Performance of ISO2631 and BS6841 Comfort Criteria for Evaluating Automobile Road Vibrations

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Abstract

This paper describes an experimental investigation of human perception of transient whole-body vibration by seated subjects. Thirty participants (25 male and 5 female) were asked to sit on a rigid seat and were exposed to combinations of 6 acceleration signals taken from experimental measurements made on a European B segment automobile. Longitudinal seat guide acceleration signals from a pave' surface, a comfort test track and a motorway segment were used. The data was acquired at a sampling rate of 250 Hz and was bandpass filtered to be in the range form 0.5 to 50 Hz. The three road signals were rescaled to two reference r.m.s amplitudes of 0.6 m/s2 and 1.2 m/s2, thus providing a base set of six test signals. The 6 base signals were used to form 30 paired-comparison test signals consisting of two 15 second bursts of road data separated by a 2 second gap. The subjective information obtained from the participants was converted to a perception scale by means of Comparative Judgment Theory, and compared to the r.m.s. and the VDV values calculated for the 15 second road data bursts in both their unweighted and their ISO 2631 and BS 6841 frequency weighted forms. The frequency weighted measures, both r.m.s. and VDV, were found to provide a better estimate of human vibrational comfort than their unweighted equivalents, with the differences being most pronounced in the case of VDV values. While the data collected to date is limited, these preliminary results also suggest that the ISO 2631 and BS 6841 evaluation procedures overestimate the subjective discomfort at low excitation levels.

Introduction

When developing automobile seats, human health [14,18,20,26] and comfort [7,12] are fundamental design considerations. Numerous experimental test methods for evaluating seat vibrational comfort have been developed over the years [10,19,25,27-28]. Some seat test procedures involve subjective testing, in which opinions are expressed by the test subjects by means of questionnaires or by means of direct magnitude estimation techniques. Many methods, however, simply measure by means of accelerometers the vibrations transmitted to the human occupant at the person/seat interfaces and determine a comfort rating by means of the frequency weighting filters defined in standards such as ISO 2631 and BS 6841 [12]. Once the human perception filters have been applied to the acceleration signals, the seat is judged based on the values of the global statistics. Global signal statistics used to summarise the acceleration time histories include the root-mean-square (r..m.s.) value defined as

$$r.m.s. \;=\; \left[\frac{1}{T} \int_0^T a^2(t)\,dt \right]^{\frac{1}{2}}$$

which provides an indication of the global energy content of the signal. Fourth power methods have also been shown to correlate well with human subjective response and are in widespread use. Fourth power methods use the root-mean-quad (r.m.q.) and the vibration dose value (VDV) which are defined as

$$r.m.q. \quad = \quad \left[\frac{1}{T} \int_0^T a^4(t)\,dt \right]^{\frac{1}{4}}$$

and

$$VDV \quad = \quad \left[\int_0^T a^4(t)\,dt \right]^{\frac{1}{4}}$$

where the r.m.q. is defined in a similar fashion to the r.m.s., simply changing the power to reflect an increased human sensitivity to high amplitude shock events. The VDV is the dose form of the r.m.q., thus the metric is a cumulative measure of the 4th power exposure over time. Another commonly used metric of seat vibration isolation performance is the Seat Effective Amplitude Transmissibility (S.E.A.T.) index defined as

$$S.E.A.T.[\%] \quad = \quad 100 \sqrt{\frac{\int G_{ss}(f)\,W^2(f)\,df}{\int G_{ff}(f)\,W^2(f)\,df}}$$

where f refers to the frequency in question, G_{ss} is the acceleration power spectral density measured at the seat pad, G_{ff} is the acceleration power spectral density measured on the floor and W is the human perceived disturbance weighting for the vibration axis in question. The S.E.A.T. index provides, for each measurement channel, a single scalar number which quantifies the isolation performance of the seat.

Industrial seat testing methods usually rely on one or more of the above methods, which in turn are normally applied in conjunction with the frequency weighting filters from either International Standards Organisation ISO 2631 or British Standards Organisation BS 6841. The frequency weighting filters of ISO 2631 and BS 6841 were developed over a number of years from experimental human testing. An extensive literature search performed as part of the activities of *Brite-Euram project BE-4186 SCOOP* [5] located a total of 42 references to tests which either provided the basis for, or validated, the frequency weightings given in the current ISO and British Standards. Of the 42 studies, 27 were carried out using sinusoidal excitation, 4 with random excitation, 3 with pseudo-random excitation, 2 were based on transient signals and 6 were performed using road signals measured in vehicles. The frequency weightings have been developed and validated using mostly stationary harmonic excitation. The Sheffield University activities of workpackage 3 of *Brite-Euram project BE-4186 SCOOP* involved investigating the limitations of the standard frequency weighting filters and investigating human response to impulsive excitation. This paper describes an activity which investigated the correlation between the frequency weighted r.m.s. and VDV values, and the subjective responses of a panel of human participants. While this paper focuses mainly on the experimental facility and the test protocol used, preliminary test results are also reported.

Test Facility

A for-aft slider bench was constructed in the Human Dynamics Laboratory at Sheffield University for the purpose of human whole-body-vibration testing. The complete test rig, including controllers and data acquisition system is shown in the photograph of Figure 1 and in the schematic layout diagram of Figure 2. The bench is driven by a Zonic 1100 series electrohydraulic shaker unit. The unit consists of a hydraulic supply, servovalve, shaker piston

(+/-1 inch stroke), LVDT displacement transducer and PD controller. The shaker unit can vibrate the bench and human occupant to frequencies in excess of 300 Hz. The first resonance frequency of the bench structure (bearings, aluminum frame and seat) is in the neighborhood of 90 Hz.

Figure 1)   For-aft direction whole-body-vibration test rig.
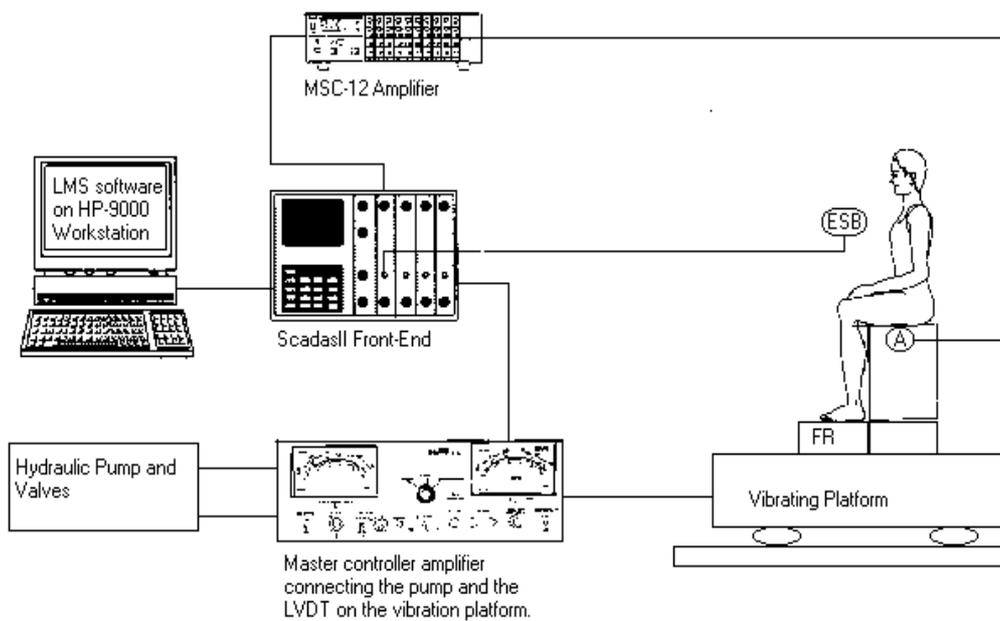

Figure 2)   Experimental layout

A rigid seat frame was used to simplify the task of controlling the sitting posture and a rigid seat surface was used to eliminate any possible effects due to seating system compliance. In order to fit UK nationals from a 5th

percentile female to a 95th percentile man, the sitting height need to be adjustable at least over the range from 351.8 to 439.2 mm [22-23]. The rigid seat, which mounts on top of the vibration platform, was therefore designed to have a height of 575 mm above the platform surface. For smaller subjects, the sitting height is reduced by means of wooden footrest plates (labeled FR in fig.2) which provide a minimum sitting height of 340 mm.

An LVDT sensor forms part of the shaker head and was used internally by the ZONIC master controller. Test measurements were made by means of an ENTRAN EGAS3–CM–25 triaxial accelerometer [8] (indicated as point 'A' in fig.2.) mounted at a point on the seat frame directly below the support surface. The three acceleration signals were amplified by means of an ENTRAN MSC-12 signal-conditioning unit [9].

Bench control and data acquisition was performed using an HP 9000 C110 workstation running LMS CADA-X version 3.5.B software and using a 12 channel Difa Systems Scadas II front-end unit. The front end unit contains all the hardware circuitry necessary for performing the various signal generation, acquisition, sampling, conditioning and amplification functions. All bench voltage drive signals were obtained by means of the Time Waveform Replication (TWR) software [17]. To permit paired-comparison subjective testing, a series of human testing software modules were developed by means of the LMS user programming language (UPA). Besides Time Waveform Replication, the activity described in this paper required the use of the LMS EMON [15] and TMON [16] software products.

The test facility incorporates several safety features [3] including a rubber end-of-travel snubber to limit bench travel in case of mechanical failure, software limits on the vibration signals, leak capacitors on the front-end unit and an emergency stop bottom (labeled ESB in fig.2) within reach of the test participant.

Test Signals

The test signals used for this investigation were longitudinal (for-aft) accelerations measured at the rear outer mounting bolt of the driver's seat of a European B segment automobile. The three signals chosen were from a pave' surface at 40 km/h, a comfort test track at 60 km/h and a motorway segment at 100 km/h. The pave' surface consisted of small cobblestone of the type found in many European cities. The Comfort test track was an asphalt segment containing large amplitude deformations, approximating a poorly kept country road. The motorway segment was a smooth, well kept, asphalt surface. The three acceleration time histories from the pave', comfort and motorway road tests were sampled at 250 Hz. In order to facilitate the establishment of the bench drive signals, the acceleration data was lowpass filtered with a cutoff of 50 Hz.
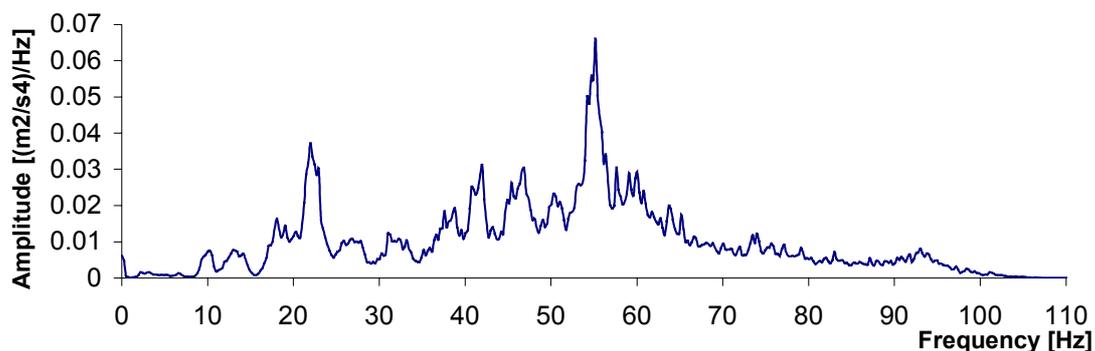

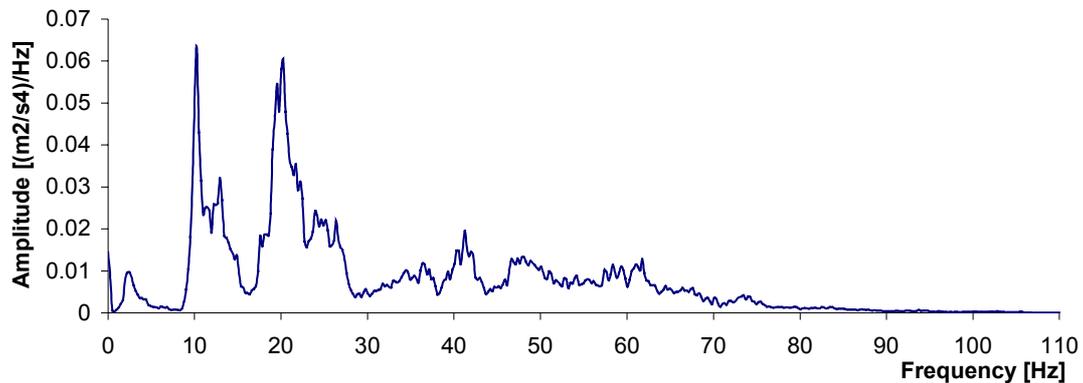Figure 3) Power Spectral Density for the pave' track.

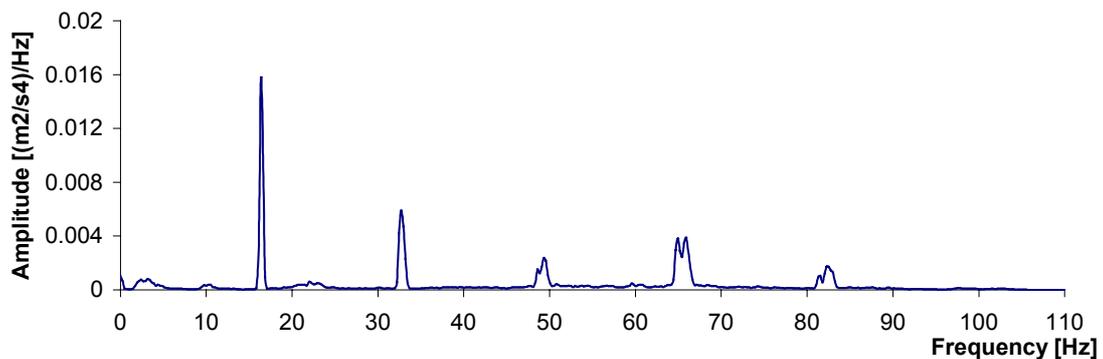Figure 4)   Power Spectral Density for the comfort track.

Figure 5)   Power Spectral Density for the highway track.

Since the objective of the research was to evaluate the accuracy of current vibrational methods based on ISO 2631 and BS 6841, it was thought important to choose acceleration time histories which represented a range of complex stimuli encountered when driving. The pave', comfort and motorway data were chosen because they provided three signal types and three different distributions of vibrational energy. The pave' data consisted of a nearly Gaussian signal with distributed energy which tended to be strongest at frequencies above roughly 30 Hz. The comfort track provided a strong Gaussian background, but also included some shock events [11]. Also, the energy distribution tended to be more concentrated towards the lower frequencies. The motorway signal was instead strongly harmonic, with dominant peaks evident at the engine harmonics and tyre resonance frequencies.

Two r.m.s. levels were used for the tests: 0.6 m/s2 and 1.2 m/s2. A multiplication factor was found for each of the three road signals so as to equalise its r.m.s. amplitude to 0.6 m/s2, and another multiplying factor was found so as to bring the r.m.s. level to 1.2 m/s2. The lower scale was chosen because it was the lowest level that a test subject could clearly distinguish from background disturbances when sitting on the rig. The 1.2 m/s2 level was chosen because it was the level of the pave' vibration signal, the strongest and subjectively the most uncomfortable of the road signals used in the study. The two levels of each of the three original experimental time histories formed a set of six base signals, from which the paired comparison tests were constructed.

The six base signals were then used to construct a set of 30 paired-comparison test signals of the type shown in Figure 6. The number 30 results from having used all possible pairings of the signals since for any number of 'n' samples the highest possible number of pairings is given by n (n - 1). Each paired-comparison signal consisted of

a 15 second "A" section, a two second gap, and a 15 second "B" section for a total of 32 seconds. The "A" and "B" sections were taken from one of the six base signals, with appropriate windowing at the ends to smooth the segment transitions. The total paired-comparison signal time of 32 seconds was chosen as the best compromise between the need to keep the signal short enough to permit both signal segments to remain in human short-term memory [4,6] and the difficulty of the control software to accurately reproduce short shocks on the test bench. Each test subject was presented all 30 test signals. After exposure to each paired-comparison test signal, the testing software paused to permit the operator to enter the subject's choice of which of the two segments was perceived to be the strongest. The complete set of vibration exposures and subjective responses provided a total test time per subject of roughly 25 minutes.
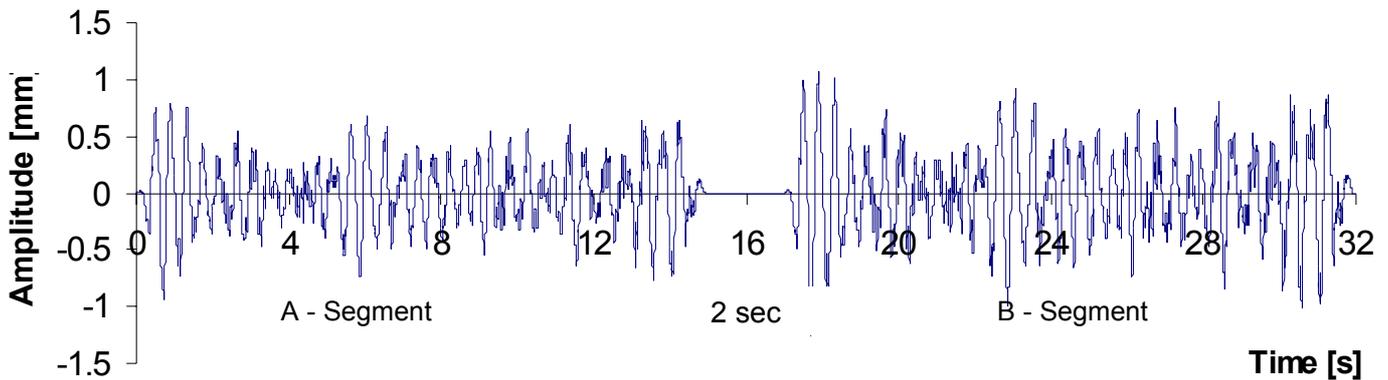
"A" and "B" drive segments

Figure 6)   Example of a paired-comparison test signal.

Accurate signal reproduction at the seat surface was considered essential for this investigation. Since electrohydraulic exciter systems are known to demonstrate varying amounts of nonlinear behavior in their response, a means of compensating for the actuator and bench response was needed. In this project, the LMS Time Waveform Replication software was used to define drive voltage signals which when sent to the exciter system would accurately reproduce the paired-comparison test signal on the bench. By means of an iteration procedure, TWR determines the complete transfer function of the control loop (controller, actuator, bench, response measurement sensors, amplifiers and signal conditioners) when actuating the actual target signal. The transfer function is then inverted to determine the drive signal voltages required to obtain the desired target signal (acceleration in our case) on the bench. Drive voltage signals were obtained for all 30 paired-comparison signals. An LMS EMON playlist was then formed in which the 30 signals were presented in random order. The randomization of the order of presentation was performed so as to minimize learning or fatigue effects in the human subjective response data.

In vibration testing, bench loading is an important factor influencing the system dynamic response. If the set of 30 paired comparison drive signals was to be used for all test participants, it was necessary to first check for variations of bench response with loading. To assess the effect of the inter-subject variability in weight and anthropometry on the response of the bench, tests were performed using light, medium and heavy persons. For the tests of signal reproduction accuracy, the subjects were chosen to be in the following weight ranges:

Category	Weight range
heavy person	above 90 kg
medium person	70 – 90 kg
light person	50 – 70 kg

A test was performed for each type of drive signal (pave', comfort and motorway) at each of the three bench loadings. Figure 4 presents a typical Power Spectral Density result for the comfort track acceleration signal. It can be seen than the accelerations obtained on the bench with the three loadings are practically superimposed, but that differences of 5 to 7 percent occurred a numerous frequencies in the range from 0.5 to 50 Hz. While 5-7 % is slightly greater than the human just noticeable difference [1-2,6] for vibration stimuli, the amount is small. Also, as a safeguard, all analysis was based not on the target acceleration signals, but rather on the actual acceleration signals acquired experimentally for each participant. Small variations in the actuated signals were therefore accounted for when calculating the r.m.s. and VDV values.
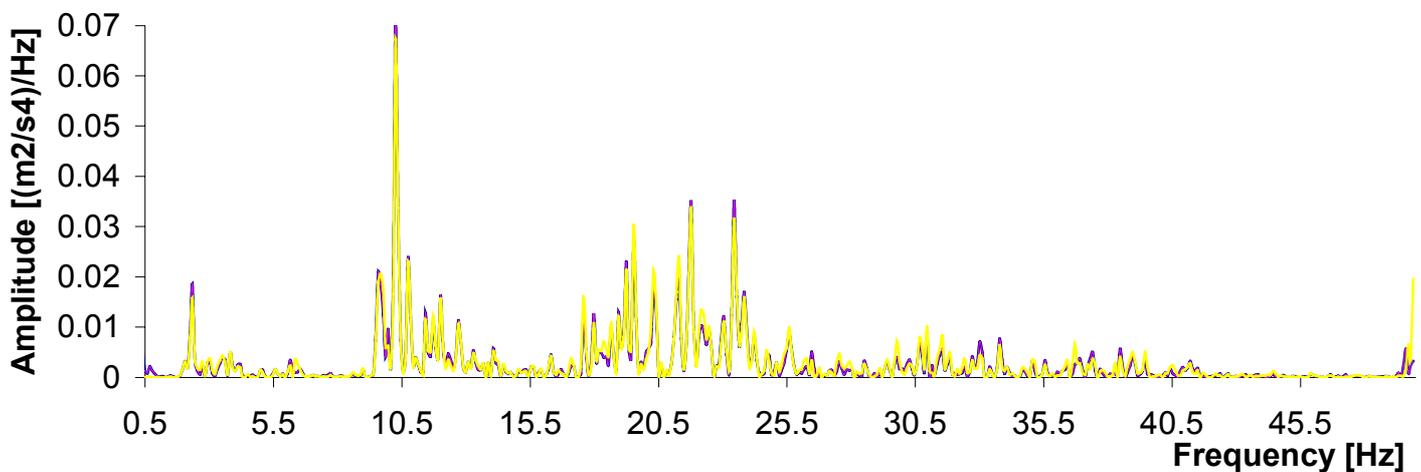

Figure 7) Acceleration Power Spectral Densities measured at the bench seat surface for three individuals of different size and weight.

Test Protocol

The test group consisted of 30 participants (25 men and 5 women). Ages ranged from 21 to 40 years, with an average age of 24.6 and a standard deviation of 4.35. The average weight was 77.5 Kg with a standard deviation of 13.3. All the subjects were in good health and only one of them made regular use of vibrating tools at their place of work.

Upon arrival, each subject was given a consent form to read and sign. They were then asked to sit on the vibration bench. Adjustments were made to the footrest by addition of extra laminates so as to ensure that the subject maintained a 90° knee-joint angle [24-25]. The knee joint angle was measured using a Diagnostic and Measuring Instruments goniometer. Back positions were also adjusted so that the subject assumed an erect position with their arms resting on their laps.

For the whole duration of the test subjects were encouraged to focus their eyes on a placard that was placed about 4 meters ahead at eye level. This was a precaution taken to prevent sight having an effect on the subject's response. Since there was no backrest or any form of constraining support, subjects were discouraged from shutting their eyes in case they felt dizzy during the test. They were also asked to wear ear protectors so as not to hear the sound of the shaker, which was audible for most test signals.

Once the participant was ready, the test began by sending a "practice" paired comparison signal. The subjective response from the first signal was not recorded, the signal being only used to familiarise the participant with the test method and the nature of the signals being used. The actual testing began from the second vibration exposure. For each of the 30 paired-comparison signals actuated, the obtained seat surface acceleration was recorded and saved to a data file on the LMS system. After each pair of stimuli, the subjects responded to the question:

"Did you feel more uncomfortable during the first or the second stimuli?"

If a participant identified the first signal as being more uncomfortable, the LMS operator entered an "A" response on the computer; and if the second was identified as more uncomfortable a "B" response was entered. If the participant indicated that he or she encountered some problem during the vibration exposure, the A-B signal was repeated.

Analysis by Means of the Law of Comparative Judgment

Once a test with a participant was completed, a UPA program was run under LMS TMON which processed all the acquired acceleration time histories. The post-processing included the splitting of the paired-comparison signals into the individual 15 second "A" and "B" segments. The data from each segment was then filtered using the frequency weighting filter W_d from ISO 2631 and BS 6841, and both the original and the filtered versions of the time history were saved to file. Both r.m.s. and VDV values were then calculated for both the "A" and the "B" segments for both the original and filtered signals.

Having gathered all filtered and unfiltered "A" and "B" segment r.m.s. and VDV values, and having gathered all subjective responses from the test participants, it was then possible to apply *Thurstone's Law of Comparative Judgment* to the data [21]. According to Thurstone's Law, any stimulus is assumed to yield a subjective reaction that correlates with the intensity of the stimulus on an interval scale, the stimulus intensity being measured by an attribute such as the signal amplitude. This reaction is termed the discriminal process. Because of sensory noise, each stimulus has a discriminal dispersion that reflects the variation in responses from one test to the next. In this paper the authors have adopted the most common assumption for the discriminal dispersion, that the reactions to a given stimulus are normally distributed. Since the individual discriminal processes are assumed to be normally distributed, the differences between them $r_A - r_B = r_d$ also follow a normal distribution. The mean of the differences which occur between the responses to the two stimuli $R_d = R_A - R_B$ after repeated applications of a test is the best estimate of the interval separating the two.

Since paired-comparison tests do not directly produce the mean subjective responses R_A and R_B of the group of participants, indirect methods must be applied. The mean response to each stimulus must be estimated from the results of direct comparison to other stimuli. For each A-B pair, the proportion of times "A" is judged greater than "B", denoted $p_{A>B}$, is recorded and converted to a percentage. The corresponding normal deviate z_{AB} is then calculated from that percentage value. For example, if $p_{A>B}$ is found to be 92%, the z score would be 1.4. This implies that if the discriminal differences $r_A - r_B = r_d$ are assumed to be normally distributed with a standard deviation of 1.0 and a mean value R_d, the zero point is 1.4 standard deviations below the mean. The mean value of R_d can be expressed in terms of the actual standard deviation of the dispersion of discriminal differences. by

$$\sigma_d = \sqrt{\sigma_A{}^2 + \sigma_B{}^2 - 2r_{AB}\sigma_A\sigma_B} \qquad (1)$$

where σ_d is the standard deviation of discriminal differences, σ_A and σ_B are the respective standard deviations of the discriminal distributions of stimuli A and B and r_{AB} is the correlation between the discriminal distributions of the two stimuli. Therefore

$$R_d = R_A - R_B = z_{AB}\sigma_d \qquad (2)$$

Thus

$$R_A - R_B = z_{AB}\sqrt{\sigma_A{}^2 + \sigma_B{}^2 - 2r_{AB}\sigma_A\sigma_B} \qquad (3)$$

At this point two simplifying assumptions are usually made. The first is that the correlations between discriminal dispersions are zero (i.e. responses are independent) and the second is that the standard deviations of discriminal dispersions are all equal. Making these assumptions, equation 3 reduces to $R_A - R_B = z_{AB}\sigma_d\sqrt{2}$. Since values on an interval scale remain unaffected when all scale values are multiplied by a constant ($\sigma_d\sqrt{2}$), the expression reduces to

$$R_A - R_B = z_{AB} \qquad\qquad (4)$$

Thus, the method simplifies to allowing the normal deviate representing the proportion of times one stimulus is preferred over another to define the interval separating the two stimuli. Equation 4 is the most frequently used form of the *Law of Comparative Judgment,* and was chosen for use in the investigation reported here.

Results

Tables 1 and 2 present the conversions of the subjective responses to percentages and to z deviates. Table 1 shows the results for the proportion of subjects preferring each signal (columns) compared to each of the other signals (rows). Values of 0.5 were placed on the diagonal position in the table as each stimulus is assumed to be judged greater than itself half of the time. Each value of $p_{A>B}$ was converted to a normal deviate, z_{AB}, which is presented in Table 2. Each normal deviate in Table 2 is the interval between the two stimuli. The sum of the normal deviates for each column (stimulus) was obtained and then averaged. Signal pairs that were widely separated ($z_{AB} > 2.0$) were eliminated from the averaging process because the assumption that these stimuli overlap on a strength scale would not be tenable [23]. The results are normal deviates expressed as deviates from the average stimulus in the set. Finally, the value of the lowest (most negative) stimulus is subtracted from each of the other values to eliminate negative values in the final scale. The data was then normalised to the interval from 0 to 1.

		Signal					
		1	2	3	4	5	6
	Signal	com06	co1.2	hig06	hi1.2	pav06	pa1.0
1	com06	0.5	0.9	0.275	0.9	0.875	0.925
2	co1.2	0.1	0.5	0.025	0.3	0.25	0.825
3	hig06	0.725	0.975	0.5	0.925	0.9	1
4	hi1.2	0.1	0.7	0.075	0.5	0.325	0.8
5	pav06	0.125	0.75	0.1	0.675	0.5	1
6	pa1.0	0.075	0.175	0	0.2	0	0.5

Table 1) Percentage conversions of the number of times stimulus "A" was judged greater than stimulus "B".

Signal	com06	co1.2	hig06	hi1.2	pav06	pa1.0
			Signal			
com06	0	1.3	-0.6	1.3	1.15	1.44
co1.2	-1.3	0	-1.96	-0.53	-0.675	0.93
hig06	0.6	1.96	0	1.44	0.53	3
hi1.2	-1.3	0.53	-1.44	0	-0.45	0.84
pav06	-1.15	0.675	-0.53	0.45	0	3
pa1.0	-1.44	-0.93	-3	-0.84	-3	0
sum	-4.59	3.535	-4.53	1.82	0.555	3.21
Average	-0.918	0.707	-1.1325	0.364	0.13875	1.07
Final scale	0.2145	1.8395	0	1.4965	1.27125	2.2025
Normalised Scale	0.09739	0.83519	0	0.67946	0.57719	1

Table 2) Conversions of percentages to z-deviates and an interval scale.

From the data of Table 2 it can be seen that the average order of preference of the base signals used for this study was the following in order from the most comfortable to the most uncomfortable:

highway (0.6 m/s2)
comfort   (0.6 m/s2)
pave'   (0.6 m/s2)
highway (1.2 m/s2)
comfort   (1.2 m/s2)
pave'   (1.2 m/s2)

The data show consistence of order both at the lower and higher amplitudes, with the highway signal being the most comfortable and the pave' being the most uncomfortable. Considering that the r.m.s. amplitudes are the same at 0.6 m/s2 and 1.2 m/s2, the results suggests that harmonic excitation was preferred to random excitation. The results also suggest that the pave' signal, which had more vibrational energy at higher frequencies, was considered more severe than the comfort signal which had more energy at lower frequencies. Considering the shape of the longitudinal direction frequency weighting filter W_d, which strongly attenuates vibration signals from frequencies above 2 Hz, it would have been more intuitive to find the comfort track rated more severely than the pave'. This point requires further investigation.

Figure 8 presents a plot of the normalized perception scale against the filtered and the unfiltered Vibration Dose Values (VDVs), while Figure 9 presents the normalised perception scale plotted against the filtered and unfiltered r.m.s. values of the "A" and "B" signals. From Figures 8 and 9 it can be seen that use of the ISO 2631 and BS 6841 frequency weighting filters greatly improved the correlation between the global statistics of the measured vibration signals and the subjective opinions voiced by the human test participants. In the case of the VDV, the use of frequency weighting filters would seem to be unavoidable given the lack of correlation demonstrated by the unfiltered data.
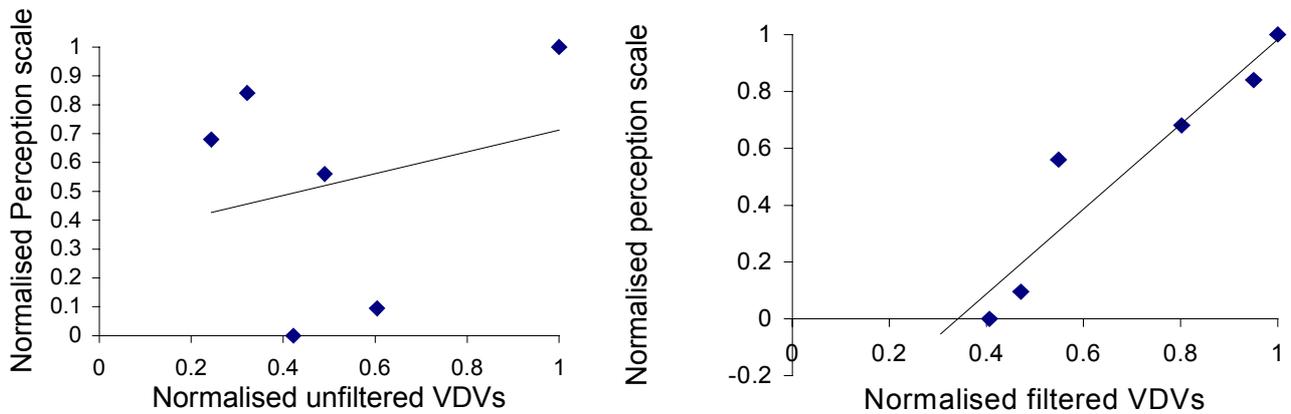
Figure 8) Normalised perception scale versus normalised VDV value
a) with W_d frequency weighting filter
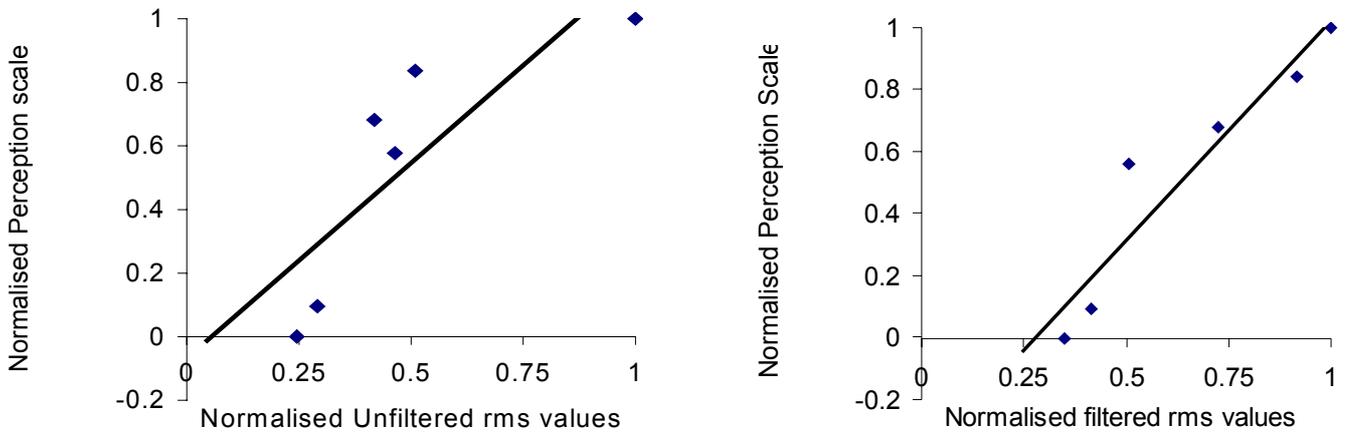b) without W_d frequency weighting filter

Figure 9) Normalised perception scale versus normalised r.m.s. value
a) with W_d frequency weighting filter
b) without W_d frequency weighting filter

Another conclusion that can be drawn for the data set provided in Figures 8 and 9 is that the comfort scale produced by the use of frequency weighting filter and the reporting of either r.m.s. or VDV values would appear to be nonlinear, with significant overestimation of the perceived level of discomfort occurring at low vibration amplitudes. The overestimation of perceived subjective comfort at low stimulus amplitudes is greater than what would be compatible with the Stevens Power Law coefficient of 1.14 reported in previous studies involving transient vibration [13, 24].

Conclusions

A human vibration facility and a suite of human testing software have been produced for permitting paired-comparison testing of short duration vibratory stimuli. The combination of high signal reproduction quality and test signals which are short enough to remain in human short-term memory has provided an opportunity to test the effectiveness of the ISO 2631 and BS 6841 methods. Results obtained to date suggest that frequency weighting filter W_d is essential for obtaining a good correlation between VDV and human subjective response, but less critical in obtaining correlation between r.m.s. value and human subjective response. The results also suggest that any weighted or unweighted r.m.s. or VDV measure will overestimate human subjective discomfort at low vibration levels. If supported by further findings, this result implies that correction factors will be required in order to produce equal subjective perception intervals starting from measured acceleration data.

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