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EVALUATION OF WHOLE-BODY VIBRATION IN VEHICLES

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The vibration in 100 different vehicles has been measured, evaluated and assessed according to British Standard BS 6841 (1987) and International Standard ISO 2631 (1997). Vibration was measured in 14 categories of vehicle including cars, lift trucks, tractors, lorries, vans and buses. In each vehicle, the vibration was measured in five axes: vertical vibration beneath the seat, fore-and-aft, lateral and vertical vibration on the seat pan and fore-and-aft vibration at the backrest. The alternative methods of evaluating the vibration (use of different frequency weightings, different averaging methods, the inclusion of different axes, vibration dose values and equivalent r.m.s. acceleration) as defined in the standards have been compared. BS 6841 (1987) suggests that an equivalent acceleration magnitude is calculated using vibration measured at four locations around the seat (*x*-, *y*-, *z*-seat and *x*-backrest); ISO 2631 (1997) suggests that vibration is measured in the three translational axes only on the seat pan but only the axis with the most severe vibration is used to assess vibration severity. Assessments made using the procedure defined in ISO 2631 tend to underestimate any risks from exposure to whole-body vibration compared to an evaluation made using the guidelines specified in BS 6841; the measurements indicated that the $17\,\mathrm{m/s^{1\cdot75}}$ "health guidance caution zone" in ISO 2631 was less likely to be exceeded than the $15\,\mathrm{m/s^{1\cdot75}}$ "action level" in BS 6841. Consequently, ISO 2631 "allows" appreciably longer daily exposures to whole-body vibration than BS 6841.

1. INTRODUCTION

Many occupations expose workers to whole-body vibration in road or off-road vehicles. Currently, there are two main standards for evaluating vibration with respect to the human responses to whole-body vibration [1, 2]. There are several differences in the measurement, evaluation and assessment procedures defined in the two standards. For example, BS 6841 [1] recommends the measurement of four axes of vibration on the seat (fore-and-aft, lateral and vertical vibration on the seat surface and fore-and-aft vibration at the backrest) and combining these in an evaluation procedure before assessing the vibration severity. In ISO 2631 [2] it is advocated that vibration in several axes is measured but that assessment is based on only the most severe axis. The two standards employ slightly different frequency weightings for vertical vibration on the seat pan. The differences between the two standards have been reviewed elsewhere [3].

Although there are clear differences between the two standards, the extent to which these affect judgments of exposure severity can only be determined from vibration measurements

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TABLE 1

Number and category of vehicles used in the study

Category	Number of vehicles
Car	25
Excavator	4
Mobile crane	2
Dumper	4
Lift truck	11
Tractor	7
Grass roller	1
Lorry	16
Mower	3
Van	9
Milk float	3
Armoured vehicle	4
Helicopter	1
Bus	10

in vehicles. This has been undertaken in a small way previously [4]. This study was conducted so as to make a more comprehensive comparison of the evaluation methods in BS 6841 [1] and ISO 2631 [2]. The study also allowed inspection of variability between vehicles within categories (e.g., within tractors), and differences between categories of vehicle (e.g., cars and tractors). The data were also used to investigate ranges of vibration magnitudes appropriate to the categories of vehicle and to characterize the vibration to which workers are exposed. To achieve these objectives, the whole-body vibration in 100 different vehicles was measured, evaluated and assessed according to the two standards.

2. EQUIPMENT AND PROCEDURE

Acceleration was normally measured at the driver's seat, using five accelerometers to obtain vertical vibration on the vehicle floor below the seat, fore-and-aft, lateral and vertical vibration on the seat and fore-and-aft vibration on the seat backrest. The vibration measurements at the vehicle floor are presented elsewhere (see reference [5]).

Vibration was measured using piezoresistive full-bridge accelerometers: Entran model types EGCS-DO-10 and EGCSY-240D-10. Measurements were obtained at the driver–seat interfaces in accord with the standards: a semi-rigid mounting disc containing mutually perpendicular accelerometers was used to measure triaxial vibration on the seat (see ISO 10326-1 [6]). A similar mounting disc containing one accelerometer was used to measure fore-and-aft backrest vibration.

The vehicles were operated on the most suitable and appropriate surface relevant to the vehicle. For example, cars and lorries were driven over roads while sit-on mowers were driven over grass. For some vehicles, several measurements were obtained in different operating conditions (e.g., with different speeds and over different terrain), depending on the availability of the vehicles, drivers and conditions. For some vehicles, measurements were also made with the vehicle in an idling mode (e.g., with the engine switched on but the vehicle stationary); however, these data were not used in the analysis presented here (see reference [7]).

TABLE 2

Frequency weightings and multiplying factors as specified in British Standard 6841 [1] for seated persons

Location	Axis	Weighting	Multiplying factor
Seat	x	W_d	1·0
	y	W_d	1·0
	z	W_b	1·0
Backrest	x	W_c	0·8
Floor	z	W_b	0·4

TABLE 3

Frequency weightings and multiplying factors for health aspects of whole-body vibration as specified in International Standard 2361-1 [2] for seated persons

Location	Axis	Weighting	Multiplying factor
Seat	x	W_d	1·4
	y	W_d	1·4
	z	W_k	1·0
Backrest	x	W_c	0·8

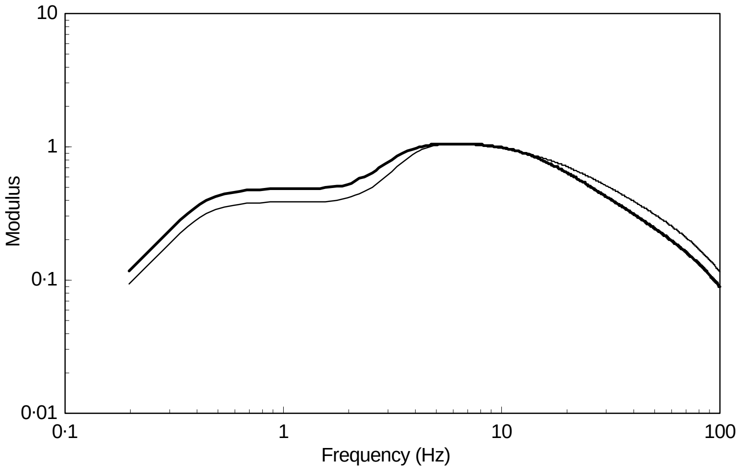

Figure 1. Frequency weightings W_b (BS 6841 [1]) and W_k (ISO 2631 [2]). ——, W_b (BS 6841); ▬▬, W_k (ISO 2631).

The signals from the accelerometers were acquired (usually over a period of 60 s) into a digital computer-based data acquisition and analysis system, *HVLab* (version 3.81). The acceleration waveforms were low-pass filtered at 100 Hz via antia–liasing filters with an elliptical characteristic (TechFilter with an attenuation rate of 70 dB in the first octave) and then digitised (PCL-818 analogue to digital converter) at 400 samples/s.

The vehicles were operated in the normal work appropriate to each vehicle. Table 1 shows the 14 categories of vehicle tested and the numbers of vehicles in each category.

A total of 100 vehicles were included in the study; 461 sets of multi-axis measurements are reported in various operating conditions (e.g., with different speeds and terrain). The vibration measurements presented in this paper should not be assumed to be fully representative of all work exposures to whole-body vibration. For example, of the seven tractors used in the observation, four were driven over grassed areas; no measurements were made while traversing ploughed fields or farm roads.

3. ANALYSIS

3.1. FREQUENCY ANALYSIS

Power spectral densities were calculated for all acceleration waveforms. The power spectra show the distribution of energy across the frequency spectrum. A frequency resolution of 0·195 Hz was used, giving 48 degrees of freedom for a 60-s measurement duration.

3.2. BRITISH STANDARD 6841 (1987) AND INTERNATIONAL STANDARD 2631 (1997)

The measurements were analyzed according to the recommendations in British Standard 6841 [1] and International Standard 2631 [2]. This involved the application of frequency weightings, the use of multiplying factors to allow for differing sensitivity of the body in different axes, the calculation of root-mean-square (r.m.s.) values and vibration dose values (VDVs), and the summation of values over the different axes.

3.2.1. *Frequency weightings*

The acceleration was frequency-weighted using the frequency weightings defined in British Standard 6841 [1] and International Standard 2631 [2]. Root-mean-square vibration magnitudes were calculated from the frequency-weighted acceleration time histories.

The frequency weightings and multiplying factors defined in BS 6841 [1] and ISO 2631 [2] for the different axes are shown in Tables 2 and 3 respectively. While the procedures defined in BS 6841 are the same for evaluating vibration with respect to both comfort and health, ISO 2631 defines slightly different procedures for the two effects. The weightings and multiplying factors in Table 3 are those defined in ISO 2631 for evaluating vibration with respect to health risks.

The frequency weightings for vertical vibration on the seat differ between the two standards: W_b (in BS 6841) and W_k (in ISO 2631). The weighting W_b applies less weight to low frequencies and more weight to high frequencies, compared to W_k. The two frequency weightings are shown in Figure 1. The differences between the two frequency weightings, W_b and W_k, have been discussed elsewhere [3].

3.2.2. *Vibration dose values*

VDVs were calculated for each axis of whole-body vibration using appropriate frequency weightings and axis multiplying factors. The VDV gives a measure of the total exposure to vibration, taking account of the magnitude, frequency and exposure duration:

$$VDV\ (\mathrm{m/s^{1\cdot 75}}) = \left[\int_0^T a(t)^4\, \mathrm{d}t\right]^{1/4}, \tag{1}$$

TABLE 4

Scale of discomfort suggested in BS 6841 [1] *and ISO* 2631 [2]

Less than 0·315 m/s^2	Not uncomfortable
0·315–0·63 m/s^2	A little uncomfortable
0·5–1 m/s^2	Fairly uncomfortable
0·8–1·6 m/s^2	Uncomfortable
1·25–2·5 m/s^2	Very uncomfortable
Greater than 2 m/s^2	Extremely uncomfortable

where $a(t)$ is the frequency-weighted acceleration time history (in m/s^2) at the input to the body.

The standards suggest that for some exposures, such as when the vibration is continuous and of low crest factor, the vibration dose value may be approximated by the "estimated vibration dose value", $eVDV$:

$$eVDV = 1{\cdot}4\ a_{r.m.s.} t^{1/4}, \tag{2}$$

where $a_{r.m.s.}$ is the frequency-weighted r.m.s. acceleration and the exposure duration is t seconds.

The exposure period required for the vibration to reach a tentative "action level" of 15 m/s$^{1\cdot75}$, as specified in BS 6841 [1], can be calculated as

$$T_{15} = \left[\frac{15}{VDV_t}\right]^4 t, \tag{3}$$

where T_{15} is the duration (in s) required to reach a VDV of 15 m/s$^{1\cdot75}$ and VDV_t is the VDV measured over a period of t seconds.

The value of 15 m/s$^{1\cdot75}$ in the above equation can be replaced by other "action levels". International Standard 2631 [2] suggests a "health guidance caution zone" with lower and upper VDV levels at 8·5 and 17 m/s$^{1\cdot75}$.

A comparison of the guidance given on the evaluation and assessment of whole-body vibration with respect to health in the ISO and the BSI standards has been presented elsewhere [3].

3.2.3. *Multi-axis vibration*

British Standard 6841 [1] indicates that when evaluating multi-axis vibration with respect to health, the fourth root of the sum of the fourth powers of the VDVs in each axis should be determined to give the total vibration dose value, VDV_{total}, for the environment:

$$VDV_{total} = (VDV_{xs}^4 + VDV_{ys}^4 + VDV_{zs}^4 + VDV_{xb}^4)^{1/4}, \tag{4}$$

where VDV_{total} is the total vibration dose value, VDV_{xs} is the VDV in the x-axis on the seat, VDV_{ys} is the VDV in the y-axis on the seat, VDV_{zs} is the VDV in the z-axis on the seat, and VDV_{xb} is the VDV in the x-axis on the backrest.

In order to compare the r.m.s. accelerations with measurements made according to BS 6841, the total VDV calculated according to equation (4) above have been converted to equivalent r.m.s. accelerations (equivalent vibration magnitude) using the relation in equation (2):

$$a_{r.m.s.\,equivalent} = VDV_{total}/(1{\cdot}4\, t^{1/4}), \tag{5}$$

TABLE 5

Frequency-weighted vibration magnitudes measured on vehicles ("equivalent r.m.s. acceleration" calculated from VDV obtained over four axes for BS 6841 [1] *and over three axes for ISO* 2631 [2])

	BS 6841 (1987)								ISO 2631 (1997)			
	Equivalent r.m.s. acceleration (m/s^2 r.m.s.)				Seat vertical acceleration (m/s^2 r.m.s.)				Most severe axis acceleration (m/s^2 r.m.s.)			
Vehicle type (number of vehicles)	Median	Min.	Max.	St. Dev.	Median	Min.	Max.	St. Dev.	Median	Min.	Max.	St. Dev.
Car (25)	0·45	0·32	0·75	0·14	0·37	0·25	0·61	0·10	0·39	0·26	0·75	0·14
Excavator (4)	1·13	0·22	4·35	1·81	0·91	0·08	3·27	1·38	0·91	0·17	3.03	1·23
Mobile crane (2)	0·71	0·64	0·78	0·10	0·57	0·50	0·64	0·10	0·59	0·50	0·67	0·12
Dumper (4)	1·40	0·98	2·76	0·85	0·89	0·52	1·61	0·50	1·28	0·73	1·90	0·62
Lift truck (11)	0·90	0·67	1·40	0·22	0·71	0·47	0·91	0·13	0·74	0·53	1·00	0·16
Tractor (7)	0·75	0·52	1·20	0·21	0·56	0·32	0·80	0·16	0·73	0·54	1·00	0·15
Grass roller (1)	0·55	0·55	0·55	—	0·53	0·53	0·53	—	0·46	0·46	0·46	—
Lorry (16)	0·72	0·43	1·25	0·28	0·44	0·36	1·03	0·21	0·50	0·42	1·28	0·26
Mower (3)	0·66	0·63	1·04	0·23	0·49	0·42	0·71	0·15	0·60	0·56	0·76	0·11
Van (9)	0·50	0·38	0·61	0·07	0·42	0·34	0·53	0·07	0·45	0·36	0·57	0·07
Milk float (3)	0·92	0·88	1·01	0·07	0·72	0·65	0·75	0·05	0·82	0·72	0·84	0·07
Armoured vehicle (4)	0·81	0·35	1·66	0·55	0·63	0·30	1·85	0·68	0·85	0·29	1·52	0·51
Helicopter (1)	1·00	1·00	1·00	—	1·17	1·17	1·17	—	1·08	1·08	1·08	—
Bus (10)	0·58	0·40	0·84	0·14	0·48	0·34	0·79	0·14	0·56	0·38	0·89	0·16

where VDV_{total} is calculated according to the procedure in BS 6841 (using the appropriate frequency weightings, multiplying factors and summation over axes) over the measurement period, t seconds (e.g., 60 s).

International Standard 2631 [2] is not entirely clear on how exposures occurring in several axes should be evaluated, but one interpretation is that assessments should be based on the axis giving the greatest frequency-weighted acceleration on the seat pan. (The standard also states that the *VDV* can be used in the evaluation procedure.) This implies that there is no summation over axes and that the vibration at the backrest is excluded. The measurement of vibration on the backrest is "*encouraged*" by ISO 2631-1 [2] but the data are not used to assess exposure severity.

3.3. COMPARISON OF MEASUREMENTS WITH GUIDANCE IN STANDARDS

3.3.1. *British Standard* 6841 (1987)

British Standard 6841 [1] gives a table offering "… *very approximate indications of the likely reactions to various magnitudes of frequency-weighted r.m.s. acceleration*" (see Table 4).

The following guidelines are offered in BS 6841 [1] regarding exposure to high VDVs:

> … It is known that vibration magnitudes and durations which produce vibration dose values in the region of 15 m/s$^{1·75}$ will usually cause severe discomfort. It is reasonable to assume that increased exposure to vibration will be accompanied by increased risk of injury.
> At high vibration dose values prior consideration of the fitness of the exposed persons and the design of adequate safety precautions may be required. The need for regular checks on the health of routinely exposed persons may also be considered.

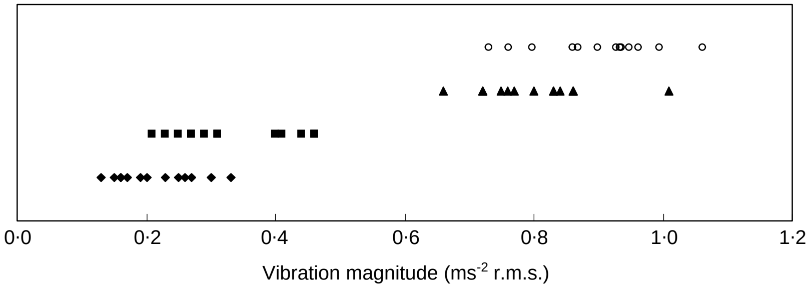

Figure 2. Variation in frequency-weighted vibration magnitudes over 13 repeat measures for a tractor (evaluated using BS 6841 [1]). ◆, *x*-seat; ■, *y*-seat; ▲, *z*-seat; ○, total.

3.3.2. *International Standard* 2631 (1997)

International Standard 2631-1 [2] also states that the scale in Table 4 may be used to assess the discomfort that might be experienced due to the vibration. However, in ISO 2631, different evaluation methods are used for evaluations of vibration in respect of comfort and health (especially for horizontal seat vibration). Consequently, if the vibration is assessed with respect to comfort, fore-and-aft and lateral vibration will appear to be less important than when the same vibration is assessed with respect to health.

International Standard ISO 2631 [2] suggests a "health guidance caution zone" with VDVs at 8·5 and 17 m/s$^{1·75}$. The standard states that:

> For exposures below the zone, health effects have not been clearly documented and/or objectively observed; in the zone, caution with respect to potential health risks is indicated and above the zone health risks are likely.

The standard also states that:

> Increased duration (within the working day or daily over years) and increased vibration intensity mean increased vibration dose and are assumed to increase the risk, while periods of rest can reduce the risk.
> There are not sufficient data to show a quantitative relationship between vibration exposure and risk of health effects. Hence, it is not possible to assess whole-body vibration in terms of the probability of risk at various exposure magnitudes and durations.

Regarding continued exposure to vibration, the standard states that:

> It generally takes several years for health changes caused by whole-body vibration to occur. It is therefore important that exposure measurements are representative of the whole exposure period.

International Standard 2631 [2] mentions several alternative means of evaluating and assessing the severity of exposures in addition to the VDV as defined above. However, as the alternatives are numerous and not well defined they are not reported in this paper.

4. RESULTS AND DISCUSSION

The frequency-weighted vibration magnitudes were calculated for the 100 vehicles. The medians and ranges of the frequency-weighted vibration magnitudes for selected types of vehicle are summarized in Table 5. Table 5 shows two sets of measures assessed using BS 6841: those calculated using the equivalent r.m.s. accelerations (as defined by equation (5) for the vibration over all four axes), and those obtained by considering only the vertical

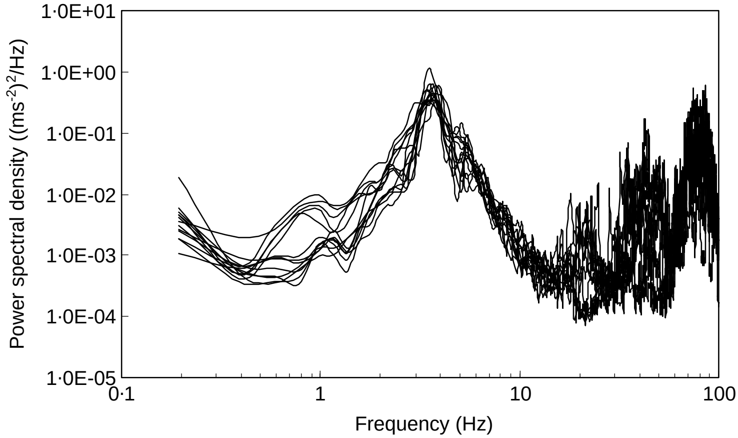

Figure 3. Power spectral densities of vertical vibration measured on the seat of a tractor during 13 repeat measures (0·195 Hz frequency resolution, 48 degrees of freedom).

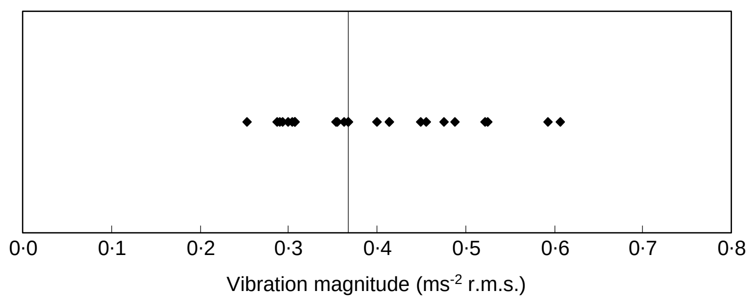

Figure 4. Variation in the magnitude of frequency-weighted vertical seat acceleration for 25 cars (evaluated using BS 6841 [1]).

acceleration on the seat surface. Frequency-weighted vibration magnitudes corresponding to the worst axis on the seat are also shown for evaluations as specified in ISO 2631. Repeat measurements in different conditions were made on many of the vehicles (e.g., for a forklift truck, the vehicle moving empty and loaded, on tarmac or over uneven concrete surfaces), giving a total of 461 sets of measurements of vibration in four axes. The data presented in Table 5 (and all data presented in this paper) are restricted to conditions while travelling: measurements while stationary and when idling are not included in the analysis. Individual vibration magnitudes and median values for all vehicles while travelling are shown in Appendix A. The data shown in Appendix A for each vehicle are an average of repeat measurements.

Table 5 shows appreciable variations in vibration magnitudes for the same type of vehicle. Comparing measures of vertical vibration on the driving seat using BS 6841 [1] with the "worst axis" according to ISO 2631 [2], the International Standard gave somewhat greater values of r.m.s. acceleration. This arose partly as a consequence of the slight difference in the frequency weightings for vertical vibration but also because the dominant vibration was not always in the vertical axis: ISO 2631 [2] gives a high weighting to low-frequency fore-and-aft and lateral vibration on the seat. The difference between the two standards was reversed when all axes were taken into account (as recommended in BS 6841 but not in ISO 2631): the summation of values over four axes according to BS 6841 tended

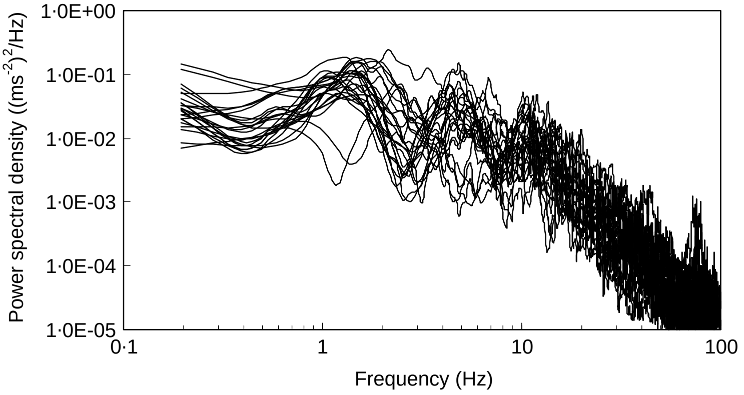

Figure 5. Power spectral densities of vertical vibration measured on the seats of 25 different cars (0·195 Hz frequency resolution, 48 degrees of freedom).

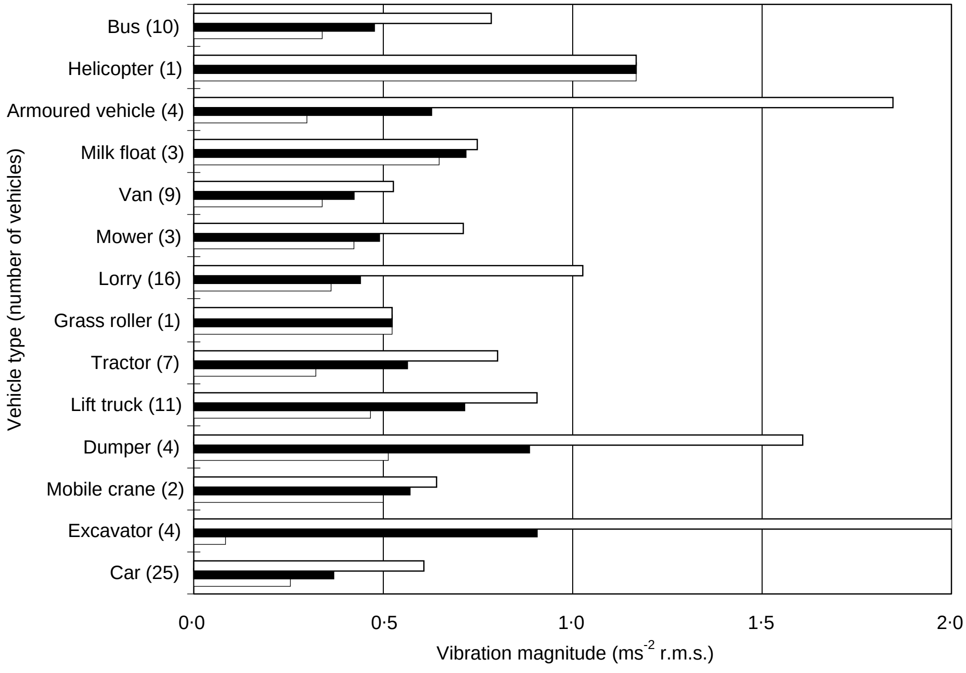

Figure 6. Variation in frequency-weighted vertical acceleration on the seat for the different categories of vehicle (using W_b from BS 6841 [1]). □, maximum; ■, median; □, minimum.

to give greater values than in the worst axis alone according to ISO 2631.

The data presented in Table 5 should not be assumed to be representative of all vehicles of the types specified: higher and lower values may occur with other vehicles in current use. Only one grass roller and one helicopter were tested in this study: the data from these two vehicles are likely to be least representative of these types of vehicle.

The spectra in each of the five axes in the various vehicles showed wide variations in the frequency content [7].

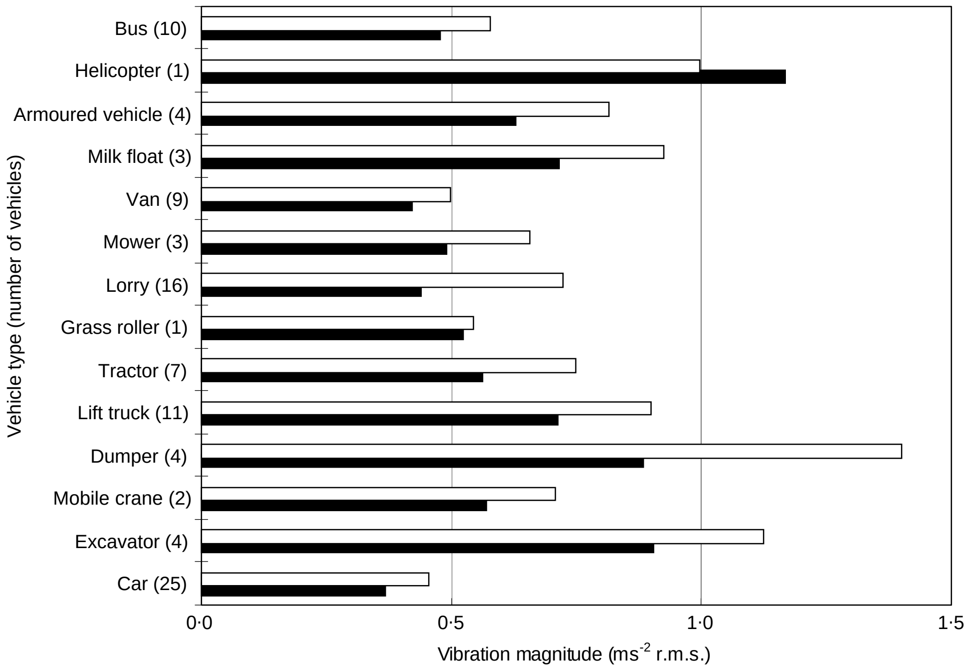

Figure 7. Comparison of median vertical r.m.s. acceleration on the vehicle seats with the median equivalent r.m.s. acceleration from measures obtained over four axes (evaluated using BS 6841 [1]). □, r.m.s. equivalent; ■, seat vertical (r.m.s).

4.1. VARIATION OVER REPEAT MEASURES WITHIN A VEHICLE

Figure 2 shows the range of frequency-weighted vibration magnitudes measured in one tractor during 13 repeat measurements: while driving over tarmac roads and over a grass field. Also shown is the "total value" on the seat for the three axes of measurement, calculated as the root-sums-of-squares over three axes. It is seen that the total value is dominated by vertical vibration on the seat. In this example, the median for the total vibration magnitude was 0·93 m/s^2 r.m.s. and vertical vibration on the seat was 0·80 m/s^2 r.m.s.: z-axis seat acceleration was 86% of the total vibration magnitude.

Power spectral densities of the vertical acceleration measured on the seat of the tractor during the 13 different runs are shown in Figure 3. Although there is variation in the spectra for the different measurements, the underlying trend is the same. Also, the variation is less than that between different vehicles of the same type (see Figure 5 below). For the tractor used in the measurements, the vertical acceleration on the seat was dominated by vibration occurring at about 3·7 Hz.

It would be unwise to assume that a single measurement of vibration in a vehicle will represent vibration in all conditions: there can be wide variations in vibration within a vehicle according to operating conditions.

4.2. VARIATION WITHIN A CATEGORY OF VEHICLE

Figure 4 shows frequency-weighted magnitudes of vertical acceleration on the seat in all vehicles within the "car" category. The vertical line at 0·37 m/s^2 r.m.s. corresponds to the median frequency-weighted vibration magnitude for the 25 cars. One car showed a vibration magnitude of 0·25 m/s^2 r.m.s. (a small car) compared to the highest value of

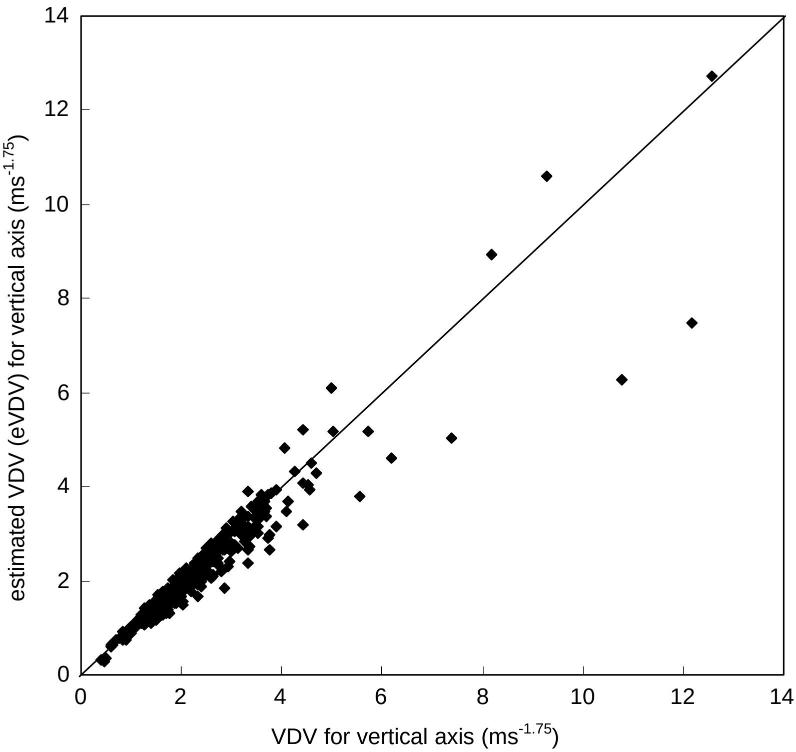

Figure 8. Comparison of *VDVs* calculated for the vertical axis on the vehicle seats (evaluated using BS 6841 [1]).

0·61 m/s^2 r.m.s. (a four-wheel drive vehicle travelling on a tarmac road). Figure 4 shows a wide variation in the vibration magnitudes measured in the same category of vehicle.

All of the 25 different cars (including small vehicles, luxury cars and four-wheel drive off-road vehicles) were driven on public roads and were relatively new (post 1985). Measurements made in older vehicles, and in vehicles driven off-road, may be expected to show greater vibration magnitudes.

Power spectral densities of the vertical vibration on the seats of the 25 cars are shown in Figure 5 and exhibit a large variation, but with some common features. It would clearly be unwise to assume that the measurement of vibration in a single vehicle will represent vibration in all other vehicles of the same type.

4.3. VERTICAL VIBRATION ON THE SEAT EVALUATED USING BS 6841

The frequency-weighted acceleration magnitudes on the seats in the 100 vehicles are summarized in Figure 6. The median and range of vibration magnitudes are shown for all vehicles grouped by category. For the four armoured vehicles, one showed vibration that was six times greater than in another vehicle (1·85 m/s^2 r.m.s. compared with 0·30 m/s^2 r.m.s.). The range of vibration magnitudes was even greater for the four excavators.

4.4. COMPARISON OF 'EQUIVALENT r.m.s. ACCELERATIONS' OVER FOUR AXES WITH VERTICAL SEAT ACCELERATION EVALUATED ACCORDING TO BS 6841

Using median values for each vehicle category, Figure 7 compares the vertical acceleration on the seat with the equivalent r.m.s. accelerations obtained over four axes. For

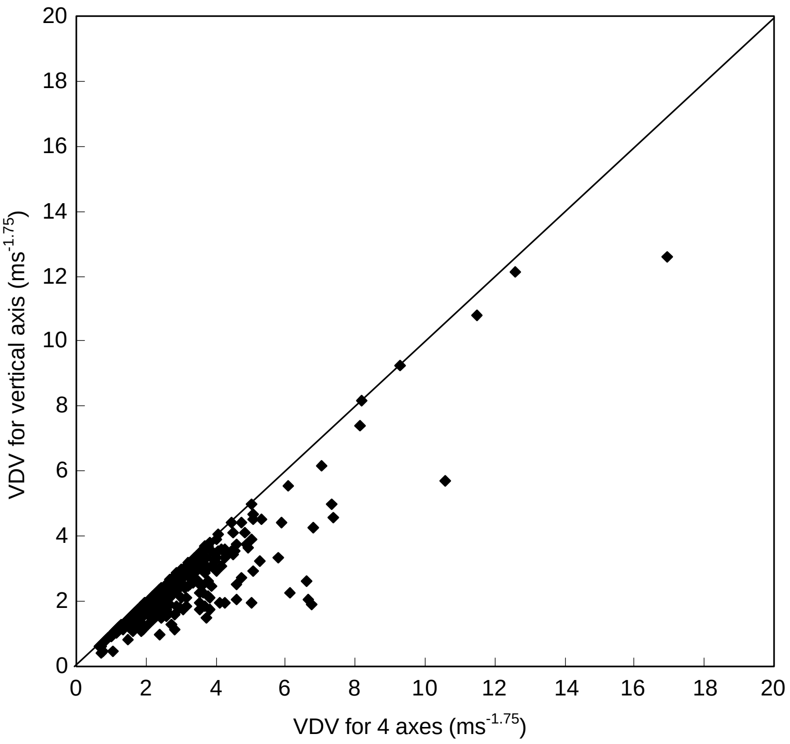

Figure 9. Comparison of *VDV*s calculated for the vertical axis and for the four axes around the vehicle seats (evaluated using BS 6841 [1]).

several categories of vehicle, the vertical seat vibration appears to give a useful indication of the equivalent r.m.s. acceleration, but in some cases there is significant underestimation if the other axes are not included in the calculation.

For the 100 vehicles, a total of 461 sets of measurements (from 1 to 13 sets of measurements per vehicle) were made. Figure 8 compares, for measurements in the vertical axis only, the *VDV* and the *eVDV*s. (The *eVDV* was calculated from the frequency-weighted r.m.s. acceleration, see section 3.2.2.) It can be seen that most of the data points show lower values when using r.m.s. acceleration (i.e., the *eVDV*) than when using the *VDV*. Indeed, the average *VDV* of all 461 points is 2·21 $m/s^{1.75}$ compared to an average *eVDV* of 2·07 $m/s^{1.75}$.

The summation of vibration over four axes increased the *VDV*s, compared with that obtained using the vertical axis alone (see Figure 9). The contribution of *VDV* in the vertical axis on the *VDV* calculated for the four axes varied from 28% up to 100%; the average contribution of vertical axis vibration on the total of the four axes for the 461 measurement runs was 87%.

Figure 10 compares the 461 data points for r.m.s. vertical seat vibration with the "equivalent r.m.s. acceleration" calculated over the four axes according to BS 6841 [1]. These are the data used to construct Figure 7. The inclusion of three additional axes in the calculation of the equivalent r.m.s. acceleration would be expected to increase the vibration magnitude so that data points would be below the diagonal line. The five points above the diagonal line come from two vehicles (a helicopter and an armoured vehicle).

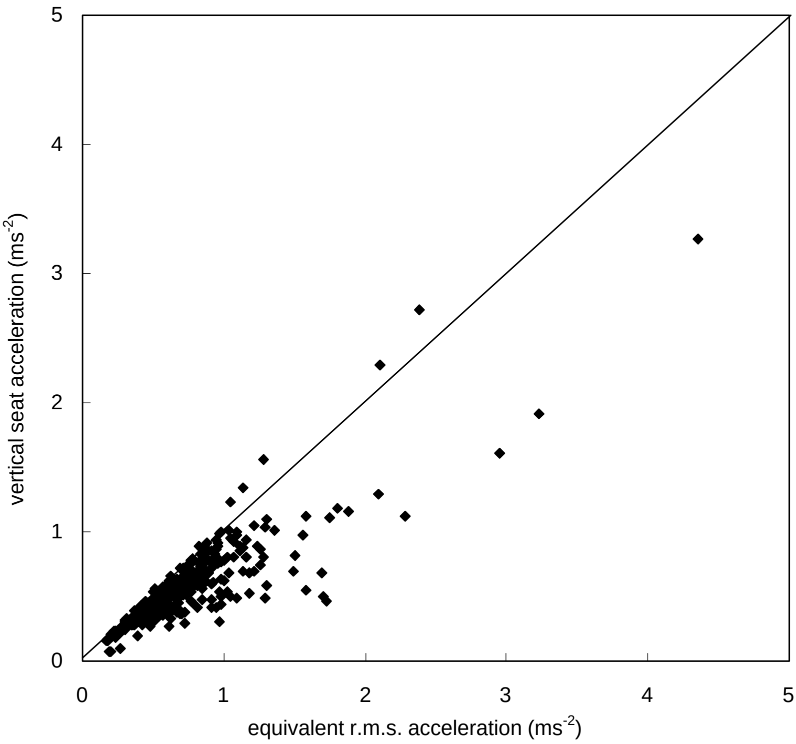

Figure 10. Comparison of vertical r.m.s. acceleration on the vehicle seats with the equivalent r.m.s. acceleration magnitudes calculated from the *VDV*s obtained over four axes (evaluated using BS 6841 [1]).

4.5. COMPARISON OF VERTICAL SEAT VIBRATION WITH THE MOST SEVERE AXIS EVALUATED ACCORDING TO BS 6841

Figure 11 compares vibration magnitudes measured in the vertical axis with those measured in the most severe of the four axes measured according to BS 6841. Since most of the points are on the diagonal, it is clear than in most cases the vibration was most severe in the vertical axis.

4.6. COMPARISON OF "EQUIVALENT r.m.s. ACCELERATIONS" ACCORDING TO BS 6841 AND FREQUENCY-WEIGHTED ACCELERATION IN THE MOST SEVERE AXIS ACCORDING TO ISO 2631

Figure 12 compares the median equivalent r.m.s. accelerations calculated over four axes according to BS 6841 [1] with the most severe of the three axes on the seat pan calculated according to ISO 2631 [2]. Although the "most severe axis" measures are determined by values in only one axis, measures are required in all three axes to identify the most severe axis.

Similar median values are obtained using the two methods, but there are differences: the ISO 2631 method, based on the most severe axis, underestimates the vibration severity relative to BS 6841.

A scatter plot for the 461 sets of measurements in the 100 vehicles is shown in Figure 13. The 461 measurements include the repeat measures for all vehicles. The r.m.s. equivalent

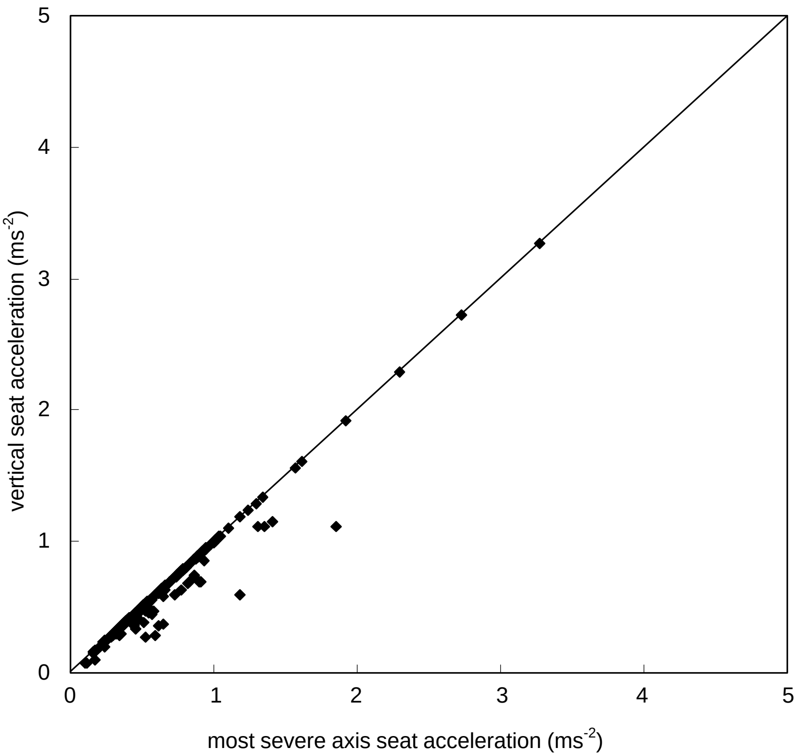

Figure 11. Comparison of vertical acceleration on the seat and most severe vibration on the seat for 461 evaluations in 100 vehicles according to BS 6841 [1].

acceleration calculated according to BS 6841 was greater than, or similar to, the r.m.s. acceleration in the most severe axis according to ISO 2631 for all except two categories of vehicle: the helicopter and the armoured vehicle (see also Figure 12). The differences arise from: (a) different frequency weightings, (b) the use of r.m.s. versus VDV methods of evaluation, and (c) the use of four versus one axis.

Over all 461 measurements, the median value for the ISO most severe axis method was $0{\cdot}66\,\mathrm{m/s^2}$ r.m.s., compared with $0{\cdot}74\,\mathrm{m/s^2}$ r.m.s. for the r.m.s. equivalent acceleration calculated according to BS 6841. Evaluations according to ISO 2631 therefore give lower values (by about 12%) compared to BS 6841. The $17\,\mathrm{m/s^{1{\cdot}75}}$ upper boundary to the "health guidance caution zone" in ISO 2631 is 13% greater than the $15\,\mathrm{m/s^{1{\cdot}75}}$ "action level" in BS 6841. Clearly, an evaluation and assessment according to the upper boundary of the health guidance caution zone in ISO 2631 will underestimate the risk due to whole-body vibration compared to the risk estimated by BS 6841. The vibration magnitudes required to reach the $17\,\mathrm{m/s^{1{\cdot}75}}$ "health guidance caution zone" in ISO 2631 will be, on average, 27% greater (i.e., $(0{\cdot}74/0{\cdot}66)/(15/17) = 1{\cdot}27$) than those required to reach the $15\,\mathrm{m/s^{1{\cdot}75}}$ action level in BS 6841. This difference in magnitude corresponds to a 260% difference in exposure duration required to reach the boundaries: much longer exposures will be "permitted" according to ISO 2631 than according to BS 6841. This is also apparent in Table 6: evaluations according to ISO 2631 give lower r.m.s. accelerations and lower vibration dose values compared to evaluations according to BS 6841. Table 6 also shows, for each category of vehicle, that much longer exposure durations are required to exceed the $17\,\mathrm{m/s^{1{\cdot}75}}$ "health guidance caution zone" in ISO 2631 than the $15\,\mathrm{m/s^{1{\cdot}75}}$ "action level" suggested in BS 6841.

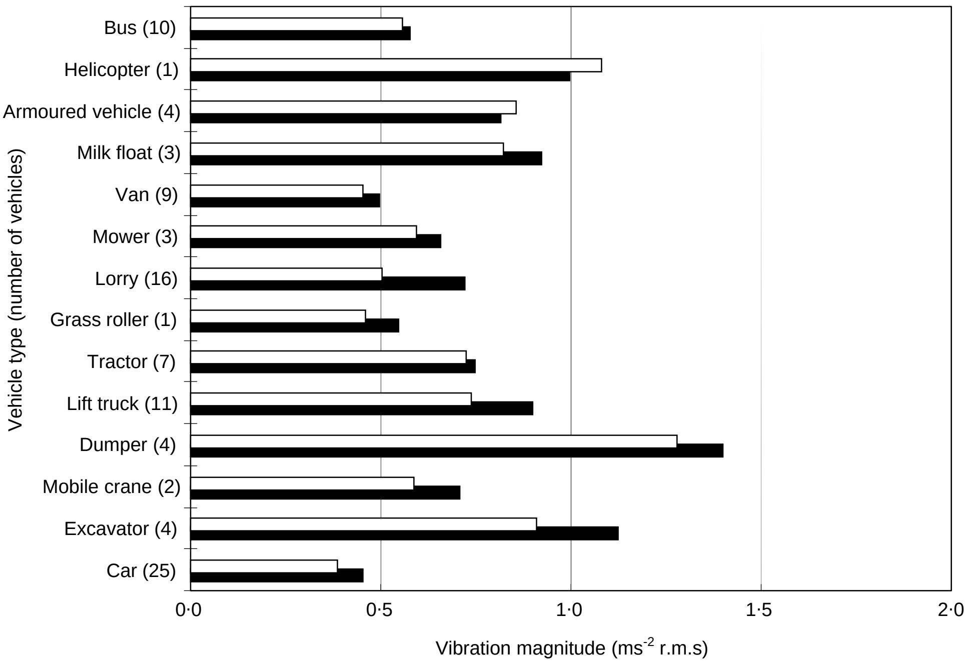

Figure 12. Comparison of median values of r.m.s. acceleration in the most severe axis (ISO 2631 [2]) and r.m.s. equivalent acceleration calculated over four axes (BS 6841 [1]). □, ISO most severe axis; ■, r.m.s. equivalent.

According to ISO 2631 [2], an 8-h exposure to a magnitude $> 0{\cdot}93\ \text{m/s}^2$ r.m.s. is required to exceed the upper boundary of the health guidance caution zone (at $17\ \text{m/s}^{1{\cdot}75}$), but an 8-h exposure to a magnitude of only $0{\cdot}47\ \text{m/s}^2$ r.m.s. is required to exceed the lower boundary of the health guidance caution zone (at $8{\cdot}5\ \text{m/s}^{1{\cdot}75}$). With the exception of three categories of vehicle (cars, vans and the grass roller) all measurements exceeded $0{\cdot}47\ \text{m/s}^2$ r.m.s. so, according to this standard, "*caution with respect to potential health risks is indicated*" in all cases if the duration of exposure is eight hours within a 24-h period. The corresponding vibration magnitude for an 8-h exposure when assessed with respect to the $15\ \text{m/s}^{1{\cdot}75}$ action level in BS 6841 would be $0{\cdot}82\ \text{m/s}^2$ r.m.s.

5. CONCLUSIONS

Repeat measurements of the vibration in a wide variety of vehicles have shown a large range of vibration magnitudes. There were large variations in vibration magnitude within and between categories of vehicle: the measurement of vibration in a single vehicle cannot be taken as being indicative of vibration in all vehicles of that category. The wide range of measured values suggests that exposures to vehicle vibration may be minimized by appropriate selection of vehicles and operating conditions.

For most measurements, the vertical axis on the seat pan gave the greatest frequency-weighted acceleration magnitude. Consequently, the equivalent r.m.s. acceleration (calculated from the fourth root of the sum of the fourth powers of the vibration dose values in each of four axes) was mostly dominated by vertical vibration on the seat pan. Evaluations of vibration in accord with ISO 2631 (using the most severe axis) gave lower values than evaluations in accord with BS 6841. This arose from a combination

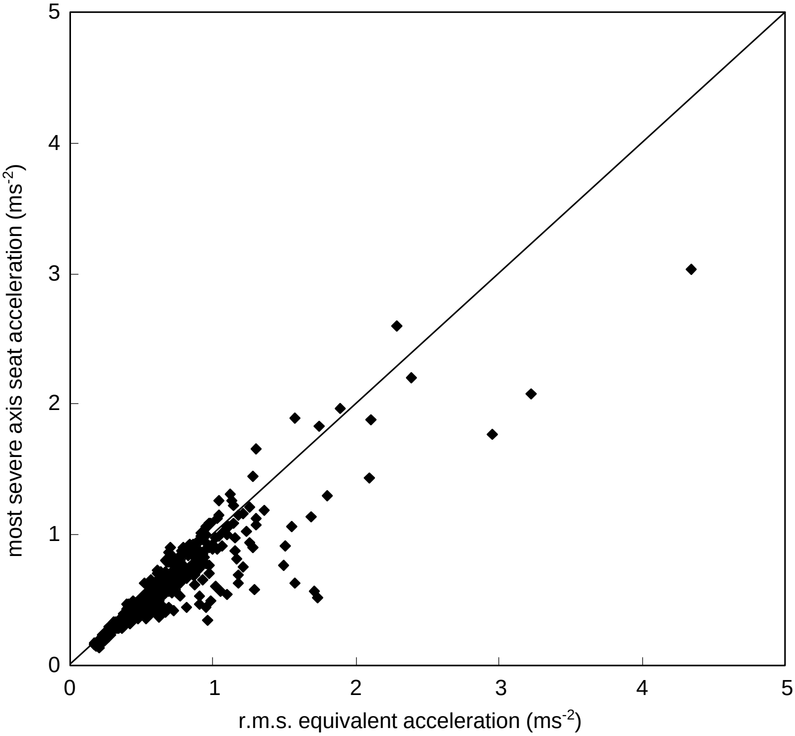

Figure 13. Comparison of the most severe r.m.s. acceleration in any of three axes on the seat according to ISO 2631 [2] with the r.m.s. equivalent acceleration magnitudes over four axes according to BS 6841 [1].

TABLE 6

Frequency-weighted vibration magnitudes measured on vehicles, VDVs (for 1 min exposure duration) and the exposure periods required to reach the different action levels ("equivalent r.m.s. acceleration" calculated from VDVs obtained in four axes)

	BS 6841 (1987)			ISO 2631 (1997)			
Vehicle type (number of vehicles)	Equivalent r.m.s. acceleration (m/s^2 r.m.s.)	VDV ($m/s^{1·75}$)	Time to reach 15 $m/s^{1·75}$	Most severe axis acceleration (m/s^2 r.m.s.)	VDV for most severe axis ($m/s^{1·75}$)	Time to reach 8·5 $m/s^{1·75}$	Time to reach 17 $m/s^{1·75}$
Car (25)	0·45	1·77	85 h 57 min	0·39	1·51	16 h 44 min	267 h 51 m
Excavator (4)	1·13	4·39	2 h 16 min	0·91	3·55	0 h 33 min	8 h 48 m
Mobile crane (2)	0·71	2·76	14 h 36 min	0·59	2·29	3 h 9 min	50 h 32 m
Dumper (4)	1·40	5·46	0 h 57 min	1·28	4·99	0 h 8 min	2 h 14 m
Lift truck (11)	0·90	3·50	5 h 36 min	0·74	2·87	1 h 16 min	20 h 30 m
Tractor (7)	0·75	2·91	11 h 41 min	0·73	2·82	1 h 21 min	21 h 51 m
Grass roller (1)	0·55	2·13	41 h 22 min	0·46	1·79	8 h 25 min	134 h 52 m
Lorry (16)	0·72	2·81	13 h 28 min	0·50	1·96	5 h 56 min	95 h 10 m
Mower (3)	0·66	2·56	19 h 38 min	0·60	2·32	3 h 0 min	48 h 11 m
Van (9)	0·50	1·94	59 h 34 min	0·45	1·76	9 h 0 min	144 h 2 m
Milk float (3)	0·92	3·60	5 h 1 min	0·82	3·21	0 h 49 min	13 h 8 m
Armoured vehicle (4)	0·81	3·17	8 h 18 min	0·85	3·33	0 h 42 min	11 h 20 m
Helicopter (1)	1·00	3·89	3 h 41 min	1·08	4·21	0 h 16 min	4 h 26 m
Bus (10)	0·58	2·25	33 h 11 min	0·56	2·17	3 h 53 min	62 h 17 m

of different frequency weightings, different axis multiplying factors (for horizontal vibration) and the use of one versus four axes in the calculation. The differences between the two standards increased when the evaluated measures were compared with the health criteria proposed in the two standards: measures are much less likely to exceed the 17 $m/s^{1.75}$ "health guidance caution zone" in ISO 2631 than the 15 $m/s^{1.75}$ "action level" in BS 6841.

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APPENDIX A

This Appendix contains vibration magnitudes calculated for the individual vehicles during travel (i.e., excluding measurements made with vehicles stationary, but including measurements with different operating conditions including different speeds). The frequency-weighted vibration magnitudes corresponding to vertical on the seat and equivalent r.m.s. acceleration were calculated using the procedures specified in BS 6841. The procedure shown in ISO 2631 was used to calculate the frequency-weighted vibration in the most severe axis. These are shown in Table A1.

The vibration magnitudes shown for each vehicle were calculated as an average of repeat measurements. There were a total of 461 measurements for the 100 vehicles.

Table A1

Frequency-weighted vibration magnitudes for the 100 *vehicles. Data for each vehicle represent an average of repeat measures*

		Frequency-weighted vibration magnitude (m/s^2 r.m.s.)		
Vehicle type	Vehicle No.	BS vertical on seat	BS r.m.s. equivalent	ISO most severe axis
Car	1	0·41	0·51	0·43
	2	0·45	0·63	0·48
	3	0·37	0·43	0·39
	4	0·46	0·50	0·48
	5	0·36	0·47	0·38
	6	0·37	0·45	0·39

TABLE A1

continued

Vehicle type	Vehicle No.	Frequency-weighted vibration magnitude (m/s² r.m.s.)		
		BS vertical on seat	BS r.m.s. equivalent	ISO most severe axis
	7	0·29	0·35	0·31
	8	0·29	0·32	0·31
	9	0·48	0·60	0·65
	10	0·41	0·49	0·41
	11	0·29	0·36	0·30
	12	0·25	0·32	0·26
	13	0·31	0·33	0·32
	14	0·31	0·34	0·32
	15	0·31	0·32	0·31
	16	0·35	0·36	0·36
	17	0·53	0·56	0·54
	18	0·49	0·63	0·52
	19	0·59	0·75	0·75
	20	0·61	0·74	0·73
	21	0·52	0·66	0·70
	22	0·30	0·34	0·31
	23	0·36	0·43	0·37
	24	0·40	0·49	0·43
	25	0·31	0·36	0·32
Excavator	1	0·81	1·16	0·82
	2	1·00	1·09	1·00
	3	0·08	0·22	0·17
	4	3·27	4·35	3·03
Mobile crane	1	0·64	0·78	0·67
	2	0·50	0·64	0·50
Dumper	1	0·52	0·98	0·73
	2	1·14	1·81	1·90
	3	1·61	2·76	1·76
	4	0·64	0·99	0·80
Lift truck	1	0·91	1·40	1·00
	2	0·75	0·91	0·82
	3	0·47	0·90	0·53
	4	0·79	1·24	0·85
	5	0·71	0·90	0·74
	6	0·55	0·67	0·66
	7	0·86	1·14	1·00
	8	0·75	0·96	0·91
	9	0·71	0·82	0·72
	10	0·56	0·69	0·58
	11	0·69	0·83	0·70
Tractor	1	0·32	0·68	0·83
	2	0·62	0·75	0·71
	3	0·44	0·65	0·73
	4	0·46	0·52	0·54
	5	0·67	1·20	1·00
	6	0·80	0·82	0·88
	7	0·56	0·82	0·70
Grass roller	1	0·53	0·55	0·46

TABLE A1

continued

Vehicle type	Vehicle No.	Frequency-weighted vibration magnitude (m/s^2 r.m.s.)		
		BS vertical on seat	BS r.m.s. equivalent	ISO most severe axis
Lorry	1	0·68	0·73	0·71
	2	0·40	0·49	0·46
	3	0·38	0·43	0·44
	4	1·03	1·25	1·06
	5	0·87	0·95	1·01
	6	0·38	0·44	0·42
	7	0·88	1·25	1·28
	8	0·59	0·75	0·65
	9	0·45	0·50	0·50
	10	0·43	0·89	0·48
	11	0·39	0·97	0·45
	12	0·44	0·90	0·51
	13	0·36	0·45	0·43
	14	0·37	0·47	0·44
	15	0·44	0·54	0·52
	16	0·61	0·72	0·72
Mower	1	0·42	0·63	0·56
	2	0·49	0·66	0·60
	3	0·71	1·04	0·76
Van	1	0·51	0·61	0·56
	2	0·41	0·47	0·45
	3	0·34	0·38	0·36
	4	0·42	0·46	0·45
	5	0·38	0·48	0·42
	6	0·44	0·53	0·48
	7	0·51	0·57	0·54
	8	0·38	0·50	0·45
	9	0·53	0·58	0·57
Milk float	1	0·75	0·88	0·84
	2	0·65	1·01	0·72
	3	0·72	0·92	0·82
Armoured vehicle	1	0·61	0·89	0·93
	2	0·65	0·74	0·78
	3	0·30	0·35	0·29
	4	1·85	1·66	1·52
Helicopter	1	1·17	1·00	1·08
Bus	1	0·42	0·51	0·51
	2	0·48	0·67	0·61
	3	0·46	0·57	0·55
	4	0·52	0·58	0·62
	5	0·79	0·84	0·89
	6	0·55	0·60	0·57
	7	0·73	0·81	0·81
	8	0·47	0·52	0·50
	9	0·34	0·40	0·38
	10	0·40	0·47	0·44