Journal of Sound and Vibration (1998) **215**(4), 927–945
Article No. sv981604

HIGH ACCELERATION EVENTS: AN INTRODUCTION AND REVIEW OF EXPERT OPINION

J. SANDOVER
Jack Sandover Consultant, Loughborough, LE11 3LB, England

(*Accepted* 18 *March* 1998)

This investigation was designed as a rapid review of available knowledge on high acceleration events in practice. The aim was to consider if the risks associated with regular exposure justifies further investigation of the problem. Three linked investigations were carried out: to gather published information, to gather expert opinion, and to analyse available vehicle records. The literature showed that although no fully acceptable epidemiological data are available, exposure to high levels of vibration and shock probably increases the risk of back problems. Experts considered high acceleration events important as regards the health of drivers of certain vehicles. They though that more research into the effects on health is needed but comfort and epidemiological investigations have some severe practical drawbacks as well as advantages. More biodynamic research is needed to engender plausible hypotheses on the effects on health before consideration of further epidemiological research and generation of dose-response relationships. Vehicle measurements confirmed information from the literature that BS6841 [1] *Wb* weighted r.m.s. values over 4 s of up to 5·8 m/s^2 and unweighted peak values of at least 20 m/s^2 occur with *Wb* weighted peak values of up to 15 m/s^2 and sometimes nearly 30 m/s^2. Daily Vibration Dose Values of the order of 20 $ms^{-1.75}$ are quite probable. Measured accelerations suggested some common features of high acceleration events. Many are of an oscillatory nature with frequencies of the order of 2–3 Hz, whilst large magnitude transient accelerations of the order of 25–50 ms duration also occur in certain situations. The long term weighted r.m.s. value does not reflect the presence of high acceleration events that occur once every few minutes and may underestimate the health risk.

1. INTRODUCTION

This paper is based on exposure to high acceleration events, that is to say events where acceleration levels are appreciably higher than normal for most of the exposure period. This term has been used consciously in order to allow consideration of a variety of possible situations to which people may be exposed. The term "repeated shock" is often used, but that is already being constrained by standardization so that ISO/TC108/SC4/WG10 has repetitive shocks limited to at least "one per several minutes". The aim has been to be able to include such events as periods of intense oscillatory acceleration or transient accelerations (shocks, impact or bumps) which could arise from external events such as potholes or obstacles or from system malfunction such as end-stop impacts.

There is some experimental and theoretical evidence that short duration, high acceleration events have a greater influence on both human health and subjective discomfort than the long term root mean square (r.m.s.) approach implies. As a result, there is some concern of the validity of the r.m.s. approach to estimate the health risk of vibration exposure of people in jobs where the vibration includes events involving higher

0022–460X/98/340927 + 19 \$30.00/0

accelerations than those prevalent for most of the normal working day—especially if long term r.m.s. acceleration levels underestimate the health risk.

The investigation was designed as a rapid review of available knowledge on high acceleration events in practice. The aim was to consider if the risks associated with regular exposure to high acceleration events in industrial, agricultural and transport jobs justify further investigation of the problem.

2. METHOD

Three linked investigations were carried out: to gather published information, to gather expert opinion, and to analyze available vehicle acceleration records.

2.1. A REVIEW OF THE LITERATURE

The aim of the review of available literature was to gather information on the types of jobs likely to include exposure to high acceleration events and on the effects of high acceleration events on the health of drivers. Consideration of discomfort, physiological and biodynamic responses and modelling were also included as there is little direct information on the effects on health. The review was brief and relied primarily on searches of international databases.

2.2. A REVIEW OF EXPERT OPINION

A recognized method for reviewing available knowledge on a topic is to gather expert opinion. Although there are many professionals involved with human response to vibration there is only a small number with expertise on high acceleration events and this makes the gathering of expert opinion a relatively simple matter. The aim of this investigation was to obtain an up to date view of experts on their perception of high acceleration events as an issue of practical importance as regards effects on health, on the prevalence of jobs with exposure to high acceleration events, on the pattern of exposure and characteristics of high acceleration events and on current activities and research.

The review was based on an open ended questionnaire to focus the respondent's attention on specific issues but respondents were encouraged to add any information they considered to be relevant. The questions are given with abbreviated responses in the Appendix. Eighteen professionals with expertise either in research into the effects of high acceleration events on people or in field measurements of high acceleration events co-operated with the review. The respondent group covered all of the known major experts in the field.

2.3. HIGH ACCELERATION EVENTS IN PRACTICE

This was intended as an exploratory study of data already available to the author. For simplicity, only vibration in the vertical z direction was considered.

A simple method was used to detect individual high acceleration events of up to four seconds duration and these were then reviewed to see if any common pattern could be observed. A variety of common measures to assess the magnitude of human response to vibration were applied to these data.

Three sets of data were used: tape recordings of vehicle vibrations, supplied digitized vibration data and supplied digitized events.

2.3.1. *Tape recordings*

Several tape recordings of seat accelerations were available from vehicles either during normal operation or on trials simulating normal operation. Samples of these were digitized by using a PCMCIA analogue to digital conversion card (Computer Boards PCM-DAS16 12 bit) and a portable computer. Software was written in "C" to digitize the data at 1600 Hz and then to low-pass filter and decimate the data to 400 Hz. The system allowed a maximum single sample duration of 18 s.

To locate possible high acceleration events in a long period of normal driving, software was written to display the 1 s BS 6841 [1] *Wb* weighted r.m.s. level continuously. This display was used to detect visually the higher 1 s r.m.s. values to select the high acceleration events.

An 18 s period of signal that encompassed the observed event was then obtained. These sections included periods of normal vibration as well as some event. A visual scan suggested that the main event could usually be included fully in a 4 s period which was then noted. The full 18 s period was first treated to have a zero mean value and then treated with the required weighting function before the 4 s event was extracted for detailed analysis.

2.3.2. *Supplied digitised data*

These data were obtained for various vehicles in mining operations and consisted of 70 s periods digitized at 714·3 Hz. These were interpolated at 400 Hz and 18 s periods chosen for treatment as above.

2.3.3. *Supplied digitised events*

These data were from the Wikström *et al*. [2] "Harbour" study of vehicle discomfort under test track conditions. The vehicle was a terminal tractor with a suspension seat driven over a track carrying various obstacles to simulate impacts during normal working. The vertical z direction accelerations were dominant and were used for this investigation. Data for fourteen subjects, each traversing the track containing 14 obstacles three times, were available. These records had been digitised at 256 Hz after low-pass filtering to 80 Hz and gave records up to 4 s in duration. Each record was treated to remove any DC offset and interpolated to 400 Hz before analysis.

Initial conditions mean that there is some disparity between a weighted 4 s event and a 4 s event taken from a weighted 18 s event so that weighting the supplied events might not be valid. However, by comparing weighted 4 s events with the same 4 s events taken from weighted 18 s sections of the tape recorded data, it was shown that the weighting functions settled down quickly so that initial condition errors were minimal after 0·5 s. In all cases, the peak occurred after 0·5 s so that it was acceptable to include weighted 4 s events in the full data set.

2.3.4. *Data treatment*

Initial data treatment consisted of frequency weighting the data in compliance with the BS 6841 [1] *Wb* function (denoted in the rest of this paper as *Wb* weighted). The program used the weighting filter algorithm published by Lewis [3] modified for use in "C". For unweighted values the data were separately treated with a low pass filter (100 Hz) using a zero phase algorithm so that no time lag occurred.

For each event, the unweighted and *Wb* weighted r.m.s. and peak values were obtained. Seidel *et al*. [4] have argued that there is a threshold, below which health effects are unlikely. Accordingly, the peak detection algorithm was designed to ignore all peaks less than $+/-5\ \mathrm{m/s^2}$. The Vibration Dose Value (*VDV*) was also calculated.

It must be emphasized that this analysis was only exploratory, being based on a small number of vehicles and conditions and a very simple detection method. The driving situations investigated are given in Table 1.

TABLE 1

The driving situations investigated

Run No	Description
F1, F2	1800 kg capacity fork lift truck with semi-solid tyres (Watts cushion tyre 15 × 5 × 111/4) driven on concrete with faults
B1, B2, B3	Double deck bus with leaf spring suspension and only nominal seat suspension being driven over traffic calming humps
B4, B5, B6	Above bus driven at normal speeds on city roads. Normal pot-holes in roads
J1, J2	JCB 525-58 earth moving vehicle with 1·2 m dia tyres, KAB 301 seat, carrying out a load and place operation
J3, J4, J5	Above JCB driving around a field test track at approx. 4 km/hr
J6–J11	Above JCB with shovel, loading, moving and unloading rocks
J12–J13	Above JCB driving over 10 mm obstacles at approx. 10·5 km/hr
J14–J20	Above JCB driving around a rough field test track
D1	Large dump truck approx. 2 m wheels, anti-vibration seat. Normal open-cast mining carry and drop activity
D2–D8	Similar to above but with seat damper inoperative
T1–T7	John Deer 3350 agricultural tractor with Grammer AV seat in poor condition. Pulling forage trailer on tarmac roads at approx. 45 km/hr, field and yard.
T8–T11	John Deer 4455 agricultural tractor with HC6 air suspension seat. Discing a field with "tramlines".
M1, M2	Caterpillar D10 Ndozer – coalmining operations
M3, M4, M5	D9 Bulldozer "ripping" mining operations
M6, M7	Moving 301 rock drill during coalmining operations
M8, M9	Rockbreaker during mining operations
T12–T25	Bollnäs PT20 terminal tractor with BeGe Pluto sprung seat. 0·25 MPa tyre pressure front, 0·7 MPa rear driving on asphalt track at 4·2 km/hr over steel obstacles of various heights from 10 mm to 70 mm

3. RESULTS

3.1. THE REVIEW OF THE LITERATURE

3.1.1. *The occurrence of high acceleration events in practice*

Only one paper describes the type of high acceleration events met in practice—Bennerhult and Axefors [5].

Papers demonstrating high vibration levels included the following. Monsees *et al*. [6] investigated agricultural tractors and chose two-minute samples from recorded field vibrations where the r.m.s. of the samples ranged from 0·7 to 4·3 m/s^2 and peak accelerations ranged from 8·5 to 53·2 m/s^2 (both weighted in accordance with ISO 2631 [7]—abbreviated to ISO weighted subsequently in this paper). All Crest Factors† were greater than or equal to 6. Lovat *et al*. [8] modelled the response of fork lift trucks driving over obstacles. They stated that such vehicles working on poor surfaces can expose the driver to high acceleration levels—up to 2·5 m/s^2 r.m.s. (weighted values—ISO assumed).

Village *et al*. [9] investigated load-haul dump vehicles in underground mining and found ISO weighted r.m.s. levels in the z direction of between 0·6 and 2·5 m/s^2 (mean *daily* exposures between 0·7 and 2·2 m/s^2) and observed that the driver sometimes left the seat during impacts that ranged from 3·8 to greater than 20 m/s^2 (ISO weighted peak value) with smaller vehicles exhibiting higher accelerations. A previous study had shown that the drivers of these vehicles were at risk of back problems. Wikström *et al*. [2] used a terminal

† The Crest Factor is usually defined as the ratio of the peak weighted acceleration to the r.m.s. weighted acceleration. See BS6841 [1] for a detailed definition.

tractor and a forestry "forwarder" for their study of subjective responses to high acceleration events. The ISO weighted r.m.s. acceleration recorded were 1·4 (0·24–7·0) m/s^2 (z direction) and 1·7 (0·28–3·4) m/s^2 (y direction, critical) respectively for the two vehicles. Cross and Walters [10] investigated injuries due to "jarring" in the New South Wales coal mining industry. In underground situations, they investigated transporters and shuttle cars. In above ground operations, they investigated loaders, dozers and dump trucks. They considered rough surfaces, holes and obstacles to be the main sources of jarring.

Attonen and Niskanen [11] investigated vibration in snowmobiles. They considered that about half of the drivers had back problems. They measured ISO weighted r.m.s. seat accelerations of between 1·1 and 6·1 m/s^2 with a mean of about 3 m/s^2. Again, rough surfaces were considered the main source of high acceleration events and they pointed out that impulse levels will be proportional to the square of the driving velocity.

Wu *et al*. [12] considered end-stop impacts with anti-vibration seats to be an important issue that should be dealt with in seat testing. Wu [13] has shown that end-stop impacts can lead to greatly increased *VDV*s.

3.1.2. *The effects of high acceleration events on health*

As early as 1960 Rosegger and Rosegger [14] pointed out that shaking and jolting may lead to macro and micro trauma to the vertebrae whilst in 1978 Troup [15] argued that transmitted road-shock may be a source of back problems.

Several reviews of published epidemiological studies concerned with the effects of vibration on health are available—the more recent ones being those of Bongers and Boshuizen [16] and Wikström *et al*. [17] (see also the paper by Kjellberg *et al*. [18]). The general conclusion was that drivers of certain vehicles are at risk of low-back problems and to a certain extent head–neck–shoulder and gastro–intestinal problems. However, most reviewers point out that there are considerable methodological problems arising from confounding (especially prolonged sitting and poor posture as regards low-back problems) and lack of vibration measurements. Bongers and Boshuizen (in reference [16]) suggested that, as a first estimate, the odds ratio for back troubles increases by 1·8 per m/s^2 of whole-body vibration.

Unfortunately, no-one appears to have carried out an epidemiological study where the prevalence of high acceleration events was considered. However, Wikström *et al*. concluded that many repeated shocks with a sufficient level and duration may lead to back problems and Bongers and Boshuizen described the hypotheses of fatigue induced damage in the spine that would indicate that high acceleration events have a disproportionate effect on health. Cross and Walters [10] considered that "jarring" was a cause of 36% of the back injuries of mobile equipment operators. They considered it not to be a general health problem but specific to certain jobs.

3.1.3. *Subjective responses*

The epidemiological studies indicate that the most likely health problems are related to disorders in the lumbar spine. Although it could be argued that discomfort in the lumbar region may be an indicator of accumulated acute strain in the lumbar spine, rarely have discomfort studies been targetted in this way. However, discomfort studies may throw light on how people respond to high acceleration events as compared with continuous vibration.

The studies of Griffin and his colleagues (see, e.g., references [19, 20]), on discomfort arising from high acceleration events are well known. The early studies were concerned with the growth of discomfort with time investigating the relationship $a^n t =$ constant (where a is acceleration, t is time and n is the exponent). They found that the exponent was usually between 3 and 4 and argued that the value 4 would indicate the use of fourth power methods for the assessment of vibration effects (the use of 3 was not considered viable as it would not lead to positive values). Kjellberg and Wikström [21, 22] found that the time effects indicated higher exponents. This approach was developed considerably by Griffin and his colleagues and resulted in the Vibration Dose Value (*VDV*) method described in BS 6841 [1] and often recommended for the evaluation of vibration with high crest factors.

Griffin and his colleagues have carried out a variety of laboratory studies that support the use of fourth power methods; see, e.g., reference [23]. However, some field based investigations have shown that simple r.m.s. methods give as good or better correlation with discomfort. Monsees *et al*. [6] pointed out that, for realistic tractor vibrations, the r.m.s. and root mean quad (r.m.q.) are often correlated and, therefore, made use of chosen sections of field recordings such that the r.m.s. and r.m.q. were not related. They then found the r.m.s. to be a better predictor of discomfort although they consider that fourth power methods may be appropriate for situations with very high crest factors (>12). Donati *et al*. [24] investigated the discomfort of lorry drivers whilst driving over artificial obstacles and found that the r.m.s. and r.m.q. methods gave similar discomfort rankings. Malchaire and Piette [25] in a study of overhead crane operators found that drivers had difficulty discriminating between vibration and shocks. They found that the use of the ISO weighting reduced the correlation between acceleration measures and discomfort and that an excedance approach (L_{10}) gave slightly better correlations than r.m.s. methods.

Vukusic *et al*. [26] investigated very high amplitude acceleration events (decaying sinusoids with peak values of 10, 20 and 30 m/s^2) produced at repetition rates such that the *VDV* was always 24·2 ms$^{-1·75}$. The total exposure time was 2 h. They found that subjects rated the lower repetition rate, higher amplitude shocks continually more uncomfortable. Although they did not investigate in detail, their data suggest that an exponent less than 4 would be more suitable. For the very high acceleration levels more typical of pilot ejection (about 100 m/s^2 peak), Payne *et al*. [27] found that subjective responses correlated very well (r^2 of the order of 0·98) with the Dynamic Response Index used for seat ejection evaluations—see for example reference [28]—but poorly with the r.m.s. and *VDV*.

Two major studies based on field measurements are those of Wikström *et al*. [1] and Spång and Arnberg [29]. Wikström *et al*. used a dock vehicle and a forestry vehicle driving around representative tracks with experienced drivers as subjects whilst Spång and Arnberg replayed field recorded high acceleration events to naive subjects in the laboratory. Both groups found that there was little to choose between r.m.s. and fourth power methods in terms of correlation with discomfort. They investigated a variety of evaluation methods and found that many had similar predictive values to r.m.s. and fourth power methods. Spång and Arnberg considered that r.m.s. and r.m.q. methods need to take time into account and recommended the use of an integration time of 1 s. Payne [30] has investigated both sets of data in some detail and included a development of the Dynamic Response Index. He found that this method gave better results than those based on the ISO and *Wb* weighting functions, including the *VDV*. However, the predictive values of many methods were quite close and there were some inconsistencies between the two data sets.

3.1.4. *Physiological and biodynamic investigations*

Both epidemiological and discomfort studies clearly have their drawbacks as knowledge sources for the effects of high acceleration events on health. A small number of investigators have considered other approaches.

In a major multi-centre study [31], a variety of approaches were investigated with the general conclusion that r.m.s. methods are not adequate for the evaluation of vibrations including shocks. One of the studies, by Dupuis *et al*. [32], is particularly relevant as they investigated biodynamic, emg, thermal and subjective responses as well as manual control and visual acuity. They used transients developed from field measurements using different repetition rates and shock amplitudes superimposed on a background stochastic vibration. Two basic shock types (positive going and positive-negative going) were used. The ISO weighted r.m.s. value for each exposure was $1{\cdot}25\ \mathrm{m/s^2}$.

They found that the exposures with high shock levels led to increased transmission up the spine which "lead to the assumption that exposure to transient vibration poses a hazard to health, particularly that of the spine". Manual control (tracking) and thermal changes in the spinal area were not influenced by the presence of shocks. However, emg changes, subjective responses and visual acuity were influenced by the presence of shocks. They concluded that evaluation methods based on the weighted r.m.s. were not sufficient for the high acceleration events investigated.

A team at the Federal Institute for Occupational Medicine, Berlin, have carried out several investigations of muscle responses and acceleration transmission along the spine in order to model forces acting on the vertebral end-plates. Two studies relate to transients—those of Blüthner *et al*. [33] and Hinz *et al*. [34]. In the first study they showed that muscle forces need to be considered even for shocks of short duration and that the immediate previous time history and the direction of the shock (whether positive or negative going displacement) had a strong influence on the ability of muscle action to stabilize the spine. In the second study they included surface acceleration measurements and used their results to calculate dynamic compressive loads at the L_3–L_4 junction. They used a simple moment–arm model similar to that suggested by Sandover [35] and for their transient accelerations of up to approx. $3\ \mathrm{m/s^2}$ peak and 0·3 s duration. They calculated peak compressive forces ranging from 165 to 1285 N with an average of about 500 N. Using a dynamic load at 30% of the ultimate compressive strength as an upper boundary for risk free dynamic loading and a static vertebral strength less than 1·6 kN and 3 kN for 5% and 20% of the population respectively, they estimated that these moderate transients were approaching the risk free boundary. The authors accepted that several limitations exist on these data so that they can only be regarded as a rough guide to health risk.

Robinson *et al*. [36] carried out a similar investigation although they concentrated on much higher level acceleration events (up to $40\ \mathrm{m/s^2}$ peak). They made use of surface acceleration measurements, emg and intra-abdominal pressure measurements to calculate the transient compressive loads at the L_3–L_4 junction. Their results were comparable with those of Hinz *et al*. for low level shocks. However, their calculations for the higher level acceleration events showed compressive forces up to 25 kN. Such levels are well beyond many estimates of vertebral yield strength. They regarded this as illustrative of a deficiency of the simple model. Nonetheless, the data, together with those of Hinz *et al*., indicate that spinal loading arising from high acceleration events may lead to damage, particularly if fatigue induced failure of vertebral structures occurs.

The fatigue approach was proposed by Sandover [35, 37] who used available data and a simple model to suggest that repeated loading could lead to damage of the vertebral endplates. He put forward hypotheses that fatigue-induced micro-fractures in the vertebral endplates could lead directly or via callus tissue to degeneration in the lumbar spine. He made use of available fatigue data for bone which suggested that quite high values (about

9 or 10) may be necessary for the fatigue exponent.† Both Bongers and Boshuizen [16] and Wikström [17] appear to agree that this approach, although speculative, has merit.

3.2. THE REVIEW OF EXPERT OPINION

The questionnaire, together with abbreviated responses are given together in the Appendix. For those questions requiring a single response, the number of experts making that response are included.

3.3. HIGH ACCELERATION EVENTS IN PRACTICE

The *Wb* weighted and unweighted values are given in Table 2 which shows *Wb* weighted r.m.s. values ranging from 0·5 to 5·8 m/s^2 (1·6 mean). Such values do not appear to be particularly high for events occurring (say) once every three minutes during the working day compared with those observed in the literature—Village *et al*. [9] observed *daily* values of 0·7 to 2·2 m/s.

The table shows that some very high accelerations occur. Although events T19 and T22 were clearly extreme, unweighted maxima of the order of 20 m/s^2 and weighted maxima of about 15 m/s^2 were common and, upon disregarding peaks less than 5 m/s^2, the mean peak value (both weighted and unweighted) was about 10 m/s^2. Some signals were truncated to some extent as the signal exceeded the capacity of the original recording system. Such events are marked in Table 2. The truncation will have had little effect on the r.m.s. values but the minimum and possibly the *VDV*, values will have been underestimated to an unknown extent.

Apart from the same two extreme events the maximum *VDV* was (after truncation) at least 7 $ms^{-1·75}$ for the 4 s. A hundred such events per day would lead to a daily *VDV* of 22·1 $ms^{-1·75}$—a level that many would consider extremely high. For instance, BS 6841 [1] states that a *VDV* of 15 $ms^{-1·75}$ approximates to the ISO 2631 [7] "exposure limit".

The long term weighted r.m.s. was updated every second and plotted together with 1 s r.m.s. values. The former did not reflect the existence of high acceleration events after the first minute or so. The long term weighted r.m.s. was much lower than the high acceleration event 4 s r.m.s. values.

The pattern of the high acceleration events appeared to be vehicle and activity dependent. However, events of an oscillatory nature with, or without, a sharp transient appeared to be quite common. Although frequency spectra resulting from single time series are not entirely reliable, they showed that, for many situations, the oscillations were between two and three Hz. These frequency characteristics are probably related primarily to the influence of the anti-vibration seat and large tyres on many of the vehicles investigated. The fork lift truck did not come into this category and its frequency characteristic was different. Clearly, a limited investigation such as this will incur selection bias and one cannot generalise.

The very large, short duration transients merit investigation. They could arise from end-stop impacts or simply because the driver has fallen back onto the measuring seat pad whilst bouncing. Such events could arise from poorly maintained, or poorly selected anti-vibration seats, probably not an uncommon situation, so such data need to be included in any review of practical working conditions. Accurate frequency analysis of these transients is difficult, especially as most were truncated. However, the durations were of the order of 25–50 ms, which suggests most energy to be at around 10 to 20 Hz. This was checked to be so in one or two cases where some frequency analysis was possible.

† A basic approach for fatigue failure is that the number of cycles to failure is inversely proportional to the stress amplitude raised to a power (s). This is referred to as the fatigue exponent here.

TABLE 2

Basic amplitude values for the data set; those events where truncation is apparent are starred **; (*Note*: *peak values between* -5 *and* $+5$ m/s^2 *discarded*)

Run	Low Pass Filtered 100 Hz r.m.s. (m/s^2)	Low Pass Filtered 100 Hz Max (m/s^2)	Low Pass Filtered 100 Hz Min (m/s^2)	*Wb* weighted r.m.s. (m/s^2)	*Wb* weighted Crest Factor	*Wb* weighted VDV (ms$^{-1·75}$)	*Wb* weighted Max (m/s^2)	*Wb* weighted Min (m/s^2)
F1	1·0	—	—	1·0	3·1	2·0	—	—
F2	1·0	—	—	1·0	4·1	2·1	—	—
B1	3·7	12·2	−8·9	1·8	5·1	4·1	5·3	−8·9
B2	2·8	8·4	−10·1	1·5	3·7	3·1	—	−5·4
B3	2·7	8·5	−5·8	1·3	2·5	2·3	—	—
B4	1·6	9·8	—	1·1	7·4	3·0	8·0	—
B5	3·0	7·3	−6·1	1·4	2·9	2·5	—	—
B6	2·4	5·8	−7·5	1·2	3·0	2·2	—	—
J1	0·9	—	—	0·6	4·0	1·2	—	—
J2	0·9	—	—	0·7	3·7	1·3	—	—
J3	3·7	9·1	−10·7	2·2	2·3	3·8	—	—
J4	3·5	8·7	−9·2	2·0	2·9	3·7	6·0	−5·3
J5	1·8	5·5	−6·6	0·9	4·3	1·8	—	—
J6	2·6	10·9	−9·5	1·4	4·1	3·0	—	−5·7
J7	1·5	—	—	1·1	3·2	2·2	—	—
J8	3·7	8·6	−13·9	2·0	3·7	4·2	7·2	−6·5
J9	1·4	—	−5·4	1·1	4·5	2·4	—	—
J10	2·4	7·4	−9·1	1·3	3·8	2·7	—	—
J11	2·3	6·6	−8·5	1·3	3·8	2·7	—	—
J12	0·7	—	—	0·5	3·7	1·1	—	—
J13	1·0	—	—	0·6	2·7	1·2	—	—
J14	3·5	8·9	−7·7	2·1	2·5	3·7	—	—
J15	2·7	9·1	−8·1	1·6	3·5	3·0	5·8	—
J16	2·9	8·3	−9·7	1·6	3·2	3·0	—	—
J17	3·1	13·2	−10·9	1·9	3·7	4·0	6·9	−6·8
J18	2·9	6·1	−10·3	1·7	3·7	3·3	6·4	−5·2
J19	2·8	10·2	−11·5	1·7	3·8	3·3	6·3	—
J20	2·8	10·3	−8·0	1·6	4·4	3·2	7·0	—
D1	3·2	6·3	−9·9	1·5	4·9	3·1	—	−7·3
D2**	2·4	6·6	−20·4	1·6	9·9	5·5	7·0	−15·6
D3	1·6	—	−16·1	1·2	10·5	4·2	5·3	−12·2
D4**	3·1	6·3	−18·9	2·0	7·2	5·9	6·9	−14·3
D5**	2·8	5·2	−18·5	1·9	8·0	5·8	—	−14·9
D6**	2·6	5·5	−17·7	1·7	8·2	5·1	—	−13·9
D7**	4·4	6·6	−18·9	2·8	5·2	7·0	7·0	−14·4
D8**	2·7	5·3	−18·3	1·8	8·2	5·5	—	−14·6
T1**	3·1	9·2	−11·3	2·2	5·0	4·8	10·9	−6·4
T2	1·4	9·0	−11·0	1·3	8·9	4·4	9·3	−11·1
T3**	3·5	12·8	−14·2	2·6	6·3	6·9	16·1	−9·7
T4**	2·2	6·0	−11·8	1·5	5·3	3·9	7·8	−8·1
T5	1·4	—	−6·8	0·9	5·2	2·2	—	—
T6**	1·8	13·6	−11·7	1·6	8·9	5·7	14·3	−12·6
T7**	2·3	9·4	−11·9	1·8	5·9	4·6	10·6	−8·0
T8**	3·6	11·6	−13·7	2·0	4·5	4·3	6·8	−9·1
T9	2·1	7·3	—	1·2	4·2	2·5	—	—
T10	2·4	7·1	−12·0	1·3	4·2	2·6	—	−5·3
T11	2·6	8·3	−7·6	1·4	3·7	2·6	—	—
M1	2·3	10·4	−8·8	1·8	5·3	3·9	9·7	—
M2	2·2	8·6	−7·5	1·7	4·1	3·4	6·8	−5·3

(*Continued on following page*)

TABLE 2—*continued*

	Low Pass Filtered 100 Hz			*Wb* weighted				
Run	r.m.s. (m/s²)	Max (m/s²)	Min (m/s²)	r.m.s. (m/s²)	Crest Factor	VDV (ms⁻¹·⁷⁵)	Max (m/s²)	Min (m/s²)
M3	1·1	—	—	0·9	3·9	1·9	—	—
M4	1·3	6·0	−8·7	1·0	4·9	2·2	—	—
M5	1·6	—	−7·7	1·4	4·8	3·0	—	−6·6
M6	2·9	—	−5·5	2·4	1·8	3·9	—	—
M7	2·4	—	—	2·0	1·6	3·1	—	—
M8	0·8	—	—	0·6	4·4	1·4	—	—
M9	1·0	7·1	—	0·9	6·8	2·2	5·8	—
T12	1·7	8·5	−8·8	1·3	6·0	3·4	6·4	−7·7
T13	1·4	—	−5·3	1·2	4·5	2·7	5·6	—
T14	0·7	—	—	0·5	3·6	1·0	—	—
T15	1·7	6·4	−6·4	1·2	4·8	2·8	—	−6·0
T16	1·8	6·7	−9·1	1·3	5·9	3·2	5·5	−7·8
T17	1·0	—	−5·8	0·9	5·3	2·4	—	—
T18	3·5	15·5	−21·1	2·6	5·7	6·6	10·5	−14·6
T19	6·8	31·0	−37·6	4·4	4·4	9·9	16·3	−19·2
T20	1·2	—	−6·7	1·0	4·9	2·6	—	—
T21	2·6	10·6	−14·2	2·1	6·1	5·4	7·9	−12·9
T22	8·3	41·2	−30·2	5·8	4·8	13·4	28·1	−20·0
T23	2·9	12·2	−18·1	2·1	6·9	6·0	12·8	−14·2
T24	2·1	9·2	−8·7	1·8	4·7	4·3	8·3	−7·3
T25	1·2	5·2	—	1·1	4·6	2·5	—	—
Mean	**2·5**	**10·0**	**−11·9**	**1·6**	**4·8**	**3·7**	**9·1**	**−10·2**
Max	**8·3**	**41·2**	**−5·3**	**5·8**	**10·5**	**13·4**	**28·1**	**−5·2**
Min	**0·7**	**—**	**−37·6**	**0·5**	**1·6**	**1·0**	**—**	**−20·0**

Some researchers have noticed a correlation between r.m.s. and *VDV* and this instigated further exploration. Analysis showed a correlation coefficient r^2 of 0·89 ($p < 0{\cdot}01$) in the relationship between the raw (i.e. low pass) r.m.s. and the *Wb* weighted r.m.s. over the dataset in Table 2. This indicates that, for the range of high acceleration events investigated, the raw r.m.s. might be used to predict the *Wb* weighted r.m.s. When the *Wb* weighted r.m.s. and the *VDV* values were compared, the correlation coefficient was 0·86 ($p < 0{\cdot}01$). The two are combined in Figure 1 to show the relationship between the raw r.m.s. and the *VDV*. Although the correlation coefficient is reduced to 0·70 ($p < 0{\cdot}01$), it is still high. For a particular vehicle working under a variety of conditions (Harbour Study, Subject 1, Repetition 2—T12–T25) the correlation coefficient was 0·97 ($p < 0{\cdot}01$).

4. CONCLUSIONS

The literature shows that a variety of high acceleration events are met in practice, the weighted r.m.s. levels over periods of a few seconds can be up to 6 or 7 m/s² with weighted instantaneous peak values of 20 m/s² and more. A small data set investigated in detail confirms this with *Wb* weighted r.m.s. values over 4 s of up to 5·8 m/s², unweighted peak values of at least 20 m/s² (in some cases 40 m/s²), and *Wb* weighted peak values of up to 15 m/s² and sometimes nearly 30 m/s². Daily *VDV*s of the order of 20 $ms^{-1{\cdot}75}$ are quite probable.

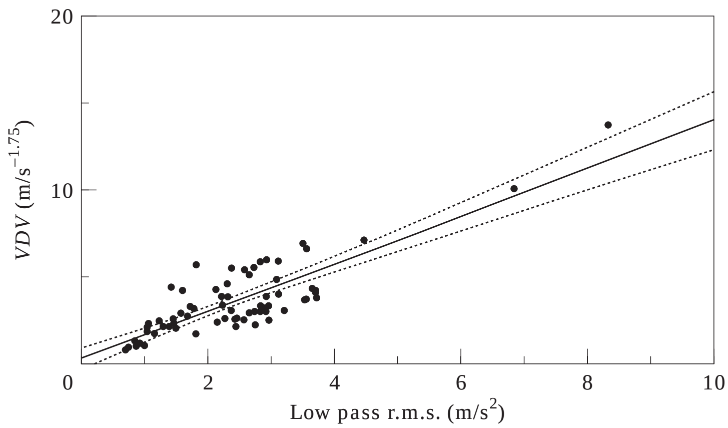

Figure 1. Relationship between low pass r.m.s. and Vibration Dose Value $r^2 = 0{\cdot}70$ ($p < 0{\cdot}01$). ——, Regression line; · · · · ·, 95% confidence interval.

Although no fully acceptable epidemiological data are available, most investigations indicate that exposure to high levels of vibration and shock may increase the risk of back problems.

Biodynamic modelling coupled with dynamic *in vivo* measurements indicates that the compressive forces in the lumbar spine arising from typical exposures can be very high and may be sufficient to lead to damage, especially if tissue fatigue processes occur. The latter indicate that fourth power methods are preferable for prediction of health risk and, indeed, that even higher powers may be more appropriate. Long term weighted r.m.s. acceleration probably underestimates the health risk.

The unweighted r.m.s. value of high acceleration events gives some information on the *Wb* weighted value, although its general use as a predictor of the *VDV* may be limited. However, when confined to a particular type of vehicle, and especially the same vehicle, the unweighted r.m.s. value of high acceleration events may be a useful predictor of both the *Wb* weighted r.m.s. and the *VDV*. This may be the reason why some investigations of discomfort using field exposure have found little difference between r.m.s. and *VDV* as predictors of discomfort.

More research into the effects on health is needed but comfort and epidemiological investigations have some severe practical drawbacks as well as advantages. Biodynamic and modelling investigations have potential at the current state of knowledge and are needed to engender plausible hypotheses on the effects of high acceleration events on health before consideration of further epidemiological research and generation of dose–response relationships for standards and legislation.

ACKNOWLEDGMENTS

The author acknowledges the ready willingness to provide data by Johan Hendrikse, Bengt-Olov Wikström and the Noise and Vibration Group of HSE, Buxton, and the important contribution of the experts who completed the questionnaire.

The investigation was supported by the Health and Safety Executive and this paper summarizes HSE Contract Research Report 134/1997 [38].

REFERENCES

1. BS 6841: 1987 *British Standards Institute*. British Standard Guide to: Measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock.
2. B.-O. Wikström, A. Kjellberg and M. Dallner 1991 *International Journal of Industrial Ergonomics* **7**, 41–52. Whole-body vibration: a comparison of different methods for the evaluation of mechanical shocks.
3. C. H. Lewis 1985 *UK Informal Meeting on Human Response to Vibration*, *September*, *Derby*. Frequency weighting procedures for the evaluation of human response to vibration.
4. H. Seidel, R. Blüthner, B. Hinz and M. Schust 1995 *Belastung der Lendenwirbelsaule durch stosshaltige Ganzkörperschwingungen*. Forshung Fb01 HK061 (English Edition Fb 777) Berlin: Bundesanstalt für Arbeitsmedizin.
5. O. Bennerhult and B. Axefors 1984 *TR* 5.349.01. *IFM Akustikbryan AB*. A compilation of transient whole-body vibrations in seated positions in the occupational environment.
6. N. Monsees, R. T. Whyte and J. A. Lines 1989 *Report* DN 1511. *AFRC Institute of Engineering Research*. Relationship between subjective assessments and objective measurements of tractor ride vibration.
7. ISO 2631 1985 *Mechanical Vibration and Shock—guide to the evaluation of human exposure to whole-body vibration*. International Standards Organisation.
8. G. Lovat, P. Mistrot, P. Donati, P. Boulanger and B. Schuler 1995 *UK Informal Group Meeting on Human Response to Vibration*, *Silsoe*, *September*. Modelling of a lift truck and its tyres to predict vibration emission values at the driver workplace.
9. J. Village, J. B. Morrison and D. K. N. Leong 1989 *Ergonomics* **32**, 1167–1184. Whole-body vibration in underground load-haul-dump vehicles.
10. J. Cross and M. Walters 1994 *Safety Science* **17**, 269–274. Vibration and jarring as a cause of back injury in the NSW coal mining industry.
11. H. Anttonen and J. Niskanen 1994 *Arctic Medical Research* **53** (Suppl 3), 24–28. Whole body vibration and the snowmobile.
12. X. Wu, M. J. Griffin and C. Lewis 1995 *ISVR Tech Rept*. 255, *University of Southampton*. The vibration transmission of lift truck suspension seats.
13. X. Wu 1994 *Proceedings of the UK Informal Group Meeting on Human Response to Vibration*. *Alverstoke*, *Sept*. A method of testing suspension seats for end-stop impacts.
14. R. Rosegger and S. Rosegger 1960 *Journal of Agricultural Engineering Research* **5**, 241–275. Health effects of tractor driving.
15. J. D. G. Troup 1988 *Clinical Biomechanics* **3**, 227–231. Clinical effects of shock and vibration on the spine.
16. P. M. Bongers and H. C. Boshuizen 1990 *Ph.D. Thesis*. *University of Amsterdam*. Back disorders and whole-body vibration at work.
17. B.-O. Wikström, A. Kjellberg and U. Landström 1994 *International Journal of Industrial Ergonomics* **14**, 273–292. Health effects of long-term occupational exposure to whole-body vibration: a review.
18. A. Kjellberg, B.-O. Wikström and U. Landström 1994 *Arbete och Halsa* 1994: 41. *Arbets Miljo Institutet pp*. 80. Injuries and other adverse effects of occupational exposure to whole-body vibration. A review for criteria documentation.
19. M. J. Griffin and E. M. Whitham 1980 *Journal of the Acoustical Society of America* **68**, 1277–1284. Discomfort produced by impulsive whole-body vibration.
20. M. J. Griffin 1990 *Handbook of Human Vibration*. London. Academic Press, 1990.
21. A. Kjellberg and B.-O. Wikström 1985 *Journal of Sound and Vibration* **99**, 415–424. Subjective reactions to whole-body vibration of short duration.
22. A. Kjellberg and B.-O. Wikström 1985 *Ergonomics* **28**, 535–544. Whole-body vibration: exposure time and acute effects—a review.
23. J. C. Hoddinott 1986 *Proceedings of the UK Informal Group Meeting on Human Response to Vibration*. Investigation of the effect of duration on alternative methods of assessing human response to impulsive motion.
24. P. Donati, P. Mistrot, J. P. Galmiche, F. Broyde, D. Lescail, D. Andoin and D. Florentin 1988 *Joint French-British Informal Group Meeting on Human Response to Vibration*, *Vandoeuvre*, *September*. Vibration discomfort experienced by a driver when a lorry runs over obstacles (Preliminary experiment).
25. J. Malchaire and A. Piette 1991 *Annals of Occupational Hygiene* **35**, 613–618. Relation between vibration levels and perceptive and appreciative judgements of overhead crane operators.

26. A. V. Vukusic, J. B. Morrison, M. J. N. Springer, D. G. Robinson and B. J. Cameron 1996 *Proceedings of the UK Informal Group Meeting on Human Response to Vibration. MIRA, Nuneaton, Sept*. Comparison of subjective responses to mechanical shocks with predictive models of human response.
27. P. R. Payne, J. W. Brinkley and J. Sandover 1994 *UK Informal Group Meeting on Human Response to Vibration. Alverstoke, September*. Shock discomfort—a comparison of approaches.
28. J. W. Brinkley, L. J. Specker and S. E. Mosher 1989 Development of acceleration exposure limits for advanced escape systems. In *Conference Proceedings No*. 472, Implications of Advanced Technologies for Air and Spacecraft Escape, Paris: AGARD, 1989: 1-1–1-14.
29. K. Spång and P. W. Arnberg 1990 *Report H*-10946-*A. DNV Ingemansson AB, Gothenburg*. A laboratory study of the influence of transient vibrations on perception.
30. P. R. Payne 1996 *Payne Associates No*: 377-12. A ride comfort study.
31. H. Dupuis (Editor) 1991 *Belastung und Beanspruchung durch stosshaltige Schwingungen*. Sankt Augustin: Hauptverbandes der gewerblichen Berufsgenossenschaften.
32. H. Dupuis, E. Hartung and M. Haverkamp 1991 *International Archives Occupational Environmental Health* **63**, 261–265. Acute effects of transient vertical whole-body vibration.
33. R. Bluthner, B. Hinz, G. Menzel and H. Seidel 1993 *International Journal of Industrial Ergonomics* **12**, 49–59. Back muscle response to transient whole-body vibration.
34. B. Hinz, R. Bluthner, G. Menzel and H. Seidel 1994 *Clinical Biomechanics* **9**, 263–271. Estimation of disc compression during transient whole-body vibration.
35. J. Sandover 1981 *DHS Report* 402, *May Department of Human Sciences, Loughborough University of Technology*. Vibration, posture and low-back disorders of professional drivers.
36. D. G. Robinson, J. B. Morrison and B. J. Cameron 1995 *Proceedings of the UK Informal Group Meeting on Human response to Vibration. Silsoe, September*. The contribution of muscle response and internal pressure to estimation of spinal compression from mechanical shocks using a simple biomechanical model.
37. J. Sandover 1983 *Spine* **8**, 652–658. Dynamic loading as a possible source of low-back disorders.
38. J. Sandover 1997 *Contract Research Report* 134/1997, *Health and Safety Executive*. High acceleration events in industrial exposure to whole-body vibration.
39. R. Prickartz 1995 *Messung und Auswertung von Schwingungsverläufen an Sitzarbeitsplätzen auf mobilen Arbeitsgeraten*. In Belastung und Beanspruchung durch stosshaltige Ganzkörperschwingungen (Schlussbericht) (E. Hartung and H. Dupuis, editors). Berlin: Bundesanstalt für Arbeitsmedizin, 15–40.
40. R. Prickartz and G. Pohle 1991 *Teilprojekt*: *Schwingungsbelastung auf Erdbaumaschinen bei Sitzhaltung in Feldversuchen*. In Belastung und Beanspruchung durch stosshaltige Schwingungen (H. Dupuis, editor). Sankt Augustin: HVBG, 21–37.
41. G. Roddan, T. Brammer, J. Village, J. Morrison, B. Remedios and D. Brown 1995 *Contract Report CR* 952. US Army Aeromedical Research Laboratory. Development of a Standard for the health hazard assessment of mechanical shock and repeated impact in army vehicles: phase 2.
42. J. A. Lines, M. A. Stiles and R. T. Whyte 1994 *Silsoe Research Institute Report*. Whole body vibration during tractor driving.
43. E. Hartung, H. Dupuis, R. Prickart, L. Trier, H. Schnauber, S. Becher, K. Weber, A. Montag, G. Jansen, U. Berg, S. Reidel, H. Seidel, R. Blüthner, B. Hinz and M. Schuct 1995 *Belastung und Beanspruchung durch stosshaltige Ganzkorperschwingungen*. Berlin: Bundesanstalt fur Arbeitsmedizin.
44. U. Berg 1994 *Johannes-Gutenberg-Universitat, Mainz*. Akute Wirkungen bei sitzender Körperhaltung (Laborstudie).
45. J. Village, J. Morrison, D. Robinson, G. Roddan, J. Rylands, B. Cameron, B. Remedios, D. Brown and B. P. Butler 1995 *Contract Reports CR* 951 *and* 953. *US Army Aeromedical Research Laboratory*. Development of a Standard for the health hazard assessment of mechanical shock and repeated impact: Phases 1 and 3.
46. B.-O. Wikström 1994 *Ph.D. Dissertation. Royal Inst. Technology, Stockholm. Arbete och halsa* 1994: 21. Evaluation of technical methods as predictors of discomfort from whole-body vibration in work vehicles.
47. F. Guillon, G. Somenzi, F. Pignolet, C. Tarriere and J. Proteau 1989 *Archives des malanes Professionelles de medecine du Travail et de Securite Sociale* **50**, 288–289. Utilisation de la mesure du pression intradiscale pour la conception des sieges de vehicules automobiles.
48. A. El-Khatib, F. Guillon, G. Somenzi, F. Pignület-grall, P. Laporte, cl. Tarriere and T. Proteau 1990 *Arch. Mal. Prof*. **51**, 595–597. Etude du comportement dynamique de plusiers etages lombaires au cours d'expositions vibratoires de basses frequences.

49. A. VUKUSIC 1995 *MSc Thesis. School of Kinesiology, Simon Fraser Univ. BC*. Subjective and associated objective response to repeated mechanical shocks in seated humans.
50. J. SANDOVER and H. DUPUIS 1987 *Ergonomics* **30**, 975–985. A reanalysis of spinal motion during vibration.
51. M. H. POPE, D. G. WILDER, L. JORNEUS, H. BROMAN, M. SVENSSON and G. ANDERSSON 1987 *Journal of Biomechanical Engineering* **109**, 279–284. The response of the seated human to sinusoidal vibration and impact.
52. B. CAMERON, J. MORRISON, D. ROBINSON, A. VUKUSIC, S. MARTIN, G. RODDAN and J. P. ALBANO 1996 *Contract Report CR* 961, *US Army Aeromedical Research Laboratory*. Development of a standard for the health hazard assessment of mechanical shock and repeated impact in army vehicles: Phase 4.
53. H. SEIDEL 1993 *American Journal of Industrial Medicine* **23**, 589–604. Selected health risks caused by long-term whole body vibration.
54. H. SEIDEL and R. HEIDE 1986 *International Archives of Occupational and Environmental Health* **58**, 1–26 Long term effects of whole-body vibration: a critical survey of the literature.
55. P. BRINCKMANN, M. BIGGEMANN and D. HILWEG 1988 *Clinical Biomechanics* suppl. 1. Fatigue fracture of human lumbar vertebrae.
56. P. BRINCKMANN, M. BIGGEMANN and D. HILWEG 1989 *Clinical Biomechanics* **4** (Suppl. 2) S1. Prediction of compressive strength of human lumbar vertebrae.
57. F. BROYDE, P. DONATI and J. P. GALMICHE 1989 *Proceedings of the UK Informal Group Meeting on Human Response to Vibration. Silsoe*. Assessing the discomfort of whole-body vibration containing transients: rms or rmq method?
58. M. L. BURNS, I. KALEPS and L. E. KAZARIAN 1984 *Journal of Biomechanics* **17**, 113–130. Analysis of compressive creep behavior of the vertebral unit subjected to a uniform axial loading using exact parametric solution equations of Kelvin-solid models—part I: human intervertebral joints.
59. B. J. CAMERON, D. G. ROBINSON, J. B. MORRISON and J. P. ALBANO 1995 *Proceedings of the UK Informal Group Meeting on Human Response to Vibration. Silsoe*. Biomechanical and emg responses to extended exposure to mechanical shocks.
60. P. M. DONATI, R. T. WHYTE and R. M. STAYNER 1987 *DN* 1409. *ARFC Institute of Engineering Research*. Determination of the effect of time upon subjective assessment of tractor seat aspects.
61. D. FLENGHI 1995 *Ph.D. Thesis INRS NS*0127. *University of Nancy*. Capacities fonctionnelles lombaires, lombalgies et contraintes professionnelles.
62. M. J. GRIFFIN 1984 *UK Informal Group Meeting on Human Response to Vibration. Edinburgh*. Vibration dose values for whole-body vibration: some examples.
63. M. J. GRIFFIN 1985 *Proceedings of the International Meeting on Criteria of Evaluation of the Effects of Whole-body Vibration on Man, PCIAOH, pp*. 30–41. A single number dose procedure for whole-body vibration and repeated shock.
64. M. J. GRIFFIN 1986 *SAE Paper* 860047. *SAE Int. Cong. & Exposition, Detroit*. Evaluation of vibration with respect to human response.
65. T. H. HANSSON, T. S. KELLER and D. M. SPENGLER 1987 *Journal Orthopaedic Research* **5,S**, 479–487. Mechanical behavior of the human lumbar spine. II. Fatigue strength during dynamic compressive loading.
66. R. HEIDE and H. SEIDEL 1978 *Zeitschnift für die gesamte Hygiene und ihre Grenzgebiete* **3**, 153–159. Folgen langzeitiger beruflicher Ganzkorpervibrations exposition.
67. H. V. C. HOWARTH and M. J. GRIFFIN 1988 *Journal of Sound and Vibration* **120**, 413–420. Human response to simulated intermiottent railway-induced building vibration.
68. H. V. C. HOWARTH and M. J. GRIFFIN 1991 *Journal of Sound and Vibration* **147**, 395–408. Subjective reaction to vertical mechanical shocks of various waveforms.
69. I. KALEPS, L. E. KAZARIAN and M. L. BURNS 1984 *Journal of Biomechanics* **17**, 131–136. Analysis of compressive creep behavior of the vertebral unit subject to a uniform axial loading using exact parametric solution equations of Kelvin-solid models—Part II: Rhesus monkey intervertebral joints.
70. P. MISTROT, P. DONATI, J. P. GALMICHE, F. BROYDE, D. LESCAIL, D. AUDOIN and D. FLORENTIN 1990 *Report INRS MAV-NT-*108/*PDi*. Inconfort vibratoire au poste de conduite d'un camion franchissant des obstacles. Experience A.
71. P. MISTROT, P. DONATI, J. P. GALMICHE, F. BROYDE, D. LESCAIL, D. AUDOIN and D. FLORENTIN 1990 *Report INRS MAV-NT-*126/*PDi*. Inconfort vibratoire au poste de conduite d'un camion franchissant des obstacles. Experience B.

72. J. B. Morrison, D. G. Robinson, G. Roddan, J. J. Nicol and B. P. Butler 1995 *Proceedings of the UK Informal Group Meeting on Human Response to Vibration. Silsoe*. Analysis of skin transfer function in response to mechanical shocks.
73. J. Nicol, J. Morrison, G. Roddan and A. Rawicz 1997 *Heavy Vehicle Systems, Special Series, International Journal of Vehicle Design* **4,** 145–165. Modelling the dynamic response of the human spine to shock and vibration using a recurrent neural network.
74. C. D. Robertson and M. J. Griffin 1989 *Technical Report* 184, *ISVR, Southampton University*. Laboratory studies of the electromyographic response to whole-body vibration.
75. C. M. Ruffell and M. J. Griffin 1995 *Journal of the Acoustical Society of America* **98**, 2157–2164. Effect of 1-Hz and 2-Hz transient vertical vibration on discomfort.
76. L. R. Schanhals and R. L. Pershing 1973 *SAE Transaction* **730770**, 1–12. Performance testing and criteria for snowmobile seat cushions.
77. R. T. Whyte and J. A. Lines 1987 *Proceedings of the UK Informal Group Meeting on Human Response to Vibration. RMCS Shrivenhan*. Subjective assessment and objective measurement of the ride vibration of a suspended cab tractor.
78. B.-O. Wikström, A. Kjellberg and M. Orelius 1987 *Proceedings of the UK Informal Group Meeting on Human Response to Vibration. RMCS Shrivenham*. Whole-body vibration: a test of different methods for the assessment of shocks.
79. D. G. Wilder and M. H. Pope 1996 *Clinical Biomechanics* **11**, 61–73. Epidemiological and aetiological aspects of low back pain in vibration environments—an update.
80. X. Wu and M. J. Griffin 1995 *Proceedings of the UK Informal Group Meeting on Human Response to Vibration. Silsoe*. Simulation study of factors influencing the severity of suspension seat end-stop impacts.
81. C. M. Zahner, M. S. Kaminaka, J. R. Duncan and E. L. Wegscheid 1983 *Proceedings of ASAE* 83-1629. Operator perception of transient motions in an off-road environment.

APPENDIX

QUESTIONNAIRE RESPONSES

The responses are given in the same form as the questionnaire. The respondent's comments have been summarized.

Basic information

1a Compared with ordinary vibration, do you consider that high acceleration events have a disproportionate effect on health? **Yes 15 No 0 Not sure 1**

1b If yes, is the difference sufficient to be of practical importance? **Yes 12 No 0 Not sure 4**

The reasons given for these opinions included:

Anecdotal evidence that drivers prefer high continuous vibration levels to vibration including shocks and that seats are often set (by drivers and manufacturers) for the avoidance of end-stop impacts in preference to vibration attenuation and that drivers returning to work with back problems find high acceleration events more distressing than basic vehicle motion.

Injury claims where shock loads feature in the plaintiff's history.

In vitro spinal fatigue investigations (fatigue theory indicates that shocks will have a disproportionate effect).

The knowledge that severe impacts can result in direct damage.

Jobs involving high acceleration events

2 The jobs listed below probably involve exposure to high acceleration events. Please indicate your opinion of the degree of health risk, taking into account both severity and

number of high acceleration events (*use the first two as reference points-not necessarily the extremes*). I am keen to find out about any other jobs – please add other jobs that you consider should be included.

	Expert opinion of health risk				
Job/activity	**None**	**Low**	**Moderat**	**High**	**Severe**
Driving a car daily over 3 km/2 mls of pot-holed (25 mm/1 in) roads	*3*	*2*	*2*		
Dropping 50 mm/2 ins onto a rigid seat regularly every 30 mins	*1*	*3*		*2*	*1*
Forestry vehicle driving			4	3	1
Fork lift truck driving		3	5	1	
Earth moving vehicle driving (esp. quarry work)			2	7	
Agricultural tractor driving		1	7	2	
Military vehicle driving		1	3	1	3
Driving high speed boats		1*		3	3
Driving regularly over traffic calming humps (usually bus driving)	1	3	2	2	
Off-road vehicle driving			2	5	
Driving with malfunctioning anti-vibration seat (end-stop impacts)			3	3	2
***Please insert your additions below*:**					
Pallet truck with operator			*1*		
Excavator in mine on frozen soil			*1*		
Snow tractor				*1*	
Helicopter	*1*				
Helicopter in turbulence				*1*	
Harbour container truck				*1*	
Test driving on bad roads					*1*
Fishing boats (USA??)			*1*		

*Due to low exposure time

Three respondents felt unable or unqualified to comment.

Your experience of jobs involving exposure to high acceleration events

3 Do you have information on the type (e.g. single acceleration peak or decaying sinewave) and level of high acceleration events met in practice? (If you have information, no matter how limited, please list here or append)

The responses are listed below:

EU project to be published 1997 will have extensive data on mobile machinery travelling over various types of ground condition.

Bennerhult and Axefors [5]—extensive collection of transients from a variety of machines.

Earth moving vehicles – Prickartz [39], Prickartz and Pohle [40], Military vehicles – Roddan *et al*. [41], Mining, Forestry.

4 Do you have information on *patterns of exposure* to high acceleration events for particular jobs? e.g. number of events per working day, regularity etc. (If you have information, no matter how limited, please list here or append)

Responses indicated that only limited information was available.

5 Do you have any recorded acceleration data that you would be prepared to share?

Several respondents had information on recorded data. The vehicle types are listed below:

Fork lift truck, pallet truck, shuttles cars used in mining (unsprung vehicles with sprung seat), mining equipment – dozer, rock drill, rock breaker, Swedish data collected from a variety of machines between 1975 and 1983—Bennerhult and Axefors

[3], EU project (see above), a full data-set on agricultural tractors working under normal conditions—Lines *et al*. [42].

Research into high acceleration events

6 Can you recommend any published information on the topic of high acceleration events, repeated impacts etc.?

This resulted in a small number of the major published reports and papers. They were:

Dupuis [31], Hartung *et al*. [43], Berg [44], Village *et al*. [45], Griffin [20], Spång and Arnberg [29], Wikstrom [46], Seidel *et al*. [4] and the papers by Guillon and colleagues – Guillon *et al*. [47], El-Khatib *et al*. [48].

7a Do you consider that more research is needed? **Yes 17 No 0 Not sure 0**

7b If yes, what are the main gaps in our knowledge?

Long term effects of repeated shocks, impacts and jarring on the spine.

Information on damage mechanisms.

Comparisons between exposure to continuous vibration and to high acceleration events.

Assessment methods.

The relationship between evaluation methods and psychological, physiological, and biochemical effects.

General biodynamics of the body exposed to high acceleration events and biomechanical estimates of disc forces.

Data on vertebral characteristics and strength – especially as a function of age and type and time-history of loading.

Information on the relationship between external accelerations and spinal forces. What is the extent of any non-linearities with increased loading?

Information on patterns and characteristics of high acceleration events met in practice.

Technical solutions, e.g. reduction in end-stop impacts, non-linear damping in suspension seats, suspended cab floor, solid tyres with less damping.

The effects of the seat cushion and the backrest on vibration transmission.

Epidemiological studies centered on high acceleration events and chronic disorders. Need to be large, longitudinal, over a long period and therefore costly.

Centralised data storage, standardisation of input and biological measures.

8a Do you believe that *discomfort studies* are practically useful in developing criteria for the effects of occupational vibration and high acceleration events on health? **Yes 10 No 4 Not sure 3**

8b What are your reasons?

Cannot dismiss easy to obtain subjective data when other data is so sparse.

They can provide a rough guideline and can be used to make sure that evaluation methods are plausible.

Practical way of getting response as an integrated measure of several effects.

May identify tissue stresses missed by other methods.

Subjective estimates of acute pain at high acceleration event levels may be useful.

Discomfort may relate to feelings at the head rather than the spine and associated muscles.

Only useful if used with high amplitudes which may not then be safe.

8c Can you supply supporting evidence?

Vukusic [49] has shown that subjective assessment of shock severity correlates with magnitude of shock transmission through the spine.

9a Do you believe that *biodynamic & physiological studies* are practically useful in developing criteria for the effects of occupational vibration and high acceleration events on health? **Yes 14 No 1 Not sure 2**

9b What are your reasons?

Apart from emg, physiological studies not very useful.

Physiological data can give objective information on state of individual during and after exposure.

A combination of biodynamics and emg measurements is probably productive.

Dynamic models vital to understand response of any system, needed to understand damage mechanisms and what parameters should be measured.

Allow predictions of internal loads from external measures – only useful if reliable and can be compared with strength data.

Needed to obtain relationships used for epidemiological studies.

Single biodynamic measures in isolation are of little value as human response is an integration of several biodynamic and physiological measures.

9c Can you supply supporting evidence? (please list below or attach)

Hinz *et al*. [34], Seidel *et al*. [4], Sandover and Dupuis [50], Pope *et al*. [51], Cameron *et al*. [52], Dupuis [31], Hartung *et al*. [43], Berg [44].

10a Do you believe that *epidemiological studies* are practically useful in developing criteria for the effects of occupational vibration and high acceleration events on health? **Yes 8 No 4 Not sure 5**

10b What are your reasons?

Epidemiological investigations are vital. However, we first need to know relevant vibration and shock measurement methods. Good longitudinal (or even well designed retrospective) investigation would help develop valid exposure criteria.

Current studies only tell us that there is a relationship between back problems and exposure to shock and vibration. However, even this is useful to determine which occupations need consideration.

Not realistic to expect reliable, long term measures of exposure taking into account other variables such as posture for studies with large numbers of subjects. One alternative would be to study a small, highly exposed group in detail using sophisticated methods of early detection of damage.

Quantification of exposure is a problem. Especially if the stimulus of interest is a rare event.

Only useful if we have reliable exposure measures AND reliable damage measures. Postural influences and other causes of back disorders give problems for epidemiological investigations.

10c Can you supply supporting evidence? (please list below or attach)

Kjellberg, Wikstrom and Lundstrom [18], Seidel and Heide [53], Seidel [54].

Your research

11 Have you investigated high acceleration events in the laboratory or in the field?

This revealed the main research groups: Dupuis *et al*., Griffin *et al*., Donati *et al*., Spång *et al*., Wilkström *et al*., DRA Farnborough, Pope *et al*., Seidel *et al*. and Morrison *et al*.

Other investigations included measurements during mining operations, earth moving vehicles, forestry vehicles, forklift trucks, military vehicles, high speed boats, off-road driving.

12 Are you planning any such investigations?

The topics below cover the plans listed.

Psychological and physiological responses to shock and impulsive vibration.
Improving end-stops in anti-vibration seats.
Analysis of field data with high acceleration events.
Improved modelling of human responses to high acceleration events.
Relationship between high acceleration events and subjective magnitude estimates for whole-body and hand-arm vibration.
Epidemiological investigations.
Gender variables.

13 Please list any published or unpublished information that you have contributed to.

The references supplied are included in the attached list of references (papers [55] on are not referred to elsewhere in this paper).