exception of the weighing of the chassis, the same as those given in Section 4. Most of the maintenance actions shown in Table 2 could be carried out by the user of the machine but in certain cases, such as damage to the leaf spring, dashpot or integrator unit, the manufacturer should be consulted.

6. IMPROVEMENTS TO THE BI

The minimum length of profile that can be measured to an acceptable level of accuracy is 400m: this is a consequence of the limited resolution of the existing integrating unit of the machine. Measurements over much shorter lengths, of the order of 100 metres, are required for maintenance management systems such as CHART⁹.

A new and economic integrating unit based on a microprocessor is being developed at TRRL to satisfy this requirement. The new unit incorporates an electric transducer for sensing the axle-chassis motion and an improved distance measuring device; it is designed to fit easily on to existing machines. Accurate index measurements over lengths as short as 50 metres can be made using the new unit and the measurements, which will be fully metricated, can be stored on magnetic media or printed to paper copy as required.
TABLE 2

Maintenance checks

<table>
<thead>
<tr>
<th>Component</th>
<th>Test</th>
<th>Parameter measured</th>
<th>Action on non-compliance with calibration requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tyre</td>
<td>Age</td>
<td>Age</td>
<td>Replace tyre with one that complies with the requirements</td>
</tr>
<tr>
<td></td>
<td>Out-of-roundness</td>
<td>Radii of tyres</td>
<td></td>
</tr>
<tr>
<td>Wheel</td>
<td>Static and dynamic balance</td>
<td>Balance</td>
<td>Restore wheel to in-balance</td>
</tr>
<tr>
<td>Leaf spring</td>
<td>‘Drop’ test with integrator not connected</td>
<td>Resonant frequency</td>
<td>Check dimensions, linkage to chassis and stiffness of leaf spring CONSULT MANUFACTURER</td>
</tr>
<tr>
<td>Dashpot</td>
<td></td>
<td>Damping factor</td>
<td>Check fluid, felt seals, piston rod and mounting of dash pot CONSULT MANUFACTURER</td>
</tr>
<tr>
<td>Chassis</td>
<td>Weigh</td>
<td>Weight</td>
<td>Incorrect weight can affect resonant frequency CONSULT MANUFACTURER</td>
</tr>
<tr>
<td>Integrator unit</td>
<td>‘Drop’ test with integrator connected</td>
<td>Damping factor</td>
<td>Check integrator spring stiffness, sticking of spring, spring tension, binding of spring-shaft, and vertical alignment of cord CONSULT MANUFACTURER</td>
</tr>
</tbody>
</table>

The same microprocessor that computes the index value is also being programmed to evaluate the dynamic response of the BI for calibration purposes, as described in Section 4. With this facility the task of carrying out the dynamic calibration is very much simplified for the operator who will only have to use a hoist to raise the chassis through the required distance, and then release the BI from the hoist. The programmed microprocessor will then compute the required resonant frequency and damping factor parameters shown in Figure 4. This facility can also help to identify the causes of any malfunction of the machine using the procedures given in Section 5 for the maintenance of the machine.

Development of the new system is well advanced and following testing of the unit at TRRL, it will be commercially developed.

7. RIDING QUALITY AND THE INDEX r

In-service a road profile may deteriorate to a level where vehicles travelling over it have vibratory motions induced in them that adversely effect:

(i) the safety of road users
(ii) the performance and/or comfort of vehicle occupants
(iii) the performance of the road pavement because of impact stresses generated by heavy vehicles
(iv) the environment in built-up areas by generating vibration and noise
(v) the economics of road transport because of increased maintenance costs of vehicles, damage to goods and increased journey times.
Although insufficient information is available on some aspects important in defining levels of surface unevenness that require correction by maintenance, on new work the level of regularity should be adequate to ensure that only riding comfort need be considered. Adequate research data are available on riding comfort on which to base recommendations for the riding quality requirements for newly resurfaced roads. Road surface unevenness affects riding comfort largely through the level of vibration it creates, and to a lesser extent through noise it generates in road vehicles. Research\textsuperscript{2,3} has shown that, for a given profile, the level of vibration in vehicles increases markedly with increase in travelling speed and that the greater the speed the longer are the profile features that influence the ride. Consequently the level of unevenness that can develop on a road before the ride becomes less than acceptable will vary with the traffic speed on that road.

The ride requirements on newly resurfaced roads with nominal speeds below 80 km/h, can be divided into two categories:

(i) roads with traffic speeds less than or equal to 65 km/h (40 mph)
(ii) roads with traffic speeds in the range 65–80 km/h (40–50 mph)

The relationship of the BI index, \( r \), to ride assessment on these roads is shown in Figure 5. It is based on the results of investigations\textsuperscript{2} carried out by the Laboratory where profile unevenness, measured by the high-speed profilometer,\textsuperscript{6} has been correlated to ride assessments in road vehicles and also to the BI index measurements, as shown in Figure 5. The abscissa in the figure gives the variance of the surface unevenness over the range of wavelengths to which the BI responds when operated at the standard speed of 32 km/h (see Figure 2).

Figure 5 shows the BI index values associated with ride assessments ranging from very good to very poor for roads in categories (i) and (ii) above. For roads in category (i) the ride assessment changes from very good to acceptable, acceptable to poor and poor to very poor as the index increases to 150, to 200 and to greater than 200 inches/mile. The index levels for the corresponding changes in ride assessment on roads in category (ii) are 125, 180 and greater than 180 inches/mile.

The recommended maximum index (\( r \)) values to ensure an acceptable ride on newly resurfaced roads in speed categories (i) and (ii) are:

(i) 150 inches/mile for roads with nominal traffic speeds of less than 65 km/h
(ii) 125 inches/mile for roads with nominal traffic speeds in the range 65–80 km/h

A limited survey of the riding quality achieved on newly resurfaced roads has shown that where adequate quality control is exercised in the preparation and laying of resurfacing materials the recommended ride levels can be achieved without difficulty by contractors.

8. CONCLUSIONS

The dynamic performance of the BI and its influence on the measurement of the ride index, \( r \), has been described and discussed. A new calibration procedure for the machine has been presented that will ensure repeatable results from the same machine and consistency of measurements from different machines. The ride index, \( r \), has been
related to ride assessment and to profile unevenness and ride criteria have been defined for newly resurfaced roads that do not carry high-speed traffic.

The new speed correction procedure, together with the new integrating unit based on a microprocessor that is being developed, will enhance the operational flexibility of the machine and will permit the assessment of riding quality requirements of in-service roads for use in maintenance systems such as CHART9.

9. ACKNOWLEDGEMENTS

The work described in this Report was carried out in the Construction and Maintenance Division (Division Head: Mr P D Thompson) of the Highways Department of TRRL. The authors acknowledge the assistance of Mr D Cooper in obtaining test data.

10. REFERENCES


MODEL OF B.I.

Chassis

Wheel axle displacement relative to chassis

Leaf springs

Dashpots (Shock absorber)

Wheel assembly

Tyre spring

Tyre damping

Road profile

Fig. 1 MODEL SHOWING COMPONENT FEATURES OF THE BI THAT GOVERNS ITS DYNAMIC PERFORMANCE
Fig. 2 FREQUENCY ANALYSIS OF THE AXLE MOTION RELATIVE TO THE CHASSIS OF THE B.I. OBTAINED FROM TEST MEASUREMENTS
Fig. 3 VARIATION OF THE B.I. INDEX $r$ WITH THE OPERATING SPEED OF THE MACHINE
Fig. 4 TYPICAL OSCILLATORY TRACE OBTAINED FROM A ‘DROP’ TEST ON THE B.I. WITH THE INTEGRATOR UNIT DISCONNECTED

Analysis of the waveform of the ‘drop’ test
Resonant frequency, $f = 1/T = 2.1$ Hz
Damping factor, $n = -f \log_{10} (A_2/A_1) = 2.0$
Fig. 5  RELATIONSHIP OF B.I. INDEX 'r' TO PROFILE UNEVENNESS AND TO RIDE ASSESSMENT ON ROADS WITH DIFFERENT TRAFFIC SPEEDS
Effect of BI operating speed on the index $r$

The effect of speed ($V$) on the index, $r$, may be examined using the following mathematical model of the index as measured over a fixed length, $L$, of profile:

$$r_V = \left\{ \sum_{i=1}^{N_2} \alpha A_i (\lambda_2) + \sum_{j=1}^{N_{12}} \beta A_j (\lambda_{12}) \right\} / L + K$$ ................................ (4)

$$r_V = \left\{ \alpha N_2 \bar{A} (\lambda_2) + \beta N_{12} \bar{A} (\lambda_{12}) \right\} / L + K$$ ................................ (5)

$A(\lambda_2)$ and $A(\lambda_{12})$ are the random profile amplitudes associated with the wavelengths $\lambda_2$ and $\lambda_{12}$ that excite the resonant frequencies of the BI; their averaged values over the profile length $L$ are denoted by $\bar{A} (\lambda_2)$ and $\bar{A} (\lambda_{12})$ respectively.

The summation terms in Equation 4 give the contributions to the index $r_V$ of the wheel oscillations relative to the chassis at the 2 and 12 Hz resonant frequencies, measured at speed $V$ over the profile length $L$. The contribution of the rotational effects of the wheel to the index value is given by $K$ which, as shown in Section 2, is essentially constant over the speed range 20–65 km/h. The number of oscillations of the wheel relative to the chassis at each of the resonant frequencies 2 and 12 Hz is related to the speed $V$, profile length $L$ and wavelength $\lambda$ by the following expressions:

$$N_2 = \frac{L}{\lambda_2} = \frac{2L}{V} \quad N_{12} = \frac{L}{\lambda_{12}} = \frac{12L}{V}$$ ............................ (6)

Analysis of road profile measurements obtained from a large number of in-service roads has shown that, for wavelengths less than 9 metres, the relation between the averaged amplitude and wavelength can be represented to a good approximation by the following expressions:

$$\bar{A} (\lambda_2) = c \sqrt{\lambda_2} = c \sqrt{V/2}$$

and

$$\bar{A} (\lambda_{12}) = c \sqrt{\lambda_{12}} = c \sqrt{V/2}$$ ........................................ (7)

where the coefficient, $c$, gives the level of unevenness of a profile and is constant for a given profile. The coefficients $\alpha$ and $\beta$ in Equation 4 define the amplification of the profile amplitudes input to the BI from wavelengths $\lambda_2$ and $\lambda_{12}$.

Substituting in Equation 5 for $N_2$, $N_{12}$, $\bar{A} (\lambda_2)$ and $\bar{A} (\lambda_{12})$, using Equations 6 and 7, and simplifying the resulting expression, gives:

$$r_V = \frac{C}{\sqrt{V}} \left\{ \alpha \sqrt{2} + \beta \sqrt{12} \right\} + K$$ ........................................ (8)
Because C, α, and β are constant for a given profile and K is constant within the speed range 20–65 km/h, Equation 8 shows that index varies with speed according to the inverse square root of the operating speed of the BI within the speed range 20–65 km/h. If in Equation 8 the index r is normalised to its value at the standard speed of 32 km/h then the following expression is obtained:

\[
\frac{r_32 - K}{r_32 - K} = \frac{\sqrt{32}}{\sqrt{V}} \quad \text{(9)}
\]

This expression is plotted in Figure 3.

The variation with speed of the index, r, given by Equation 6, depends on the profile amplitude model of Equation 7. This model has been found to give a good representation of profile unevenness on in-service roads within the wavelength range 0.3–9 metres. However on some newly resurfaced roads with very even profiles \(r_32 < 100 \text{ inches/mile}\) the profile amplitudes have been found not to increase with wavelength over the range 4–9 metres but to remain essentially constant.

For these cases which in practice are relatively few, the variation with speed of the index r is given by:

\[
\frac{r_32 - K}{r_32 - K} = \frac{32}{V} \quad \text{(10)}
\]

Here the index varies with the inverse of the speed in the range 20–65 km/h, as shown in Figure 3. Using Equations 9 and 10 the index \(r_32\), obtained using the BI at a non-standard speed, can be converted to the index \(r_32\) appropriate to the standard operating speed as follows:

From Equation 9

\[
r_32 = r_32 \sqrt{\frac{V}{32}} + K \left(1 - \frac{V}{\sqrt{32}}\right) \quad \text{(11)}
\]

and from Equation 10

\[
r_32 = r_32 \left(\frac{V}{32}\right) + K \left(1 - \frac{V}{32}\right) \quad \text{(12)}
\]

If \(r_32\) and K are in units of inches/mile and V is in kilometres/hour then \(r_32\) is given in inches/mile. From Section 2, K takes the constant value of 30 inches/mile.
ABSTRACT

DEVELOPMENTS IN THE CALIBRATION AND USE OF THE BUMP-INTEGRATOR FOR RIDE ASSESSMENT:
PG Jordan and J C Young: Department of the Environment Department of Transport, TRRL Supplementary Report 604: Crowthorne, 1980 (Transport and Road Research Laboratory). For roads, other than those where speeds of over about 50 mph (80 km/h) can be maintained, the Bump-integrator provides a suitable means of monitoring riding quality. The ride index measurement of the Bump-integrator is determined by the machine's dynamic response to the unevenness of a road profile.

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