Paper 5.1

The Definition of Hazard Dose Values for Whole-Body Vibration and Shock

by

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ABSTRACT

A method of quantifying the severity of occupational exposures to whole-body vibration and shock is evolved. The method defines an accumulated measure (the Hazard Dose Value) of vibration during the day. The Hazard Dose Value is given by:

$$HDV = \frac{1}{60} \int_{t=0}^{t=T} a^4(t)\,dt,$$

where the acceleration time history a(t) is in units of ms^{-2} and the time t is in seconds. (T is the total period of time during which exposure to vibration may occur).

It is shown that the Hazard Dose Value defines a time-dependency which is consistent with available information over the widest possible range of durations. Combined with a suitable frequency weighting the procedure also appears to give reasonable indications of the severity of isolated shocks. The application of an integration time is reviewed but tentatively considered unnecessary.

Examples are presented of Hazard Dose Values determined from measured vehicle vibration and from shocks. It is proposed that the procedure should be tested with a wider range of vibration, shock, repeated shock and intermittent vibration and shock.

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INTRODUCTION

There is some doubt as to which characteristics of whole-body vibration and shock cause which types of injury or disease. The uncertainty is such that neither theoretical nor emperical considerations provide comprehensive and precise indications of the relative importance of the three principal physical variables: vibration amplitude, frequency and duration. A consensus of opinion exists in certain areas but much remains to be determined. It is therefore desirable to measure severe vibration conditions - but measurement requires assumptions regarding the relative importance of vibration amplitude, frequency and duration. This paper considers the problem of measuring the complex whole-body vibration and shock conditions that may be associated with hazard.

Figure 1a shows the vibration acceleration waveform recorded in a vehicle during a five hour period. The vertical vibration acceleration time history on the vehicle seat is represented by several hundred thousand values. For practical purposes these numbers must be reduced to a single value which indicates the severity of the total vibration exposure.

The root mean square values obtained by true integration during the 18000 adjacent one second periods are shown in Figure 1b. Similar rms values obtained during the same period using a 1 minute averaging time are shown in Figure 1c. It is clear that whatever 'averaging' procedure is used to quantify the exposure it must give appropriate weight to both long periods of low level vibration and short periods of high level vibration. In many environments it must additionally give correct weight to occasional, or repeated, shocks of very short duration.

SIGNAL AVERAGING

Root-Mean-Square and Root-Mean-Quad Measures

Common methods of quantifying vibration magnitude employ some average of the waveform. The most common current procedure is to calculate the average squared value of the acceleration. This

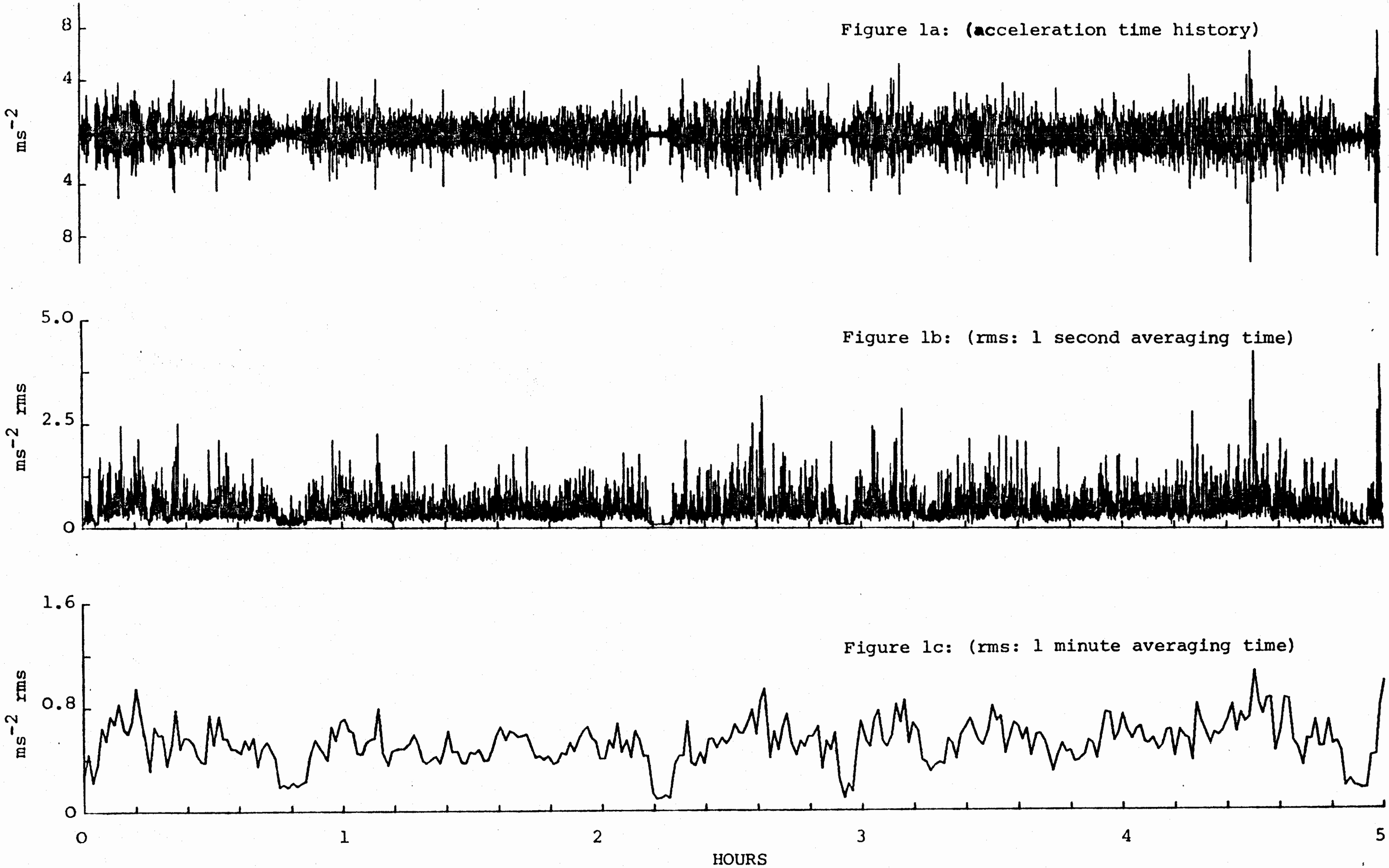

Figure 1: Acceleration time history of 5 hour recording in a van and the rms values determined using 1 second and 1 minute averaging periods.

may either be reported as a 'root-mean-square' value or shown as a frequency distribution in a graph of 'power spectral density'. These measures assume that the average 'power' is the prime quantity - but this cannot be the case. The relation between vibration magnitude and time cannot be such that a doubling of the vibration magnitude requires only a four-fold reduction in vibration duration. (On this basis 1 second at 29 ms^{-2} rms is equivalent to 24 hours at 0.1 ms^{-2} rms - yet 29 ms^{-2} rms is intolerable and 0.1 ms^{-2} rms is near the perception threshold). It has been suggested that the 'root-mean-quad' unit (i.e. $rmq = (\frac{1}{T} \int a^4 \, dt)^{\frac{1}{4}}$) may better represent the subjective relation between duration and vibration magnitude (see Griffin and Whitham (1980)).

For the purposes of quantifying the severity of an occupational exposure to vibration *no average* value is likely to be sufficient if it is accepted that long periods at constant level are more hazardous than short periods at the same level. A measure of the total dose is necessary. Any average value will be sensitive to the period of time over which the average is taken. (e.g. the rms value over an eight hour day will be less than that over half of the same day if most of the exposure is in one half of the 8 hour period.) Limiting the *average* vibration in any given period may be a convenient means of enforcing rest periods but it fails to adequately accumulate the exposure during a full day of intermittent vibration.

Time Dependency

The general approach to time dependency has been one of defining the 'averaging procedure' (e.g. root-mean-square) and defining a 'time dependency' showing how the averaged values should be reduced for increased duration of vibration. It has generally been overlooked that an 'averaging procedure' contains some 'time-dependency'. Furthermore, if the time dependency inherent in the 'averaging procedure' differs from that shown in the recognised 'time-dependency', a single and precise averaging time must be specified for the overall procedure to be unambiguous.

There are few data showing how the effects of vibration exposures depend on vibration duration. Experimental studies of discomfort show that discomfort increases with increased duration of vibration up to a few seconds (e.g. Miwa (1968)) and up to about 30 seconds (e.g. Griffin and Whitham (1980a)). If asked to predict the effect of longer exposure times, subjects indicate that they would prefer lower vibration levels with increasing periods of exposure up to several hours.

Voluntary tolerance to very high levels of vibration also appears to depend on exposure time up to a few minutes (e.g. Magid et al (1960)). This might be related to a subjects opinion of the changing hazard to his health with increasing vibration exposure period.

A few of the studies of worker health in relation to whole-body vibration have considered the effect of exposure time (e.g. Sliosberg (1962), Kelsey and Hardy (1975)) and concluded that symptoms of back disorders increase with increasing daily exposure to vibration. An alternative approach to defining a time-dependency is to consider the mechanical response of the body and attempt to 'model' the action of vibration (e.g. Sandover (1981)).

Irrespective of the absence of substantial quantitative data it can hardly be questioned that any exposure limit to whole-body vibration should decrease with increasing exposure duration from a few seconds to many hours. Two additional considerations may then be applied:

(i) is the time-dependency convenient and unambiguous?

(ii) is the time dependency reasonable in relation to the considerable variety of combinations of levels and durations of whole-body vibration exposure patterns in existence?

For periods up to 30 seconds the subjective data of Griffin and Whitham (1980a) were summarised by a 10:1 change of vibration magnitude being associated with a 10000:1 change in duration -

i.e. (acceleration magnitude)^4 x time = constant. (The experimental data suggest a somewhat lower change in duration is required - i.e. an exponent between about 3 and 4 depending on frequency and vibration magnitude). A 'reasonable' time dependency for all exposure durations from 1 second up to 24 hours would appear to be given by the same relation: a^4t = constant (see Griffin and Whitham (1980b)). This is shown in Figure 2 in comparison with the time dependencies given by a^nt = constant, where n = 1, 2, 3, 4 and ∞. All curves are drawn to coincide at 4 hours. The curves corresponding to n = 1 and ∞ show too much and too little change in level with time to be reasonable. The n = 2 line corresponds to rms integration. For small changes in long duration exposures this may not appear to differ greatly from the n = 4 line. However all long exposures are comprised of many shorter periods and the time dependency must therefore be appropriate at short as well as at long durations. The very high levels allowed at short durations with n = 2 render this line unacceptable.

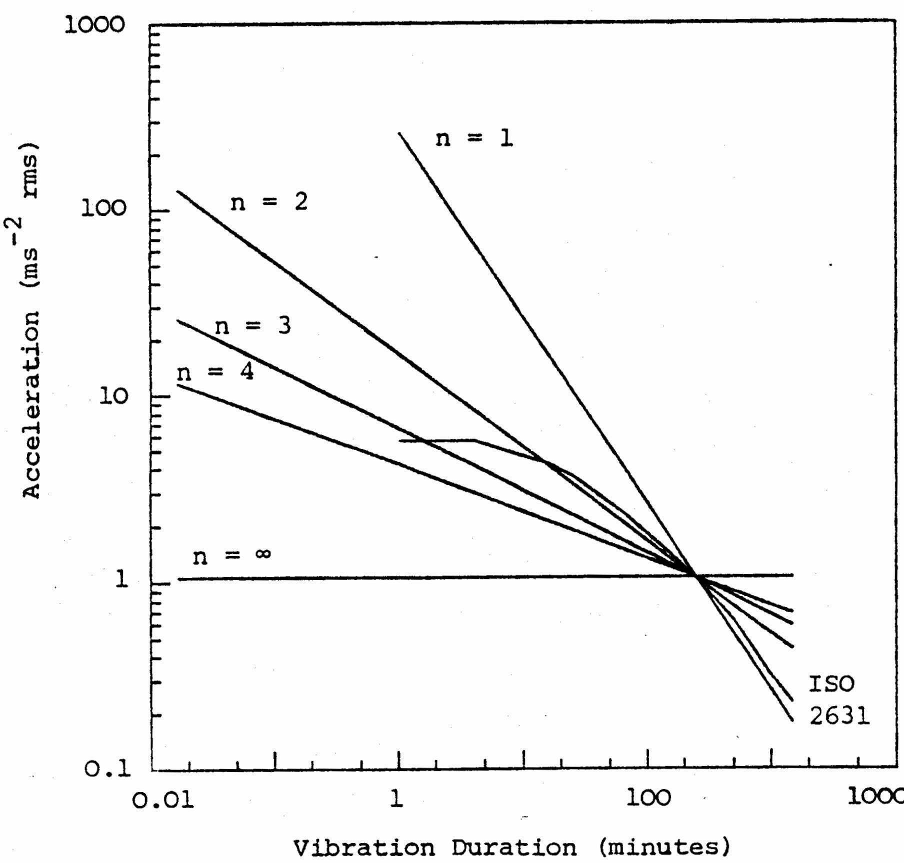

Figure 2: Relation between vibration magnitude and exposure time given by (acceleration)^n x time = constant (for n = 1, 2, 3, 4 and ∞) compared with time dependency in ISO 2631 (1974).

Also shown in Figure 2 is the 4 to 8 Hz exposure limit defined in ISO 2631 (1974) for exposure times from 1 minute to 24 hours. This approximates the n = 2 line from about 10 minutes to about 8 hours. For periods of vibration between about 1 minute and 10 minutes there is little change in the allowable level given by the ISO 2631 curve. For periods below 1 minute the time dependency is not defined. The graphical presentation of the ISO 2631 time dependency might appear to strongly imply horizontal extrapolation at constant level for all durations below 1 minute. However root-mean-square averaging is commonly used and a very different interpretation then arises with the time dependency taking the slope of the n = 2 line for periods less than the averaging time of the rms integration. If the averaging time is made equal to 1 minute there is no gap or double definition in the time dependency. However the use of n = 2 (i.e. rms integration) between 1 second and 1 minute implies an exposure limit of approximately 43 ms^{-2} rms for 1 second and this is not reasonable. For long exposure times the International Standard time dependency defines surprisingly low vibration limits for 24 hours at 4 Hz 0.28 ms^{-2} rms (in ISO 2631 (1978)) and 0.224 ms^{-2} rms (in ISO 2631 (1974)). (Data from ISO 2631 (1974) are used in Figure 2). This is so low that Draft Addendum 1 to ISO 2631 indicated that in workshops major complaints would occur at more than half this level only if prior warning was not given. Another standard in preparation gives vibration limits for ships which are based on subjective judgements and are above the 24 hour ISO 2631 exposure limits (ISO DP 2631/DAD3).

The use of n = 4 appears to define a time-dependency which is not obviously unreasonable over a wide range of durations. Although this does not prove its correctness it is sufficiently encouraging to consider the detailed nature and consequences of employing this relation between vibration magnitude and duration.

HAZARD DOSE VALUES FOR VIBRATION

Definition of a Vibration Dose

Although an 'average' value can be useful for some applications a total accumulated value is more likely to reflect hazard. If n = 4 is accepted as providing appropriate relative weight to vibration magnitude and duration it may be used as the basis of accumulating a vibration dose during a day. This may be expressed as:

$$\text{Hazard Dose Value } (m^4 s^{-7}) = \frac{1}{60} \int_{t=0}^{t=T} a^4(t)\, dt$$

where a(t) is the acceleration time history in units of ms^{-2} after appropriate frequency weighting (see below). The constant 60 is employed to convert values to a basic period of 1 minute dose but the total time T is virtually unrestricted and may be a fraction of a second or many hours.

(Note: a(t) is a time history and cannot be replaced by either the peak or the rms value of a motion to calculate the HDV of a long period of a given motion. However, if the motion is stationary a(t) may be replaced by the rmq value determined over a representative period).

Application of Hazard Dose Value Calculation to Waveforms

Figure 3 shows a digitised sinewave. The squared sinewave is the basis of n = 2 (i.e. root-mean-square) measurements. The fourth power of the sinewave is the basis of n = 4 (e.g. root-mean-quad) measurements. It may be seen that the change in the value of n is a means of weighting the distribution - the higher the value of n the proportionally greater the contribution of the peak values. (The probability density distributions are shifted so that the number of low values is increased with increasing value of n). In Figure 3 a similar effect of n = 2 and n = 4 on a gaussian random wave is shown.

Examples of Hazard Dose Values for Vibration

(a) Sinusoidal vibration

For a steady state sinusoidal vibration of peak value 1.0 ms^{-2} the rms value is 0.7071 and the rmq value is 0.7825. The

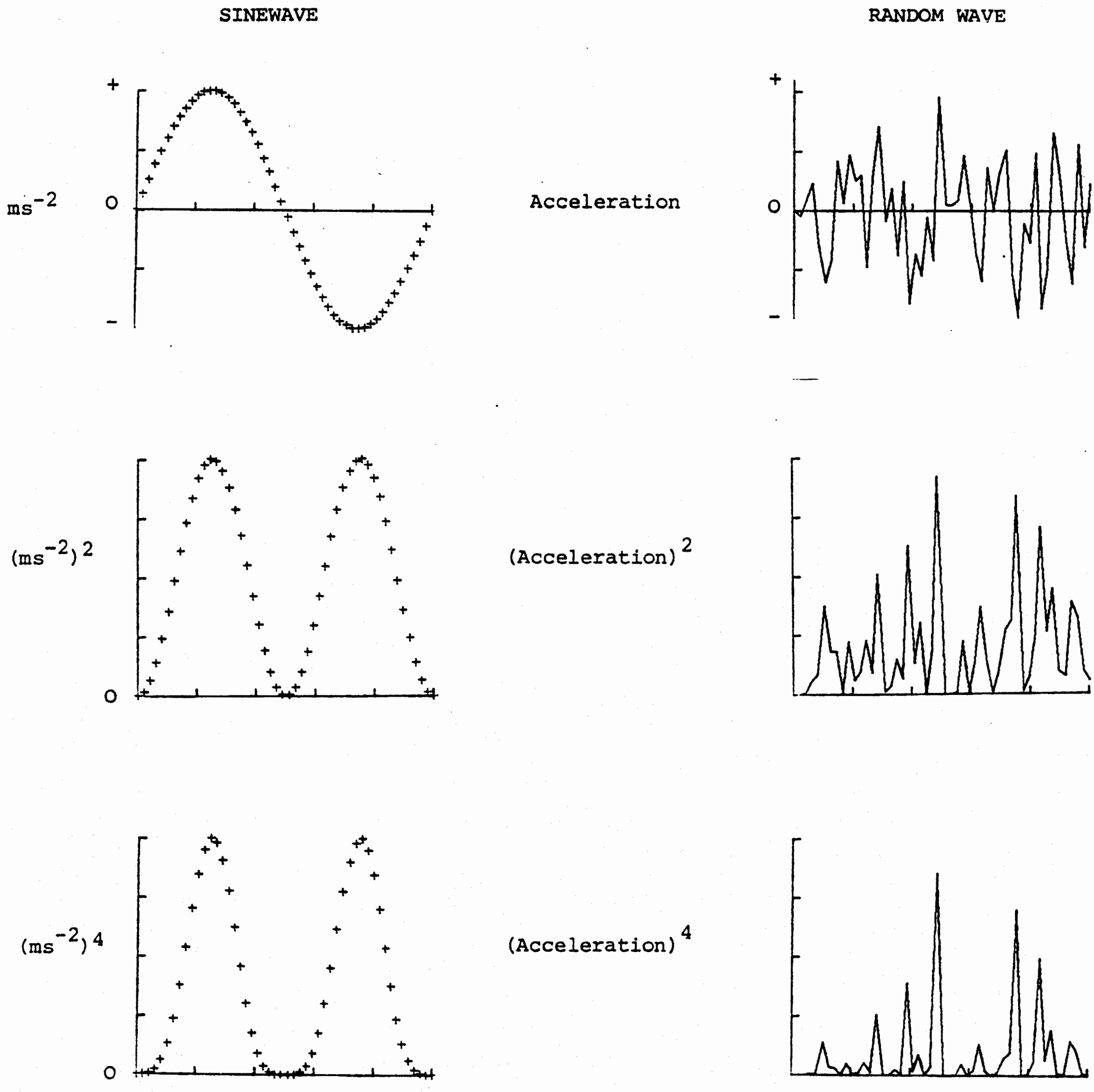

Figure 3: Effect of squaring (as in rms) and taking the fourth power (as in rmq) of a sine wave and random wave

Hazard Dose Value is proportional to the duration of the vibration and proportional to the fourth power of the rmq value. Thus the H.D.V. of a 1 minute period of sinusoidal motion of plus and minus 1 ms^{-2} peak = $(0.7825^4 \times 60) \times \frac{1}{60} = 0.3749$.

In general Table 1 shows some typical H.D.V. values for a range of levels and durations of sinusoidal vibration.

Magnitude of Sinusoidal Vibration

Peak rms rmq	0.500 0.345 0.391	1.000 0.707 0.783	2.000 1.414 1.565	4.000 2.828 3.130	7.920 5.600 6.197
1s	0.0004	0.0062	0.1000	1.600	24.59
1 min	0.0234	0.3749	5.999	95.98	1475
1 hr	1.4058	22.49	359.9	5758	88509
8 hrs	11.2464	180.0	2879	46070	708075
24 hrs	33.7392	539.9	8638	138210	2124225

Table 1: Hazard Dose Values for selected levels and durations of sinusoidal vibration.

The levels and durations of sinusoidal vibration corresponding to Hazard Dose Values from 0.0625 to 4096 are shown in Table 2.

Hazard Dose Values

	0.0625	1	16	256	1024	4096
1 s	1.392	2.783	5.566	11.13	15.74	22.27
1 min	0.6390	1.278	2.556	5.112	7.229	10.22
1 hr	0.1796	0.3593	0.7186	1.437	2.033	2.874
8 hrs	0.1068	0.2136	0.4273	0.8546	1.209	1.709
24 hrs	0.0812	0.1623	0.3247	0.6493	0.9183	1.687

Table 2: Peak magnitudes ($\pm$ ms^{-2}) of sinewaves which produces given HDV values after selected durations.

The effect of vibration is known to be frequency dependent. For some frequencies the values shown in Tables 1 and 2 must be frequency weighted as described below.

(b) Random vibration

For a gaussian random vibration having an rms value of 1 ms^{-2} and a duration of 1 minute the Hazard Dose Value is approximately 2.9 m^4s^{-7}. (Again, if the rms value doubles, the HDV value increases by a factor of 16 and if the duration doubles the HDV values doubles).

For a gaussion random motion the HDV value is therefore approximated by 2.9 times the fourth power of the rms value multiplied by the duration in minutes. For a sinusoidal motion the HDV value is approximately 1.5 times the fourth power of the rms value multiplied by the duration in minutes (i.e. $(\frac{0.7825}{0.7071})^4$). (The difference in HDV between 1.5 for sinusoids and 2.9 for gaussion random vibration does not necessarily imply that random vibration is approximately twice as harmful as sinusoidal vibration. Only about 18% reduction in the rms magnitude of the random motion is required to obtain the same Hazard Dose Value as a sinusoid of the same duration. There are some subjective data suggesting slightly greater sensitivity to random vibration - e.g. Griffin (1976)).

(c) Vehicle vibration

Most realistic vibration exposures involve some periods of little or no motion. The relation between Hazard Dose Values and the root mean square acceleration averaged over a complete exposure period will vary according to the time spent with little vibration. When a short test road is employed and the conditions appear constant throughout the measurement period it becomes more meaningful to relate rms vehicle vibration to Hazard Dose Values. Table 3 shows the statistics of vertical vibration obtained on the seats of 3 types of vehicle during 60 second periods on test roads. It may be seen that the Hazard Dose Values vary from about 3.8 to 4.6 times the fourth power of the rms value. Taking a value of 4.0, the difference in the vibration magnitude between the HDV of a vehicle and an equivalent sinusoid is about 27% of the magnitude of the vehicle vibration.

		Analysis of 1 min period						
vehicle	road	rms ms^{-2}	rmq ms^{-2}	peaks ms^{-2}	crest factor	unweighted dose m^4s^{-7}	duration for HDV=1024 m^4s^{-7}	ISO 2631 exposure limit
Small car	A	0.502	0.729	-2.50+1.91	4.98	0.281	60 hrs	12 hrs
Small car	B	0.779	1.125	-4.07+3.16	5.22	1.597	10.7 hrs	6.5 hrs
Van	A	0.430	0.630	-1.92+2.06	4.79	0.158	108 hrs	16 hrs
Van	B	0.947	1.328	-5.24+3.57	5.53	3.105	5.5 hrs	4.5 hrs
Rigid truck	C	1.47	2.066	-5.83+7.35	5.00	18.94	0.9 hrs	2.5 hrs

Table 3: Various statistical values of vertical vibration recorded on the seats of three vehicle types. (Frequency range 0 to 64 Hz with no frequency weighting).

It appears that if the rms value of acceleration in a vehicle is known the HDV value for 1 minute is approximated by 1.4 (i.e. $(4)^{\frac{1}{4}}$ times the rms value. This will only apply when there are no pauses in the motion and the crest factor is low (e.g. less than about 6).

The Hazard Dose Value increases during exposure to vibration but remains constant during breaks. Figure 4 shows the accumulation of the Hazard Dose Value during the 5 hour vehicle vibration exposure shown in Figure 1. The total dose after 5 hours was 219 m^4s^{-7}. This vibration spectra was dominated by energy centred on 1.4 Hz. The driver described the journey as "very fatiguing".

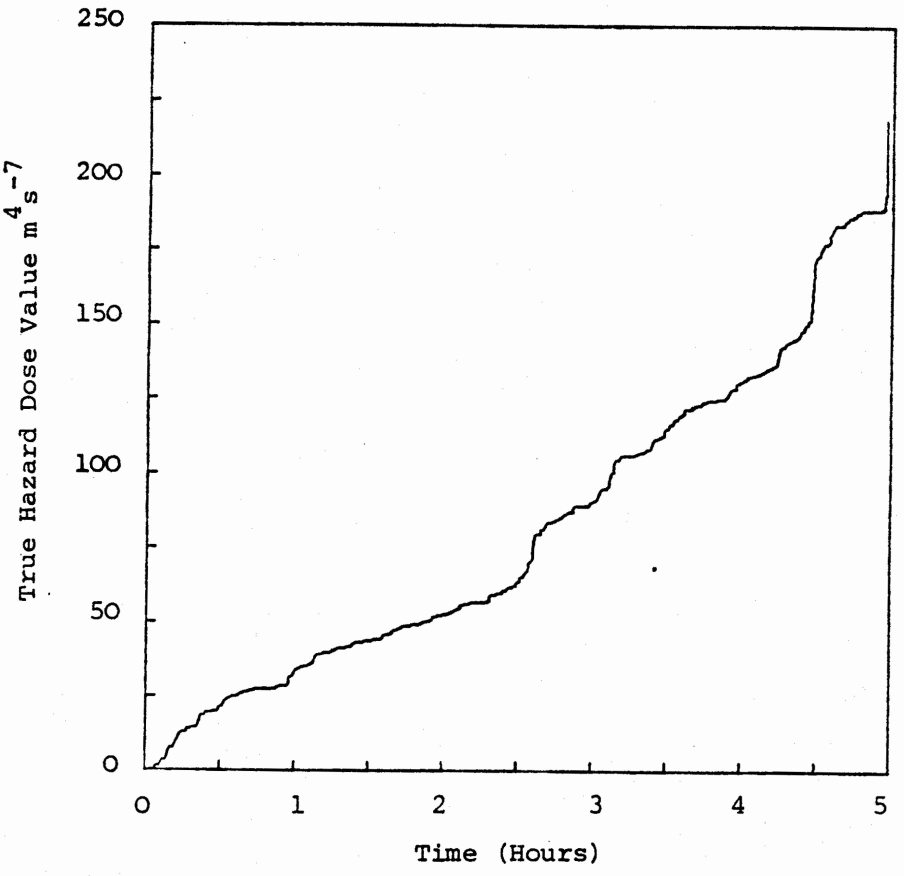

Figure 4: Increase in true Hazard Dose Value with time for the five hour vibration exposure shown in Figure 1.

HAZARD DOSE VALUES FOR SHOCKS

Triangular, Rectangular and Half-Sine Shocks

The final portion of the 5 hour vehicle vibration recording shown in Figure 1 contains two substantial shocks as the vehicle drove over two speed control ramps. Most vehicle vibration contains some shocks and they should contribute appropriately to the calculation of the vibration dose. If the procedure calculates a meaningful value for shocks within a vibration condition it should also provide a good estimate of the relative severity of various isolated shocks.

Figure 5 shows a triangular, a rectangular and a half sine shock all with the same peak amplitude. (The duration of the rectangular shock may be considered to be half that of the other shocks - depending on the definition of shock duration).

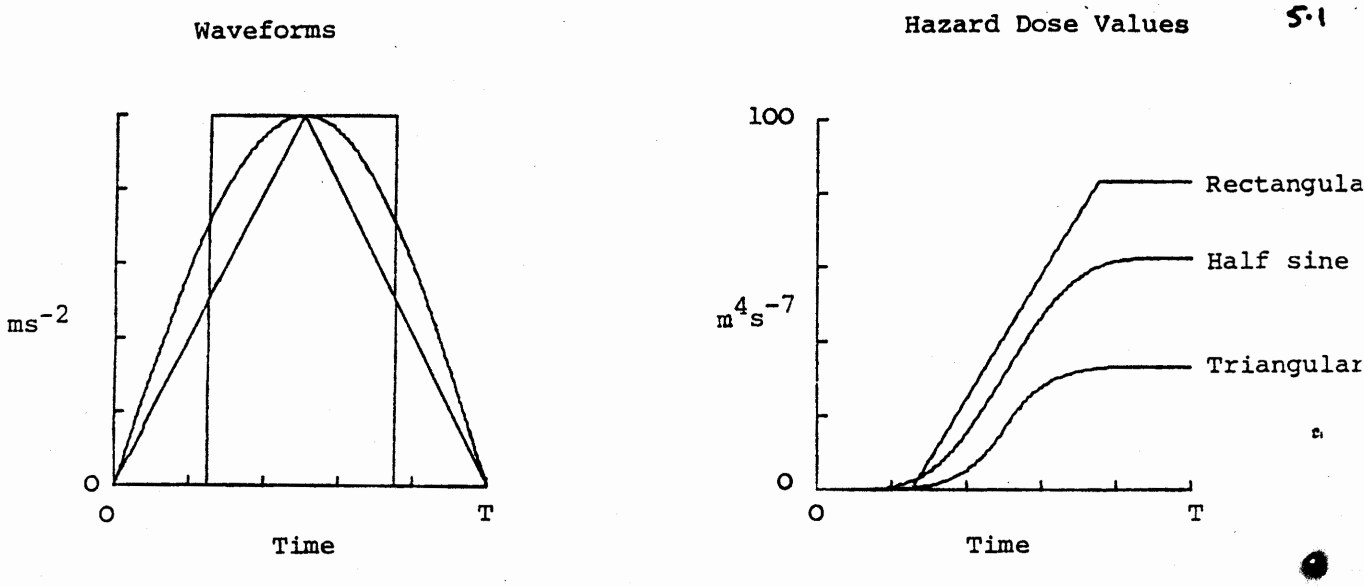

Figure 5: Acceleration time histories and Hazard Dose Values for triangular, rectangular and half sine shocks.

The accumulation of the dose values of the three shocks is also shown. The Hazard Dose Value of the half sine shock (62.5 m^4s^{-7}) is nearly twice that produced by the triangular shock (33.3 m^4s^{-7}) but less than that produced by the rectangular shock (83.3 m^4s^{-7}).

The Hazard Dose Value relates vibration magnitude to its duration and a discrete event produces lower values for shorter events. In consequence a half sine pulse of a high frequency (i.e. short duration) gives a lower Hazard Dose Value than a similarly shaped pulse of a low frequency. This may appear to be a frequency weighting for pulses. (For continuous vibration the HDV does not change with frequency if the duration does not alter, i.e. if the number of cycles of motion increases in proportion to any increase in frequency). The peak magnitude of a half sine pulse of 100 Hz fundamental frequency must be 3.16 (i.e. $\sqrt[4]{100}$) times greater than that of a 1 Hz half sine pulse to give the same Hazard Dose Value.

Realistic Shock

The acceleration time history, the fourth power of the time history and the accumulated dose of a vibrator driven into hydraulic buffers is shown in Figure 6. In this case the peak acceleration is -110 ms^{-2} and the Hazard Dose Value is 13900 m^4s^{-7}. (The above calculation employed no frequency weighting. The use of 12dB/octave filtering above 20 Hz reduced the Hazard Dose Value to 3567 $m4s^{-7}$ - see below).

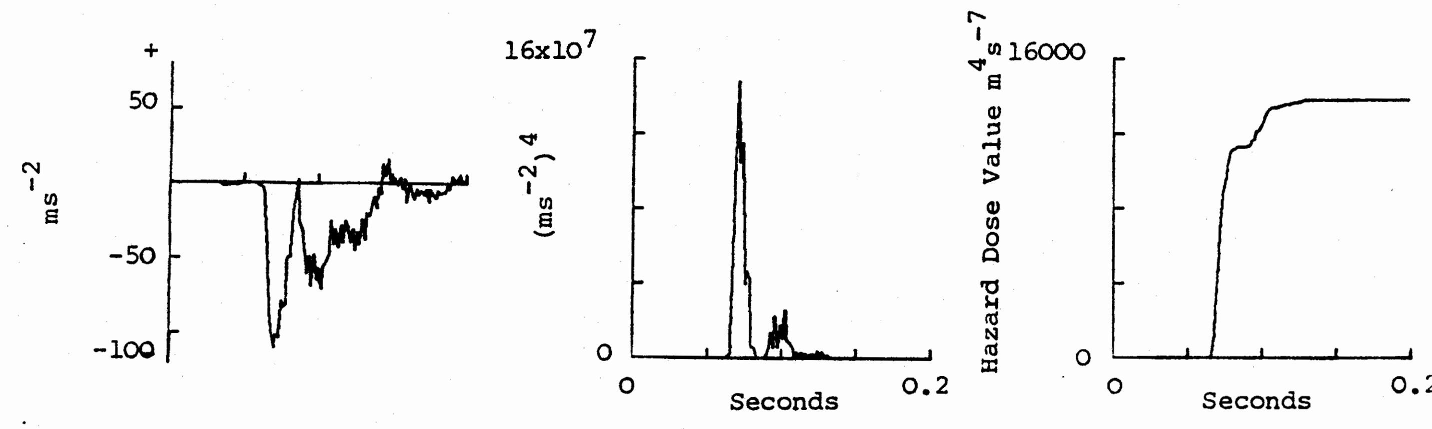

Figure 6: Acceleration, $(acceleration)^4$, and accumulation of Hazard Dose Value for vibrator entering hydraulic buffers. (Duration of motion: 200 ms).

Comparison With Shock Standards

There are various existing proposed shock limits which define methods by which the relative severity of shocks may be quantified. Most methods assume a particular shape for the acceleration waveform (often trapezoidal) and are concerned with the maximum rate of onset of acceleration and a combination of the duration and magnitude of a period of uniform acceleration. It is generally considered that a simple acceleration limit applies for long duration shocks but that higher levels are allowed when the shock duration falls below some short value. The critical duration and the magnitude of the acceleration limit depend on how they are measured and this depends on the assumed shapes of the pulses. In practice shocks may have characteristic but complex shapes which deviate from the simple geometric forms which are assumed. (See, for example, Figure 6).

The Dynamic Response Index has been used to quantify the severity of shocks from ejection seats. It is based on a single degree of freedom model intended to predict the maximum stress imposed within the vertebral column. This model (natural frequency

52.9 rad/sec and a damping ratio 0.224) can be used to filter a shock acceleration time history. The peak value of the filtered waveform gives the DRI value. This technique reduces the severity of single high frequency shocks (i.e. short duration motions) in common with other procedures. However, it will also reduce long duration shocks containing repeated cycles of high frequency motion (see below). In its simple form the DRI is intended to give only one maximum value for each shock. If the waveform is complex it would be reasonable to expect that the peak value at more than one moment may be important. The DRI has been suggested for use with repeated shocks (Allen (1976)). A reduction in shock magnitude is proposed if there is more than one shock. The method of summing a combination of very many shocks of different levels is not defined. However the shape relating number of shocks to their magnitude as proposed by Allen is not dissimilar to the a^4t = constant relation which is the basis of the Hazard Dose Value time dependency. (See Figure 7).

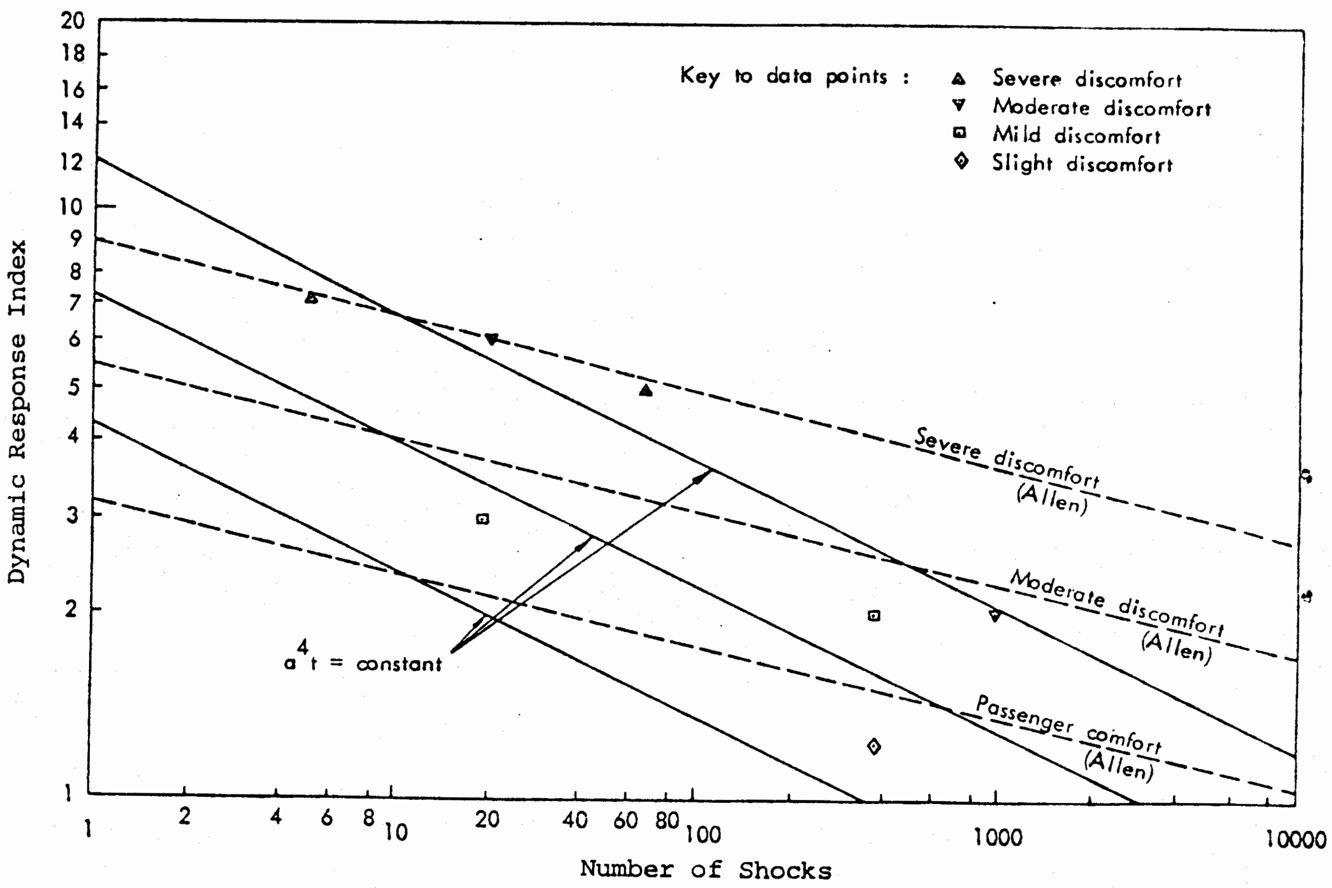

Figure 7: Comparison of $(\text{acceleration})^4$ x time = constant time dependency with repeated shock limits proposed by Allen (1976).

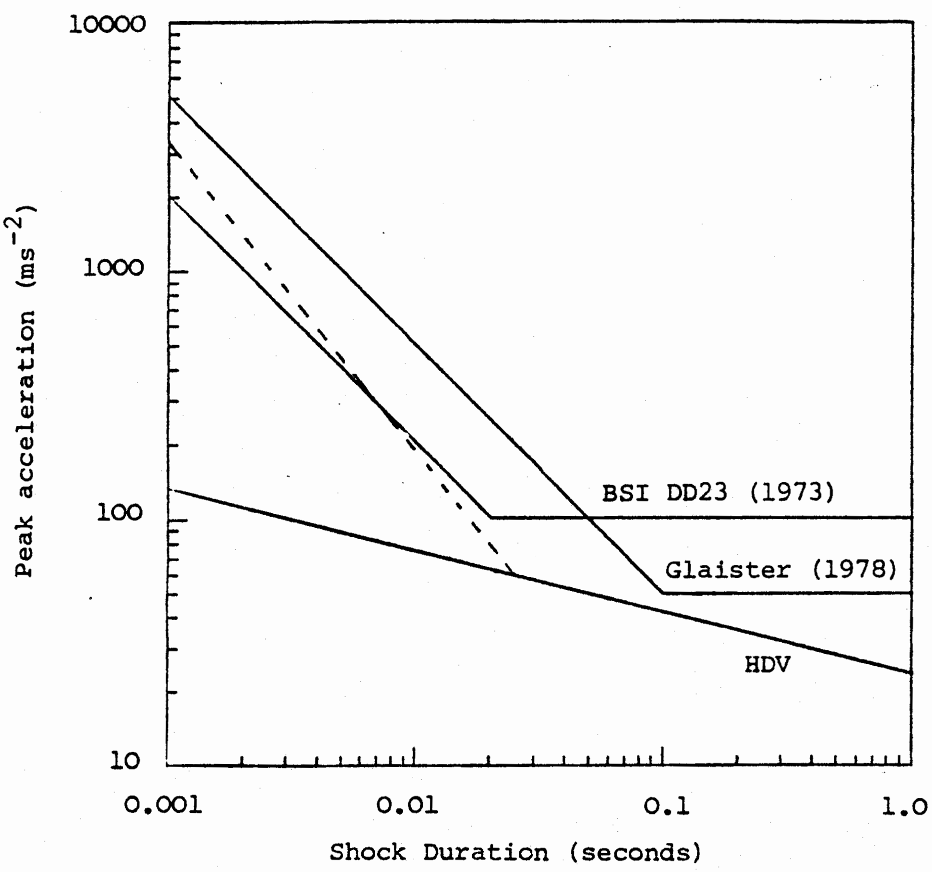

Figure 8: Comparison of Hazard Dose Value method of evaluating shocks with limits proposed in BSI DD23 (1973) and by Glaister (1978) (broken line indicates approximate HDV values when using a 20 Hz 6 dB/octave low pass filter; see text for pulse shapes).

Figure 8 compares two proposed shock limits with the values that correspond to a Hazard Dose Value of 1024. Since the procedures employ different means of quantifying shock severity the comparison is dependent on the shock shape. The British Standard Institute Draft for Development DD23 (1973) specifies shock limits for the failure of man-carrying vibrators. The velocity change should not exceed 2 ms^{-1} for durations less than 0.02 s. For durations greater than 0.02 s the mean acceleration should not exceed 50 ms^{-2}. Neither the shape of the pulse nor the method of calculating the mean are specified but the values have been drawn for a triangular shock pulse. The peak accelerations of 0.001 s to 1 s duration triangular pulses which may relate to this limit are shown in Figure 8. (The velocity change for the data shown is 1 ms^{-1}).

In a review of human tolerance to impact acceleration Glaister (1978) proposes tolerance limits for various postures. For a rectangular $+G_z$ acceleration pulse applied to a seated person without any restraint he proposes limits of 50 ms^{-2} for durations greater than 0.1 second and a velocity change of 5.0 ms^{-1} for shorter durations. The peak acceleration corresponding to these limits for a rectangular pulse are shown in Figure 8.

The line shown in Figure 8 for a 1024 Hazard Dose Value is calculated for the peak values of a triangular pulse. The broken line is that which is obtained when applying an idealised low-pass filter having a 6 dB/octave cut-off above 20 Hz. (The exact value will depend on filter characteristics). The continuous line shows the values without the use of this filter.

FREQUENCY WEIGHTINGS

In the evaluation of human response to vibration some filtering is common since the increased attenuation of higher frequencies in the body appears to reduce their effect. Evidence of a general biomechanical resonance in the range 4 to 8 Hz has led to this being quoted as the region of maximum sensitivity. Although this resonance has an effect, it is an oversimplification to assume that one frequency weighting is applicable to all effects of vertical vibration. Hand activities may be disturbed by large resonant-type movements around 4 Hz but not at 16 Hz. However for a single axis vertical seat input the discomfort produced by acceleration is broadly independent of frequency between 4 and 16 Hz. Since the area of the body most effected by vibration (e.g. hand, eyes etc) varies with frequency, the response of a single simple model cannot accurately predict the total effect. A spinal model may be the most appropriate for predicting spinal injury if the site and nature of injury is well established. However the mechanism of such injury due to vibration is not well established. In consequence a fully developed model to predict injurious effects of broadband continuous vibration is not available.

Figure 9 compares the sensitivity contours corresponding to three different frequency weightings. The ISO 2631 (1974) z-axis weighting was evolved as a composite weighting for the effects of vibration

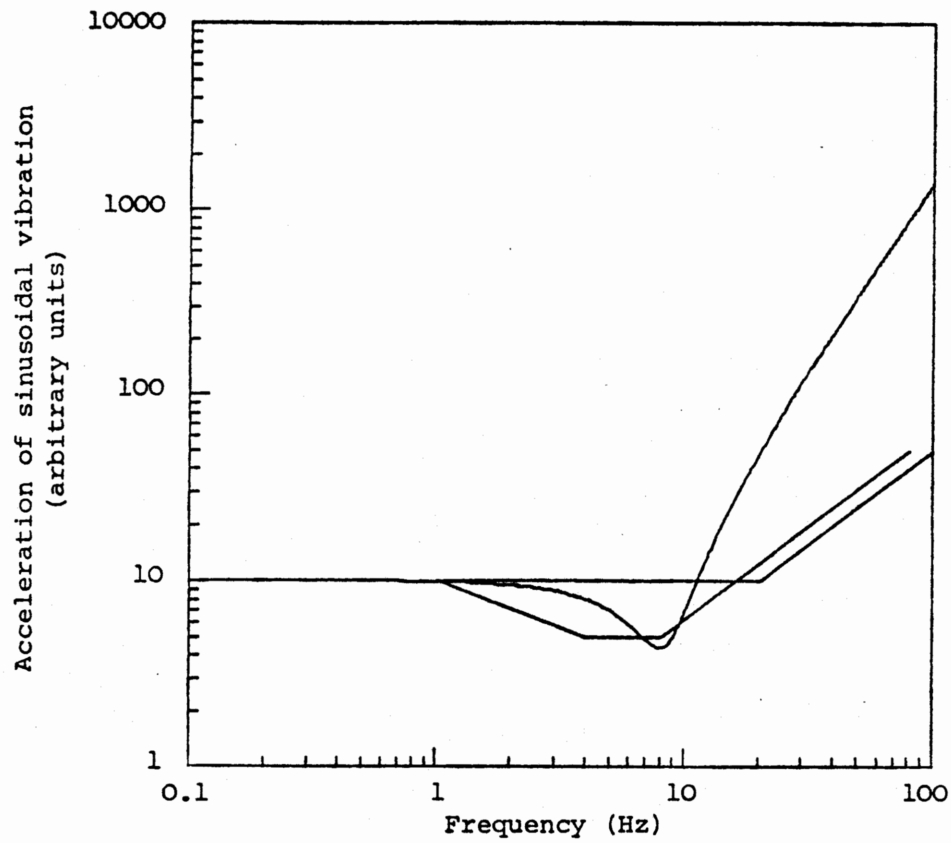

Figure 9: Comparison of equivalent acceleration levels when using frequency weightings defined by the Dynamic Response Index, ISO 2631 and a filter with flat response from 0.5 to 20 Hz and 6 dB per octave attenuation above 20 Hz.

on comfort, performance and health. The DRI weighting was evolved for discrete impact but has been proposed for repeated shock (i.e. vibrations containing high crest factors). It is drawn in terms of its response to continuous sinusoidal vibration. The third curve is simply constant acceleration from 0.5 to 20 Hz and rises at 6 dB/octave from 20 to 100 Hz. This curve is an approximation to some z-axis equivalent comfort contours (see Griffin, Parsons, and Whitham (1982)). All three curves have been drawn so as to coincide at 1 Hz.

The 12 dB/octave cut-off in the DRI response allows apparently excessive levels at high frequencies. The levels of continuous vibration at 20 Hz cannot be considered likely to be tolerable. This is not necessarily inconsistent with its reported applicability to discrete shocks. (When the DRI is applied to the shock occurring during aircraft ejection the response will be dominated by only part of the frequency weighting.) The high attenuation of high frequencies serves to reduce the severity of shorter duration pulses in line with other shock evaluation procedures. However, as this is achieved by a frequency weighting and not a duration weighting, it also has a large and apparently inappropriate effect for continuous vibration.

The ISO 2631 frequency weighting is broadly similar to the DRI at frequencies between about 1 and 10 Hz but gives more weight to higher frequencies. The ISO weighting is a somewhat inconvenient shape and not defined below 1 Hz. The greatly reduced sensitivity at 1 Hz relative to 4 Hz gives rise to a 1 minute exposure limit of ±1.61g at 1 Hz in ISO 2631 and this does not appear reasonable for an unrestrained subject. The 1 minute exposure limit is also ±1.61g at 16 Hz. Although soft seating will often attenuate these higher frequencies (which will rarely occur at this level) the limit should apply to the vibration input to the body and this does not appear reasonable for the vibration from, for example, a rigid seat.

The third weighting is often simple to apply in practice since most motion exists below 20 Hz and the frequency weighting may not need to be applied. However, as with the ISO 2631 weighting, a full definition of the gain and phase characteristics of a suitable filter is necessary.

A full comparison of the three weightings must review the origins of the relevant experimental data and this is not within the scope of the current paper.

INTEGRATION TIMES

An alternative means of allowing for a change in response to vibration with duration is to define an integration time. There may be different time dependencies above and below the integration time. For example, rms averaging might be employed up to 1 minute and the ISO 2631 time dependency used from 1 minute to 24 hours.

Table 4 shows that the choice of a short integration time cannot be made arbitrarily since the Hazard Dose Value in a vehicle is significantly influenced by changes in the integration time.

	INTEGRATION TIME (s) 1.0	0.5	0.25	0.125	0.0625	0.0313	0.0156	True HDV
	Hazard Dose Values m^4s^{-7}							
Small Car (Road A)	0.092	0.105	0.120	0.144	0.179	0.223	0.264	0.281
Small Car (Road B)	0.711	0.798	0.898	1.112	1.362	1.482	1.550	1.597
Van (Road A)	0.062	0.068	0.077	0.091	0.106	0.131	0.148	0.158
Van (Road B)	1.577	1.784	1.923	2.245	2.748	2.981	3.061	3.105
Rigid Truck (Road C)	6.57	7.26	8.25	9.68	11.22	14.09	17.03	18.94
1 cycle $\pm 10ms^{-2}$ 4Hz	2.408	4.423	7.277	9.345	12.482	14.691	15.427	15.625

Table 4: Effect of integration time on Hazard Dose Values. (rms integration below integration time; rmq integration above integration time).

Figure 10 shows how the accumulated dose in a five hour vehicle ride reduces from 219 m^4s^{-7} to 35 m^4s^{-7} as the integration time is increased to 1 minute. (In Table 4 and Figure 10 true rms integration has been used below the integration time).

The definition of an integration time provides a means of changing the slope of a time dependency. Three parameters are therefore necessary: the integration time, and the time-dependencies above and below the integration time. Assuming rms averaging at short duration and rmq averaging at long duration the integration time will serve to steepen the slope so allowing greater levels of short duration 'shock' than would be allowed by rmq averaging throughout.

In relation to injurious effects of vibration and shock a change in slope may appear appropriate in the range 0.02 to 0.1 seconds (see Figure 8). However such a change in slope is also achieved by the use of a frequency weighting (see broken line in Figure 8). Without a frequency weighting but with true rms integration below 0.025 s the peak level for a 0.001 second pulse with HDV = 1024 is approximately 253 ms^{-2}. With a 6dB/octave frequency weighting above 20 Hz this is increased to a value in excess

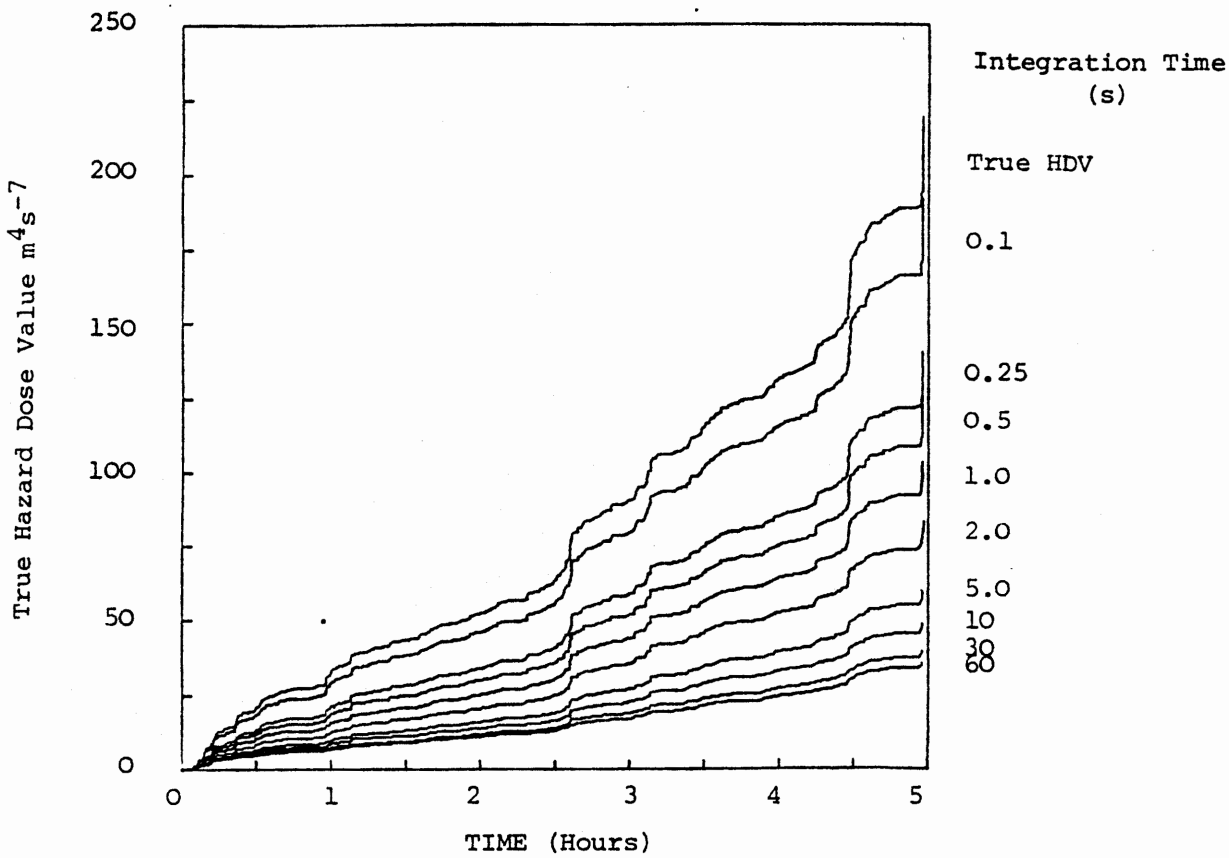

Figure 10: Effect of root mean square integration time on accumulation of Hazard Dose Values during five hours vibration exposure shown in Figure 1. (Integration times of 60, 30, 10, 5, 2, 1, 0.5, 0.25, 0.1 s and true Hazard Dose Value).

of the other limits shown on the Figure. Still higher values are obtained if either longer integration times or the ISO 2631 frequency weighting is used.

VIBRATION AND SHOCK LIMITS

The setting of limits is a prerogative of Governments and some other responsible groups and must take into account the state of relevant knowledge, the quantity and severity of health problems, the full and various effects of a limit and the level of acceptable risk. It is not the purpose of this paper to propose limits. The Hazard Dose Value procedure which has been proposed is therefore illustrated by comparing various values of dose with the exposure limits in ISO 2631 and the shock limits proposed in BSI DD23.

Figure 11 shows the ISO 2631 z-axis exposure limit for 4 Hz vibration for durations from 1 minute to 24 hours. Also shown are the BSI limits for triangular pulses having durations from 0.001 to 1 second.

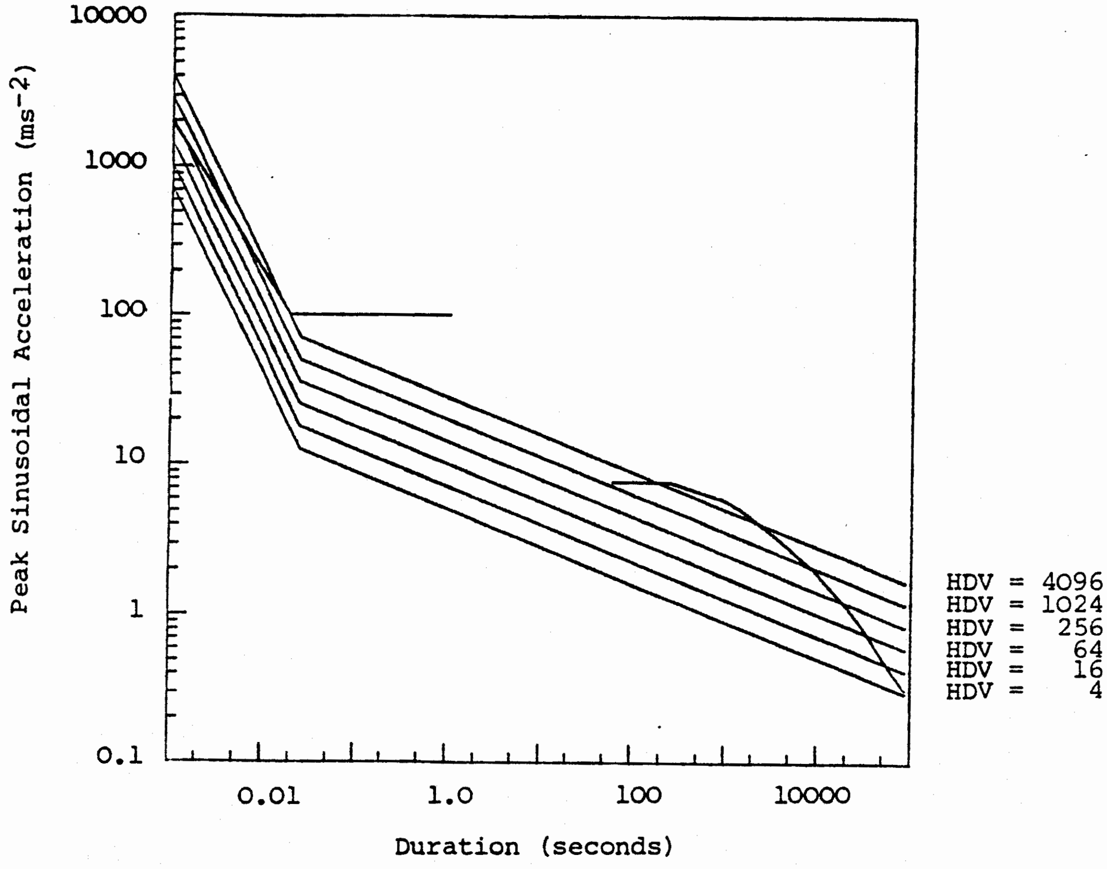

Figure 11: Comparisons of ISO 2631 (1974) vibration time dependency, shock limits in BSI DD23 and Hazard Dose Values of 4, 16, 64, 256, 1024 and 4096 when using frequency weighting above 20 Hz.

The ordinate of the graph is the peak acceleration of the waveforms. The peak acceleration of sinusoidal vibration corresponding to Hazard Dose Values of 4 to 4096 are drawn on the same graph for durations from 0.001 seconds to 86400 seconds (24 hours) (i.e. a duration range of 1 to 8.64×10^7). The values are appropriate for any motion consisting solely of one or more complete half cycle sinewaves). (For long durations there will normally be many cycles of motion of the given level. For short durations the values may apply to only one half cycle). The Hazard Dose Values are drawn assuming 6 dB/octave attenuation above 20 Hz. The inclusion of very short pulses presumes that the frequency range extends to about 500 Hz. However further definition of the filter characteristics and bandlimits is necessary.

It may be observed that the Hazard Dose Value procedure combined with a suitable frequency weighting gives the basis of a set of limits which are reasonably consistent with both the shock limits in BSI DD23 and the vibration limits in ISO 2631.

The most notable differences are a reduction in the levels for short duration vibration and an increase in the levels for long duration vibration. These changes are consistent with common views on the appropriateness of the ISO 2631 time dependency. (A Hazard Dose Value of the order of 1024 m^4s^{-7} appears most consistent with the previous limits).

In contrast to the alternative methods, the Hazard Dose Value procedure defines a common, simple and unambiguous procedure for the quantification of the severity of vibration or shock as well as mixtures of vibration and repeated shocks with any number of rest periods.

CONCLUSIONS

The concept of a dose value for assessing the potentially harmful effects of vibration and shock has been evolved. A Hazard Dose Value based on rmq integration (i.e. HDV = $\frac{1}{60}\int_0^T a^4(t)\,dt$) appears to give appropriate relative weight to the magnitude and duration of vibration and shock over a range of magnitudes of about 100 to 1 and a range of durations of about 100 million to one. This makes it possible to use the same procedure to assess both vibration and shock and, therefore, also evaluate vibration containing repeated shocks and having high crest factors.

Tentatively it is concluded that the procedure should be applied without an integration time but with a frequency weighting having low pass characteristics and a cut-off frequency of the order of 20 Hz. Further definition of the procedure is desirable in parallel with its trial application to a wide range of vibration and shock environments. Although the procedure is apparently consistent with existing standards it is possible that some combinations of levels, durations and frequencies have not been adequately tested.

A vibration dose procedure is desirable so as to define a method of quantifying total exposures. However rest periods without vibration do not reduce the total dose. It may therefore be appropriate to encourage rest periods when the dose exceeds some critical value.

Hazard Dose Values cannot currently be used to predict the type, prevalence or severity of any particular chronic or acute effects of vibration. However they appear to provide an improved means of quantifying and comparing the relative severity of complex motions. The possible hazards associated with complex vibration and shock environments may be assessed by comparing the relevant Hazard Dose Values with those of existing conditions.

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