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A COMPARISON OF EVALUATIONS AND ASSESSMENTS OBTAINED USING ALTERNATIVE STANDARDS FOR PREDICTING THE HAZARDS OF WHOLE-BODY VIBRATION AND REPEATED SHOCKS

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There are three current standards that might be used to assess the vibration and shock transmitted by a vehicle seat with respect to possible effects on human health: ISO 2631/1 (1985), BS 6841 (1987) and ISO 2631-1 (1997). Evaluations have been performed on the seat accelerations measured in nine different transport environments (bus, car, mobile crane, fork-lift truck, tank, ambulance, power boat, inflatable boat, mountain bike) in conditions that might be considered severe. For each environment, limiting daily exposure durations were estimated by comparing the frequency weighted root mean square (i.e., r.m.s.) accelerations and the vibration dose values (i.e., *VDV*), calculated according to each standard with the relevant exposure limits, action level and health guidance caution zones. Very different estimates of the limiting daily exposure duration can be obtained using the methods described in the three standards. Differences were observed due to variations in the shapes of the frequency weightings, the phase responses of the frequency weighting filters, the method of combining multi-axis vibration, the averaging method, and the assessment method. With the evaluated motions, differences in the shapes of the weighting filters resulted in up to about 31% difference in r.m.s. acceleration between the "old" and the "new" ISO standard and up to about 14% difference between BS 6841 and the "new" ISO 2631. There were correspondingly greater differences in the estimates of safe daily exposure durations. With three of the more severe motions there was a difference of more then 250% between estimated safe daily exposure durations based on r.m.s. acceleration and those based on fourth power vibration dose values. The vibration dose values provided the more cautious assessments of the limiting daily exposure duration.

1. INTRODUCTION

National and international standards have provided procedures for evaluating human exposure to whole-body vibration and repeated shock. Currently, there are three standards for assessments with respect to possible effects on health: (i) the 'old' International Standard (ISO 2631/1:1985) [1]; (ii) British Standard (BS 6841:1987) [2]; (iii) a 'new' International Standard (ISO 2631-1:1997) [3]. The standards provide procedures for measuring vibration, evaluating the vibration severity and assessing whether exposures to the vibration are likely to cause injury. Each standard provides frequency weightings and averaging procedures that can be applied to the accelerations measured at the interfaces between a seat and the human body.

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There are differences between the frequency weightings, averaging procedures and assessment methods described in the three standards [4]. In the case of ISO 2631-1 [3] there are alternative averaging procedures and alternative assessment methods in the same standard. It is desirable to understand the effects of the differences in the evaluation and assessment procedures when applying such standards to predict whether a particular motion is likely to cause injury.

This paper presents comparisons of the vibration measured on the seats of a range of transport environments when evaluated and assessed according to ISO 2631/1 [1], BS 6841 [2] and ISO 2631-1 [3]. The purpose of the comparisons is to determine the range of different estimates of acceptable exposure durations for each environment, and show how the differences between the evaluation procedures are affected by the magnitude, frequency and direction of the accelerations on the seat.

2. METHOD

Evaluations were performed on seat accelerations measured in examples of nine very different transport environments. The nine environments are described in Table 1.

The seat accelerations were frequency weighted according to the requirements of each standard. ISO 2631/1 [1] defines the gains of frequency weightings applicable to the x-, y- and z-axis accelerations on a seat surface over the frequency range from 1–80 Hz. These weightings were implemented by fast convolution in the frequency domain. BS 6841 [2] and ISO 2631-1 [3] define s-plane equations which can be used to define weighting filters that can be applied in the time domain. These were implemented using bilinear mapped IIR digital filters.

Alternative methods of implementing the weighting filters were employed for each standard so as to investigate the differences in results caused by differences in the weighting method. For ISO 2631/1[1] approximations to the standard weightings were defined by s-plane equations given in the corresponding instrumentation standard, ISO 8041:1990 [5]. For BS 6841 [2] and ISO 2631-1 [3], alternative weightings were implemented by fast convolution, with the same magnitude response as the standard filters, but with a flat phase

TABLE 1

Characteristics of the nine vehicle environments

Transport	Conditions	Measurement axes	Duration of recordings (s)
Bus	City route with speed ramps	x, y, z on seat x on seat-back	2070
Automobile	Un-made road surface, 20 kph	x, y, z on seat x on seat back	34
Dockside crane	Loading operations	x, y, z on seat x on seat-back†	60
Fork-lift truck	Mixed hard surfaces	x, y, z on seat x on seat-back	490
Military tank, commander's seat	Cross country, 30 kph	x, y, z on seat x on seat-back	30
Four wheel drive ambulance	Pavé, 40 kph	z on seat	88
Power boat (14 m)	Sea state 3, 35–40 kts	z on seat	60
Inflatable power boat (8 m)	Sea state 3, 40 kts	z on seat	60
Bicycle	Off-road: rough tracks	z on seat	240

† seat back vibration not evaluated due to incomplete contact

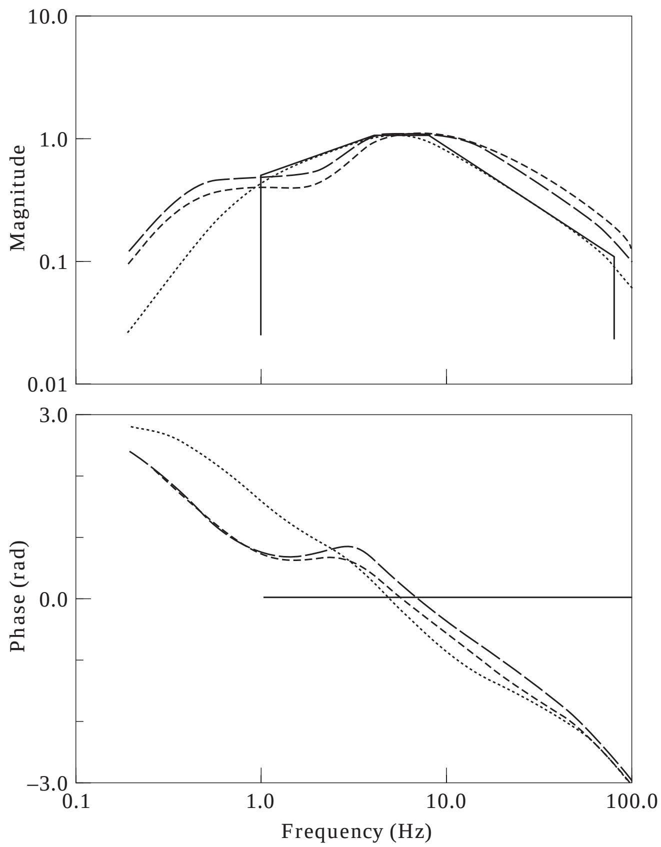

Figure 1. Comparison of gain and phase response of the weighting filters for vertical (z-axis) seat acceleration defined by the alternative standards. Key: —, ISO 2631/1 (1985); . . . . . , ISO 8041 (1990); - - - - , BS 6841 (1987); – – – –, ISO 2631-1 (1997).

response over all frequencies. The gain and phase responses of the weighting filters for vertical (z-axis) seat acceleration are compared in Figure 1.

The frequency weighted r.m.s. acceleration, a_w, was calculated from

$$a_w = \left[\frac{1}{T} \int_0^T a_w^2(t)\,\mathrm{d}t \right]^{1/2}, \tag{1}$$

where T is the measurement duration. The frequency weighted vibration dose value, VDV, was calculated according to BS 6841 and ISO 2631-1:

$$VDV = \left[\int_0^T a_w^4(t)\,\mathrm{d}t \right]^{1/4}, \tag{2}$$

The estimated vibration dose value, $eVDV$, was calculated according to BS 6841 and ISO 2631-1:

$$eVDV = 1{\cdot}4 a_w T^{1/4}. \tag{3}$$

Vertical acceleration measured on the seat beneath the ischial tuberosities of a driver or passenger were evaluated for each form of transport. Where horizontal (x- and y-axes) seat acceleration was also available, the multiple axis vibration was evaluated according to the requirements of each standard. A maximum transient vibration value ($MTVV$) was calculated for z-axis acceleration according to ISO 2631-1 [3],

$$MTVV = \max\left[\frac{1}{\tau}\int_{t_0-\tau}^{t_0} a_w^2(t)\,\mathrm{d}t\right]^{1/2}, \tag{4}$$

where t_0 is the time of observation and τ is the integration time. An alternative method for calculating $MTVV$, based on exponential averaging, is also defined within ISO 2631-1 and was used to calculate estimates of $MTVV$:

$$MTVV_e = \max\left[\frac{1}{\tau}\int_{-\infty}^{t_0} a_w^2(t)\exp\left(\frac{t-t_0}{\tau}\right)\mathrm{d}t\right]^{1/2}. \tag{5}$$

All three standards offer methods of assessing the severity of vibration as a function of the frequency weighted acceleration and the duration of the exposure. ISO 2631/1 [1] gives exposure limits for r.m.s. acceleration that reduce with increasing duration of exposure according to a function which is not mathematically defined. However, an approximation to this function is defined: an acceleration magnitude of 5·6 ms^{-2} r.m.s. for exposures from 1–10 min and a magnitude which falls inversely in proportion to the square root of the exposure duration for exposures from 10 min–8 h.

British Standard 6841 [2] defines what is sometimes called an "action level" given by a vibration dose value of 15 $\mathrm{ms}^{-1\cdot75}$; for daily vibration exposures which exceed this value it is suggested that prior consideration of the fitness of exposed persons, the design of safety precautions and health checks should be considered.

International Standard 2631-1 [3] defines two different "health guidance caution zones" for daily vibration exposures. An "r.m.s. health guidance caution zone" is not defined mathematically but is assumed to be given by a 2:1 range of acceleration for durations between 1 min and 10 min, and r.m.s. acceleration decreasing in inverse proportion to the square root of exposure duration for exposures between 10 min and 24 h. In this paper it is assumed that the limits of the r.m.s. health guidance caution zone are 2·8 and 5·6 ms^{-2} for exposure durations between 1 min and 10 min, but other interpretations are possible (see [4]). A "VDV health guidance caution zone" is defined by vibration dose values between 8·5 and 17 $\mathrm{ms}^{-1\cdot75}$ (see Figure 2).

For the purposes of this paper, the limiting exposure durations were estimated from the frequency weighted r.m.s. accelerations, a_w according to the "old" ISO 2631/1 [1] by calculating the equivalent exposure durations, T_c, which would be required to reach the "exposure limit",

$$T_c = T_{5\cdot6}[5\cdot6/a_w]^2, \qquad \text{for} \qquad a_w \leqslant 5\cdot6\ \mathrm{ms}^{-2}, \tag{6}$$

where $T_{5\cdot6} = 10$ min. The limiting exposures according to the "r.m.s. health guidance caution zone" in the "new" ISO 2631-1 [3] were determined from the assumed level of the upper boundary of this health guidance caution zone, also by using equation (6).

Limiting exposure durations can be calculated by using vibration dose values according to both BS 6841 [2] and ISO 2631-1 [3]. In the case of BS 6841 [2], the limiting exposures were determined from the frequency weighted vibration dose value, VDV, measured over a period, T, by calculating the equivalent exposure time, T_c, required to reach a vibration dose value of 15 $\mathrm{ms}^{-1\cdot75}$:

$$T_c = T[15/VDV]^4. \tag{7}$$

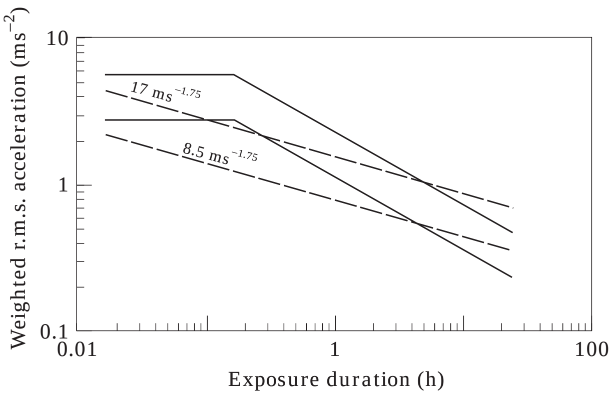

Figure 2. Health guidance caution zones according to ISO 2631-1 (1997). The *VDV* zone is defined by estimated vibration dose values of 8·5 and 17 ms$^{-1·75}$; it is assumed that the r.m.s. caution zone is also defined by a 2:1 range (2.8–5·6 ms^{-2} r.m.s. at 1 min) and that it falls in inverse proportion to the square root of acceleration for exposures from 10 min–24 h. Key: —, limits of r.m.s. acceleration caution zone; – – –, r.m.s. acceleration equivalent to limits of *eVDV* caution zone.

In the case of ISO 2631-1 [3], the limiting exposures were determined from the frequency weighted vibration dose value, *VDV*, measured over a period, *T*, by calculating the equivalent exposure time, T_c, required to reach the upper boundary of the "*VDV* health guidance caution zone" at 17 ms$^{-1·75}$:

$$T_c = T[17/VDV]^4. \tag{8}$$

3. RESULTS

Seven of the nine example motions were severe, with acceptable exposure durations of less than 8 h indicated by all three standard evaluation methods.

3.1. WEIGHTED R.M.S. ACCELERATION—THE EFFECT OF WEIGHTING SHAPE

The method of evaluating whole-body vibration with respect to health in the "old" ISO 2631/1 [1] involved comparing the vibration in each third octave band separately with the corresponding limit for the band. Only the band highest with respect to the limits was included in this recommended "rating procedure". A permissible approximation, the "weighting procedure", was defined so as to simplify measurements where spectral analysis was not required. This method involved the calculation of the frequency weighted r.m.s. accelerations on the seat in the x-, y- and z-axes. In this paper only the weighting method has been used, with the weightings implemented in the frequency domain according to ISO 2631/1 [1] and in the time-domain using ISO 8041 [5]. An assessment of the risks to health is then based on the frequency weighted r.m.s. acceleration in the axis giving the most severe evaluation. The "basic evaluation method" in the "new" ISO 2631-1 [3] is similar, except that different frequency weightings are used. British Standard 6841 [2] recommends that the evaluation of vibration with respect to health should be based on vibration dose values rather than r.m.s. acceleration; however, the estimated vibration dose value, *eVDV*, can be calculated from the r.m.s. frequency weighted acceleration when the crest factor is low. Table 2 compares the frequency weighted r.m.s. accelerations in the "worst axis" on the seat, after frequency weighting according to ISO 2631/1 [1], ISO 8041 [5], BS 6841 [2] and ISO 2631-1 [3].

TABLE 2

Effect of weighting shape on weighted root mean square accelerations (ms^{-2})

Transport	Standard (weighting filter) ISO 2631/1 (1985) (straight line)	ISO 2631/1 (1985) (ISO 8041)	ISO 2631-1 (1997) (W_k)	BS 6841 (1987) (W_b)
Bus	0·58	0·56	0·51	0·44
Car: unmade road	1·78	1·80	1·70	1·51
Crane	0·57	0·57	0·58	0·57
Fork-lift truck	0.92	0·93	0·89	0·82
Tank	2·36	2·30	2·53†	2·16
Ambulance	1·95	1·93	2·08	2·00
Power boat	1·87	1·92	2·20	2·03
Inflatable boat	0·85	0·98	1·17	1·02
Mountain bike	2·35	2·29	3·01	3·13

† x-axis acceleration on seat with W_d weighting ($a_{wz} = 2{\cdot}33$)

The differences between the frequency weighted r.m.s. accelerations shown in Table 2 for each form of transport depend on the shapes of the acceleration spectra. The power spectral densities of the unweighted z-axis acceleration on the 9 seats are shown in Figure 3. For eight of the seats the weighted r.m.s. acceleration was greatest in the z-axis; the exception was the tank for which the "new" ISO 2631-1 gave a weighted x-axis acceleration on the seat 9% greater than the weighted z-axis acceleration on the seat. It may be seen that similar results were obtained when using the "straight line" weightings in the old ISO 2631/1 [1] and when using the ISO 8041 [5] filter equations, except for the inflatable boat where the r.m.s. acceleration was 15% greater with the ISO 8041 weighting filter due to the large proportion of energy below 1 Hz; motion at frequencies below 1 Hz

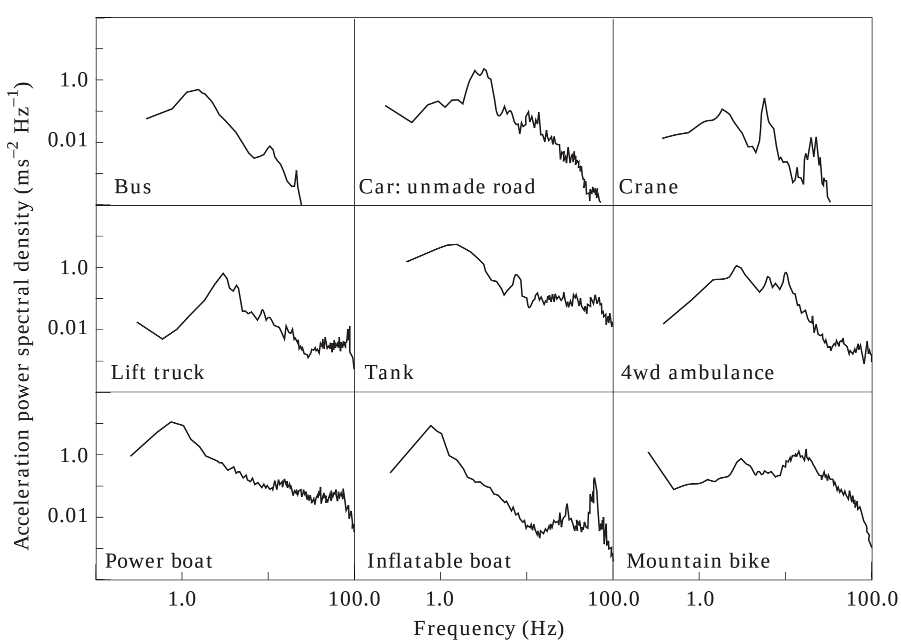

Figure 3. Power spectral densities of unweighted z-axis accelerations on the seat surfaces of the nine vehicles.

was attenuated when using the "straight line" weighting (see Figure 1). Where there was a high proportion of energy at frequencies above 8 Hz (e.g., the moutain bike), the frequency weighted accelerations were higher when using the "new" ISO 2631-1 [3] weightings than when using the weightings in the old standard. Where there was a high proportion of energy at frequencies between 1 Hz and 4 Hz (e.g., the car and the bus), the frequency weighted accelerations with the new standard were slightly lower than those obtained with the old standard. Where the vibration was predominantly at high frequencies the frequency weighted accelerations were higher when using BS 6841 than when using the "new" ISO 2631-1 [3]; conversely, where the vibration was predominantly at low frequencies the frequency weighted accelerations were lower when using BS 6841 than when using the new ISO standard. However, in most cases the differences between the values obtained with the different vertical axis weightings were fairly small.

Table 3 shows estimated limiting exposure durations, T_c, for each of the assessment methods. For the nine example motions, the exposure durations required to reach the upper limit of the r.m.s. health guidance caution zone in ISO 2631-1 [3] ranged between 70% and 120% of the durations given by the exposure limits in ISO 2631/1 [1] (when the latter were evaluated using the ISO 8041 weighting filters).

3.2. VIBRATION DOSE VALUES AND ESTIMATED VIBRATION DOSE VALUES

BS 6841 requires all evaluations with respect to health to be based on the fourth power VDV (see equation (2)). If the crest factor of the frequency weighted acceleration is less than six, an estimated vibration dose value ($eVDV$) can be used (see equation (3)). ISO 2631-1 [3] also allows evaluations based on the $eVDV$ and the VDV, and recommends that the true VDV should be determined when either the crest factor of the acceleration is greater than nine, or the VDV exceeds the $eVDV$ by a factor of 1·25.

Table 4 shows the vibration dose values and estimated vibration dose values for the nine forms of transport when evaluated according to both BS 6841 [2] and ISO 2631-1 [3]. The absolute value of a measured vibration dose value depends on the duration of measurement in addition to the magnitude, frequency and direction of the vibration. To assist the comparison of the measured values they are shown in Table 4 as equivalent values for a 1 min exposure. These have been calculated by multiplying the vibration dose measured over a period of t seconds by $(60/t)^{1/4}$. The values shown in Table 4 may therefore be compared across different environments and with the different evaluation methods.

As may be expected, for some of the measurements there were large differences between the estimated vibration dose values and the true vibration dose values. For the fork-lift truck the true VDV was 71% higher than the $eVDV$ when evaluated according to ISO 2631-1 and 83% higher than the $eVDV$ when evaluated according to BS 6841.

When evaluated according to ISO 2631-1, the automobile on a rough unmade road required 27 min to reach a VDV of 17 $\mathrm{ms}^{-1\cdot 75}$; evaluated by using the $eVDV$, a 44 min exposure would be required to reach 17 $\mathrm{ms}^{-1\cdot 75}$ (see Table 3). A limiting exposure of 109 min would be suggested when evaluating the same motion by using the r.m.s. frequency weighted acceleration and comparing the value with the upper limit of the "r.m.s. health guidance caution zone". For the tank motion, the VDV would exceed 17 $\mathrm{ms}^{-1\cdot 75}$ in less than 9 min, but it would require 49 min for the r.m.s. acceleration to exceed the upper limit of the "r.m.s. health guidance caution zone". For these two examples, the crest factor was less than nine and the VDV did not exceed the $eVDV$ by a factor of 1·25, so either the r.m.s., the $eVDV$ or the VDV might reasonably be applied to evaluate these motions according to the "new" ISO 2631-1, leading to estimates of the limiting daily exposure durations varying by up to a factor of 5·5, even when evaluated with the same standard. The vibration on the mountain bike was very severe,

TABLE 3

Effect of averaging method and limiting exposure criterion on durations to reach upper limit of the appropriate caution zone or action level (r.m.s. accelerations evaluated with respect to r.m.s. caution zone; VDVs evaluated with respect to the VDV caution zone)

		Duration to reach upper limit of caution zone or action level (min)								
Standard	Integration method	Bus	Car: unmade road	Crane	Fork-lift truck	Tank	Ambulance	Power boat	Inflatable boat	Mountain bike
ISO 2631/1 (1985)	r.m.s.	1014	97	953	365	59	85	85	324	60
ISO 2631-1 (1997)	r.m.s.	1200	109	926	395	49	72	65	227	35
ISO 2631-1 (1997)	*eVDV*	5305	44	3157	574	8·9	19	15	190	4·4
ISO 2631-1 (1997)	*VDV*	1373	27	2296	68	9·1	22	4·3	135	1·1
BS 6841 (1987)	*eVDV*	5460	36	1352	244	5·2	14	13	205	2·3
BS 6841 (1987)	*VDV*	1467	22	977	22	4·3	16	3·3	119	0·6
crest factor (ISO 2631-1)		10·2	5·8	4·8	20·0	7·4	4·1	9·1	9·3	12·2
VDV/eVDV ratio (ISO 2631-1)		1·40	1·12	1·08	1·71	0·99	0·97	1·38	1·09	1·40

TABLE 4

Equivalent one minute vibration dose values (VDVs) and estimated vibration dose values (eVDVs) for the nine forms of transport when evaluated according to both BS 6841 [2] and ISO 2631-1 [3]

	Standard			
	ISO 2631-1 (1997) (worst axis)		BS 6841 (1987) r.s.q. sum	
Transport	*eVDV*	*VDV*	*eVDV*	*VDV*
Bus	1·99	2·79	1·74	2·42
Car: unmade road	6·62	7·43	6·14	6·92
Crane	2·27	2·46	2·47	2·68
Fork-lift truck	3·47	5·92	3·80	6·95
Tank	9·85†	9·79	9·94	10·40
Ambulance	8·10	7·83	7·78	7·52
Power boat	8·57	11·81	7·90	11·09
Inflatable boat	4·58	4·99	3·96	4·54
Mountain bike	11·73	16·45	12·18	16·99

† x-axis $eVDV$ on seat (z-axis $eVDV = 9{\cdot}06\ \mathrm{ms}^{-1{\cdot}75}$); vibration dose value in $\mathrm{ms}^{-1{\cdot}75}$

reaching a VDV of 17 $\mathrm{ms}^{-1{\cdot}75}$ in only 1·1 min but taking 35 min to reach the r.m.s. caution limit. This motion did exceed the criteria for recommended evaluations based on VDV, so it could be assumed that the lower limit should be used in this case. However, the posture of the rider and the forces applied to the body at the seat may make this an inappropriate application of this standard.

British Standard 6841 requires that all evaluations with respect to health are based on the fourth power vibration dose value. The $VDVs$ in the worst axis calculated according to BS 6841 were between 18% lower and 3% higher than those calculated according to ISO 2631-1 [3], due to differences in the frequency weighting. However, since BS 6841 specifies a lower caution value than ISO 2631-1 [3], the limiting daily exposure durations indicated by BS 6841 for vibration in the worst axis were mostly lower (between 45% and 120%) than those indicated by ISO 2631-1.

British Standard 6841 requires assessments to be based on a sum of the $VDVs$ in the x-, y- and z-axes on the seat and in the x-axis on the seat back (calculated from the fourth root of the sum of fourth powers of the VDVs in each axis). Table 5 compares overall VDVs calculated from the root sum quad of the VDVs in each axis with the VDV in the worst axis. The table shows only the VDVs for the five examples where measurements were available in the x-, y- and z-axes on the seat and in the x-axis on the seat back.

The "new" International Standard 2631-1 suggests that if there is no clearly dominant axis the "vector sum" of the weighted x-, y- and z-axis accelerations on the seat could be calculated from the root-mean-square of the accelerations in each direction, but it is not clear how the "vector sum" should be calculated when evaluating motions with respect to vibration dose values.

3.3. MAXIMUM TRANSIENT VIBRATION VALUES

The new International Standard 2631-1 [3] recommends that the $MTVV$ (see equation (4)) should be determined if either the crest factor of the acceleration is greater than nine or the $MTVV$ exceeds the overall r.m.s. acceleration by 1·5. British Standard 6841 does not advocate the use of the $MTVV$.

TABLE 5

Effect of method of axis combination on vibration dose values (VDVs) and the durations, T_c, to reach the upper limit of the VDV caution zone or the action level

	Standard		
		BS 6841 (1987)	
Transport	ISO 2631-1 (1997) (worst axis)	(worst axis)	(r.s.q. sum)
Bus VDV ($ms^{-1.75}$)	6·77	5·71	5·87
T_c (min)	1373	1640	1467
Car: unmade road VDV ($ms^{-1.75}$)	6·43	5·71	6·00
T_c (min)	27	27	22
Crane VDV ($ms^{-1.75}$)	2·46	2·47	2·68
T_c (min)	2296	1368	977
Fork-lift truck VDV ($ms^{-1.75}$)	10·01	10·05†	11·75
T_c (min)	68	40	22
Tank VDV ($ms^{-1.75}$)	8·23	7·73	8·74
T_c (min)	9·1	7·1	4·3

† x-axis VDV on seat back (z-axis $VDV = 9{\cdot}58\ ms^{-1.75}$)

The ISO standard recommends an integration time, τ, of 1 s, when calculating the $MTVV$, but this value is not mandatory. Table 6 shows that varying the integration time between 0·125 s and 8·0 s can result in variations of between a factor of two and four in the value of the $MTVV$ for the vertical motions considered here.

It can also be seen from Table 6 that when using an integration time of 1 s, the criterion for deciding to determine the $MTVV$ in addition to the r.m.s. value (i.e., $MTVV/a_w > 1{\cdot}5$) is exceeded in all nine cases. However, the value of $MTVV/a_w$ is highly dependent on the chosen integration time: the criterion was not always exceeded when the integration time was lengthened to 8 s.

$MTVV$ values obtained with an exponential integration time of 1 s (as in equation (5)) were between 87% and 100% of the values calculated with a rectangular averaging window (as in equation (4); see Table 6).

TABLE 6

Comparison of maximum transient vibration values (MTVVs), with different integration times, τ, and weighted r.m.s. acceleration, a_w

	$MTVV$ (ms^{-2}r.m.s.)		exponential $MTVV$		a_w	$MTVV/a_w$
Transport	$\tau = 0{\cdot}125$	$\tau = 1{\cdot}0$	$\tau = 8{\cdot}0$	$\tau = 1{\cdot}0$	(overall r.m.s.)	$\tau = 1{\cdot}0$
Bus	4·14	2·30	1·30	2·09	0·51	4·50
Car: unmade road	6·92	4·29	2·25	3·75	1·70	2·53
Crane	1·85	1·53	1·12	1·44	0·58	2·63
Fork-lift truck	9·33	5·06	2·39	4·56	0·89	5·68
Tank	8·54	4·33	2·87	3·78	2·33	1·86
Ambulance	5·13	3·52	2·37	3·10	2·08	1·69
Power boat	10·22	4·37	3·16	4·30	2·20	1·99
Inflatable boat	4·19	2·30	1·46	2·10	1·17	1·95
Mountain bike	18·29	10·95	7·32	10·00	3·01	3·64

TABLE 7

Effect of phase response of weighting filter on weighted z-axis vibration dose values (VDVs) ($ms^{-1.75}$)

	Standard			
	ISO 2631-1 (1997)		BS 6841 (1987)	
Transport	*s*-plane IIR	zero phase	*s*-plane IIR	zero phase
Bus	6·77	6·94	5·71	5·84
Car: unmade road	6·43	6·70	5·71	5·98
Crane	2·46	2·37	2·47	2·35
Fork-lift truck	10·01	10·88	9·58	10·40
Tank	8·23	8·46	7·73	8·04
Ambulance	8·62	8·73	8·27	8·37
Power boat	11·81	10·43	11·09	10·05
Inflatable boat	4·99	4·56	4·54	4·13
Mountain bike	23·26	23·39	24·03	24·20

The new ISO 2631 does not state how a *MTVV* can be used to assess the risk of injury. It is therefore not possible here to compare the consequences of using *MTVV*s with the consequences of using *VDV*s.

3.4. EFFECT OF PHASE RESPONSE OF WEIGHTING FILTERS

Table 7 shows that the vibration dose values calculated according to BS 6841 and ISO 2631-1 were, to some extent, sensitive to the phase of the frequency weighting filters. Some evaluations were virtually unaffected, but the *VDV* varied by up to about 11% for others. A variation of 11% in *VDV* would result in a variation of about 50% in the indicated times to reach a *VDV* action limit or health guidance caution zone.

4. CONCLUSION

Different estimates of limiting durations of daily exposure to whole-body vibration and repeated shock can be obtained by using the methods described in three currently available standards. Extremely large differences are possible even when using alternative methods presented in the same standard.

Differences in the shape of the weighting filters between the three standards resulted in variations in limiting durations of daily exposure of up to 75% among the nine example motions. Combining the motion in different axes on the basis of vibration dose values resulted in a reduction of up to 85% in limiting durations of daily exposure compared with estimates based on the worst axis alone.

The largest variations in limiting durations of daily exposure arose from differences between evaluations based on r.m.s. acceleration and those based on fourth power vibration dose values. The differences arise partly from the waveform of the motion and, in the "new" ISO 2631, the different method of assessing r.m.s. and *VDV* measures. When comparing the estimated vibration dose values (calculated from r.m.s. measures) and true vibration dose values, the difference varied up to about 70%. The differences tended to be greatest for the more severe motions. These differences between the *eVDV* and *VDV* measures resulted in larger differences in the limiting daily exposure, but this is not a problem if the standard makes it clear that the true vibration dose value should be used where there is doubt or difference between the two values (as in BS 6841). International

Standard 2631-1 [3] does not clearly identify when the r.m.s., *eVDV* or *VDV* measures should be used. This can result in large differences in limiting daily exposure. The true vibration dose value provided the more cautious assessment of safe exposure durations.

In the "new" ISO 2631-1 [3], the large differences between the "r.m.s. health guidance caution zone" and the "*VDV* health guidance caution zone" may often be compounded with the choice of method of measurement: r.m.s. measures may be compared with the "r.m.s. health guidance caution zone" and *VDV* measures may be compared with the "*VDV* health guidance caution zone", as in Table 3. However, r.m.s. measures can also be compared directly with the "*VDV* health guidance caution zone" either by using the graph presented in the standard or by calculating the estimated vibration dose value. The differences between the two methods will be least when the limiting daily exposures are in the region of 4–8 hours. With shorter exposures the limiting daily exposure durations can be different by a factor of 10 or more.

Methods of implementing the frequency weighting filters such that the gains were correct but the phases differed, resulted in up to an 11% variation in vibration dose value and up to a 50% variation in limiting daily exposure durations. This form of variability will be eliminated if the frequency weightings are implemented in accord with the definitions in the standards.

REFERENCES

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