Subjective Equivalence of Steering Wheel Vibration and Sound

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Abstract

The subjective equivalence between steering wheel vibration and sound was investigated in two experiments. In each experiment 20 subjects were presented 64 pairs of simultaneous sound and vibration stimuli in a simulator which reproduced a realistic driving posture. The first used stimuli measured in an automobile when driving over a coarse asphalt road surface, while the second used data obtained by driving over a 1.0 cm square metal bar. In both experiments the acceleration time histories were scaled to eight r.m.s. levels from 0.5 to 4.0 m/s^2 and the sound pressure time histories were scaled to eight levels from 85 to 106 dB SPL. Test subjects were asked to indicate which stimuli, the sound or the vibration, was felt to be the "more unpleasant". Regression expressions of subjective equivalence were developed for both stimuli types, in both the unweighted (dB versus r.m.s. acceleration) and the frequency-weighted (dB(A) versus VDV) forms. Regression slopes were found to be in the range from 23.8 to 26.8, similar to values for whole-body vibration exposures. Subjective equivalence was, however, found to be 5 to 15 dB(A) lower for the coarse asphalt stimuli and 15 to 25 dB(A) lower for the square metal bar stimuli. All other conditions remaining equal, the human response to the vibration was found to increase in relative importance with respect to the sound in the case of short duration, transient, square metal bar stimuli.

Relevance to Industry

For vehicle and vehicle component manufacturers, the proposed expressions of subjective equivalence between sound and vibration will permit a more accurate diagnosis of the sources of human discomfort.

Keywords: vibration, sound, human, steering wheel, automobile

1. Introduction

Motor vehicle drivers are regularly exposed to vibrational and acoustic stimuli from various sources. The steering system is one important source of vibration (Pak et al., 1991). The acceleration level and spectral content of steering wheel vibration depend on several factors including the direction of vibration, the nature of the road surface, the dynamic characteristics of the tyres and the design of the vehicle main suspension and steering mechanism. Vibrational energy at the steering wheel can reach frequencies of up to 300 Hz (Giacomin et. al., 2004) and vibrational modes of the steering wheel and column can produce large resonant peaks in the steering wheel power spectrum at frequencies from 20 to 50 Hz (Pottinger et al., 1986). For the steering wheel, an interesting question is which of the stimuli reaching the driver, vibration or sound, produces greater discomfort. Knowing the relative importance can help to establish which of the two requires greater attention during the vehicle development program.

The question of the subjective equivalence of vibration and sound is not a new one. Fleming and Griffin (1975) asked each of 20 subjects to compare 64 combinations of simultaneous whole-body vibration and sound. A 10 Hz vertical sinusoidal vibration was applied through a rigid seat, and a 1000 Hz sinusoidal sound pressure was applied binaurally through headphones. Eight root mean square (r.m.s.) acceleration levels were used from 0.20 m/s^2 to 1.2 m/s^2 and eight sound pressure levels from 65 to 100 dB. The stimuli were applied simultaneously for 10 seconds and the subjects indicated which stimuli, the vibration or the sound, they would prefer reduced. Subjective equivalence was defined as the combination for which 50% of the subjects preferred the noise reduced. By means of regression analysis, subjective equivalence was described by the expression

$$0.03 \, SPL \;\; = \;\; 0.99 \, Log_{10}(\boldsymbol{f}_v) + 2.77 \tag{1}$$

where $\boldsymbol{f}_v$ is the r.m.s. amplitude of the acceleration in m/s^2 and SPL the sound pressure level in decibels.

Sandover and Champion (1984) investigated the subjective equivalence of broad band vibration and sound with 6 subjects. Three vibration stimuli were used which contained energy from 2 to 25 Hz and which had frequency-weighted (ISO2631-1, 1997) r.m.s. acceleration amplitudes of 0.59, 0.83 and 1.18 m/s^2. The whole-body stimuli were applied in the vertical direction through a seat. The sound consisted of random noise in the interval from 31 to 5000 Hz which was applied through headphones. Subjects were exposed to the vibration for 12 minutes and were then asked to indicate adjustments to the sound until the two were equal in terms of subjective discomfort. The intensity of the matching sound was reported in units of A-weighted sound pressure level (IEC 60651, 1979). Significantly lower sound pressure levels were found than in the study by Fleming and Griffin. The authors did not speculate on the possible causes, but these may include vibration isolation by the seat.

Kjellberg et. al. (1985) investigated the change in whole-body vibrational discomfort with time for exposures lasting up to one hour. These authors determined the subjective equivalence for 15 subjects. Seated, vertical, whole-body vibration was applied for 8 seconds using sinusoidal excitation at either 3.1 or 6.3 Hz at amplitudes from 0.95 m/s^2 to 3.5 m/s^2. A random noise spectrum, defined from 40 Hz to 2000 Hz, was applied through headphones. Test subjects indicated amplitude adjustments such that the discomfort produced by the sound matched that produced by the vibration. The test results suggested lower sound pressure levels than found by Fleming and Griffin. Again, the reasons for the differences may include vibration isolation by the seat cushion.

Howarth and Griffin (1990 and 1991) investigated the perception of combined vibration and sound of the type measured in buildings during the passing of trains. Their 1990 study used stimuli which were 24 seconds in length. The vibration contained energy in the frequency interval from 5 to 70 Hz while the sound contained energy from 20 to 5000 Hz. The vibration was scaled to six levels of frequency-weighted vibration dose value (VDV) from 0.07 to 0.40 ms$^{-1.75}$, corresponding to W_b frequency weighted r.m.s. levels from 0.02 to 0.125 m/s^2. The noise was scaled to six levels from 54 to 79 dB(A). While on a rigid seat, 24 subjects were exposed to 42 combinations of vertical whole-body vibration, and sound produced by loudspeakers. The method of magnitude estimation was used to determine subjective response. The results suggested that the vibration did

not influence the judgment of the sound, but that the sound could influence the judgment of the vibration. Regression analysis lead to the equivalence expression

$$L_{AE} = 26.7\,Log_{10}(VDV) + 81.7$$

(2)

where L$_{AE}$ is the A-weighted sound pressure level (IEC 60651, 1979) and VDV is the vibration dose value in units of ms$^{-1.75}$ (ISO 2631-1, 1997). For their 1991 study Howarth and Griffin used six types of vibration stimuli whose duration ranged from 7 to 29 seconds and whose power spectrum contained energy from 10 to 60 Hz. The whole-body acceleration stimuli were scaled to provide VDV values from 0.056 to 0.4 ms$^{-1.75}$. The sound stimuli used were pink noise signals with energy from 20 to 3000 Hz and A-weighted levels from 52.5 to 77.5 dB. While on a rigid seat, 20 subjects were exposed to 90 combinations of vertical direction vibration, and sound produced by loudspeakers. The method of magnitude estimation was used with a fixed reference which was assigned a value of 100. For the 1991 data, regression analysis suggested subjective equality defined by

$$L_{AE} = 29.3\,Log_{10}(VDV) + 89.2$$

(3)

Paulsen and Kasta (1995) investigated the subjective equivalence of vertical whole-body vibration and sound. The stimuli, of 16 seconds in duration, consisted of acceleration and sound pressure time histories measured in a building. The energy sources producing the stimuli were of one of two types: the passing of a tram and the emission of an industrial hammermill. The vibration contained energy from 1 to 150 Hz while the sound contained energy from 20 to 20,000 Hz. The vibration stimuli had velocity levels from 0.05 to 0.32 mm/s while the sound stimuli had A-weighted pressure levels from 34 to 60 dB(A). 16 subjects were asked to rate the "intensity and the annoyance of the stimuli" using a 10 point scale. Regression analysis lead to subjective equivalences defined by

$$(Tram)\quad L_{AE} = 14.4\,Log_{10}(VDV) + 51.9$$
$$(Hammer\ Mill)\ L_{AE} = 13.7\,Log_{10}(VDV) + 50.8$$

(4)

suggesting slopes of approximately one-half those reported in the studies by Howarth and Griffin. The differences may be due to the use of velocity for expressing the vibratory stimuli rather than acceleration as in the other studies mentioned above.

While expressions have been defined for the subjective equivalence of whole-body vibration in the vertical direction and sound, the authors know of no similar results for the hand-arm vibration and sound. The human subjective response to steering wheel vibration (Giacomin et. al. 2004) has been measured, as has the steering wheel induced fatigue (Giacomin and Abrahams, 2000), but combined stimuli have not been considered. This paper therefore describes a study performed to determine the subjective equivalence between rotational steering wheel vibration and sound.

2. Experiment

2.1 Test Facility

All tests were performed using the steering wheel rig presented in Figure 1. The rotational system consisted of a 325mm diameter aluminum wheel attached to a steel shaft which was mounted to bearings and connected to an electrodynamic shaker. Table 1 presents the main geometric dimensions of the rig, which were chosen based on data from a small European automobile. The seat was fully adjustable in terms of horizontal position and back-rest inclination as in the original vehicle. Rotational vibration was applied by means of a G&W V20 electrodynamic shaker and PA100 power amplifier. Steering wheel tangential acceleration was measured by means of an Entran EGAS-FS-25 accelerometer attached to the top left side of the wheel and an Entran MSC6 signal-conditioning unit. Vibration control and data acquisition was performed by means of the EMON software system (LMS International, 1999), coupled to a DIFA SCADASIII electronic frontend unit. The EMON software permitted the fixing of safety cutoff limits which were set to 20.0 m/s^2 peak acceleration.

The rig has a first resonance frequency which is greater than 350 Hz under normal loading conditions. Calibration tests were performed using three subjects and sinusoidal excitation at frequencies from 4.0 to 250 Hz and amplitudes from 0.2 to 20.0 m/s^2 r.m.s..

A maximum total harmonic distortion (THD) of 15% was found at 4 Hz and 20 m/s^2. With both increasing frequency and decreasing amplitude the THD dropped to a minimum of 0.002% at 250 Hz and 0.2 m/s^2. Fore-and-aft acceleration was found to be no greater than -50 dB with respect to the tangential acceleration. The safety features of the rig and the acceleration levels used conform to the health and safety recommendations outlined by British Standards Institution BS7085 (1989).

Sound reproduction was achieved by means of a B&K ZE0769 4 channel amplifier and Sennheiser HD 580 matched-impedance headphones. Frequency response for the headphones was linear over the frequency range from 20 to 20,000 Hz and the headphone maximum linear output was found to be greater than 114 dB sound pressure level (SPL).

2.2 Test stimuli

Stimuli were chosen from a group of measurements performed using one European mid-sized automobile which was driven over six road surfaces. Both 175/65 R14 and 225/45 R16 tyres were used at inflation pressures of 1.5 and 2.0 bars respectively. Acceleration was measured in three orthogonal directions at two positions (90 and 270 degrees) along the steering wheel using two tri-axial accelerometers (DJB 3D A/31) mounted on clamps. Sound pressure was measured in both the left and right ears of a Head Acoustics HMS.II.1 head and torso simulator which was in the front passenger's seat. The sampling rate for all measurements, both vibrational and acoustic, was 4096 Hz.

Analysis showed that all steering wheel acceleration spectra contained significant energy in the tangential direction from 10 to 60 Hz. The root mean square acceleration level in the tangential direction ranged from 0.74 m/s^2 to 4.86 m/s^2 across all test conditions. The power spectral densities of the sound pressures measured at the left and right ears contained significant energy in the interval from 15 to 150 Hz, and the r.m.s. levels ranged from 0.49 Pascals (87.7 dB) to 3.10 Pascals (103.8 dB). The difference in sound pressure level between the left and right ear was less than 1.0 dB in all cases.

Data from two road surfaces was selected for the laboratory experiment. Each data set consisted of the tangential acceleration time history measured at the 270 degree position and the sound pressure time history from the right ear of the mannequin. The first data set was from an 80 km/h test performed over a course asphalt surface which provided a representative steady-state random stimuli. A fifteen second section, having an r.m.s. acceleration level of 1.12 m/s^2 and a sound pressure level was 91.8 dB, was used. The second data set was from a 40 km/h test performed by driving over a 1.0 cm square metal bar which provided a transient stimuli. A one second section was used which began at the start of contact between the front tyres and the square metal bar and ended when the vibration had decayed after contact with the rear tyres. The r.m.s. acceleration level was 1.28 m/s^2 and the sound pressure level was 97.3 dB. Photographs of the two road surfaces are presented in Figure 2 while the power spectral densities of the stimuli are presented in Figure 3.

Eight copies of each of the two vibration time histories were constructed by rescaling the data such that the r.m.s. acceleration amplitudes were exactly 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5 and 4.0 m/s^2. Eight copies of each of the two sound pressure time histories were also constructed by rescaling to sound pressure levels of exactly 85, 88, 91, 94, 97, 100, 103 and 106 dB SPL. By arranging all possible combinations of vibration and sound, a total of 64 pairs were produced for the coarse asphalt stimuli and 64 for the square metal bar stimuli. A check of stimuli reproduction accuracy was performed with 10 subjects under test posture and grip strength. Tangential acceleration was measured at the wheel using the ENTRAN EGAS-FS-25 accelerometer while the sound achieved at each ear was measured using a B&K type 4101 binaural probe microphone. For each subject 10 applications of each stimuli pair were performed and the response measurements averaged. Maximum r.m.s. acceleration error was found to be 20 percent while the mean r.m.s. error was 5 percent. The maximum difference in sound pressure level was 4 dB, while the mean difference was less than 1 dB.

2.3 Test Protocol

Experiment 1 consisted of 64 stimuli pairs produced from the data of the course asphalt surface while experiment 2 consisted of 64 stimuli pairs produced from the data of the

1.0 cm square metal bar surface. To minimise fatigue and learning effects the order of presentation of the test stimuli pairs was randomized for each subject. Except for the stimuli type and the total time duration, all other aspects of the two experiments were identical. Total time was 37 minutes for experiment 1 and 27 minutes for experiment 2. Room temperature was from 20 to 25° C during all tests. The facility and protocol were externally reviewed and found to meet the University of Sheffield guidelines for good research practice.

Twenty Sheffield university students and staff participated in each experiment. Upon arriving in the laboratory each was issued an information and consent form. Gender, age, height, and weight data were then collected, and the participant was requested to state whether he or she had any physical or mental condition which might effect perception of either vibration or sound, and whether he or she had smoked, or ingested coffee, within the 2 hours previous to arriving in the laboratory. The test group of experiment 1 consisted of 18 males and 2 females who had a mean age was 25.5 years, a mean mass of 74.0 kg and a mean height of 1.76 m. The group which participated in experiment 2 consisted of 17 males and 3 females who had a mean age of 25.2 years, a mean mass of 70.5 kg and a mean height of 1.75 m. No participant from either group declared any condition which might effect his or her perception of vibration or sound, and none declared having smoked or ingested coffee prior to arriving in the laboratory.

Before commencing each participant was asked to remove any articles of heavy clothing such as coats, and to remove watches and jewellery. He or she was then asked to adjust the seat so as to achieve a realistic driving posture and to put on the headphones and to grip the steering wheel using both hands, applying the grip strength that would be used when driving on a winding country road. The participant was then asked to close his or her eyes so as to avoid visual cues which might affect perception and to indicate verbally, after every stimuli pair, which of the two he or she felt was the "more unpleasant". Two preliminary tests (whose data was not analyzed) were performed so as to familiarize the participant with the procedure. One involved vibration and sound stimuli which were near the maximum possible values (3.5 m/s^2 and 103 dB) while the other involved stimuli which were near the minimum (1.0 m/s^2 and 88 dB).

3.0 Results

At each r.m.s. acceleration amplitude a Gaussian distribution model was fitted, and used to estimate the 25th, 50th and 75th percentile preferences of sound as the "more unpleasant" stimuli. The 50th percentile values, which are taken in this research to define the subjective equivalence between the two stimuli, are presented in table 2. Sound pressure levels are not given for several vibration amplitudes of the coarse asphalt and the square metal bar stimuli. In each case the statistical distributions deviated substantially from a Gaussian assumption due to a near complete preference of one stimuli over the other at the specific acceleration amplitude. Only data from tests whose probability density functions approximated a Gaussian distribution are presented.

Figures 4 and 5 present the curves defined by the points of 25th, 50th and 75th percentile preference for sound as the "more unpleasant" stimuli at each acceleration level of the coarse asphalt and square metal bar stimuli respectively. Both data sets suggest monotonically increasing relationships for all curves. Comparison of the 50th percentile curves suggests that that the mean sound levels obtained for the 1 second square metal bar transient stimuli were from 1 to 3 dB SPL higher than those obtained for the 15 second coarse asphalt stimuli. The 1 second square metal bar stimuli contained two large shocks caused by the impacts with the obstacle of first the front, then the rear, tyres. Each shock had a maximum duration of approximately 0.2 seconds, thus approaching the minimum integration time of human hearing. All other conditions remaining equal, the higher dB levels for the square metal bar stimuli suggest that the human subjective response to sound decreases in relative importance for short, transient, stimuli.

Frequency-weighting the acceleration stimuli by means of the W_h weighting of ISO 5349-1 (2001), or frequency-weighting the sound pressure stimuli using the A-weighting of IEC 60651 (1979), does not change the monotonic equivalence relationship. Frequency-weighting the stimuli does, however, modify the numerical values, thus affecting any regression analysis involving the two data types. To facilitate comparison of the current results to data reported in the literature for whole-body vibration exposures, the stimuli used in this study were analysed in both unweighted and frequency-weighted form. The

results of a linear regression analysis performed on the sound and vibration data are presented in Table 3 which contains the expressions for the equivalence curves and their coefficients of determination, in both the unweighted and frequency-weighted forms. The slope values of the regression equations range from 23.8 to 26.8, thus they are similar to previously reported values for whole-body vibration. Unlike whole body vibration, the constant offset values are lower, being 86.4 and 88.8 in unweighted form and 64.8 and 56.6 in frequency-weighted form.

4.0 Discussion

Figure 6 presents the equivalence expressions determined in this study between steering wheel rotational hand-arm vibration and sound, and those of Fleming and Griffin (1975), Sandover and Champion (1984), Kjellberg et. al. (1985) and Howarth and Griffin (1990 and 1991) for whole-body vibration. For the data of the current study the expressions obtained from both the coarse asphalt and the 1.0 cm square metal bar stimuli are presented. All equivalence curves of Figure 6 are presented over the range of vibration levels reported by the original authors. The curves of the current study, those reported by Fleming and Griffin and those reported by Howarth and Griffin (both 1990 and 1991) have been determined directly by use of the stated equivalence expression. For the studies by Sandover and Champion and by Kjellberg et. al. the data has been reanalyzed to determine the equivalence expression. For ease of comparison all data is presented in Figure 6 in frequency-weighted form, thus the vibration is a dose value in units of $ms^{-1.75}$ and the sound pressure level is in dB(A).

Comparison of the equivalence curves determined from whole-body vibration studies suggests large differences in dB(A) level. The curve determined from the data reported by Kjellberg et. al. is more than 5 dB(A) lower than the expressions from the group of studies by Griffin, while the curve determined from the data of Sandover and Champion is more than 10 dB(A) lower. In the case of the studies by Kjellberg et. al and by Sandover and Champion these differences may in part be due to the seating condition which was not reported as rigid, and which may therefore have introduced compliance between the vibrator platform and the test subject. In the case of the group of studies by Griffin, however, differences of 6 dB(A) are also found between the various curves for nominally

similar sitting and sound reproduction conditions. Some part of these differences must therefore be due to changes in human perception associated with the changes in the statistical properties of the stimuli.

Comparison of the current hand-arm results to those reported for whole-body vibration suggests that the point of subjective equivalence is from 5 to 15 dB(A) lower for the curve obtained from the coarse asphalt stimuli and from 15 to 25 dB(A) lower for the curve obtained using the square metal bar stimuli. These results are consistent with the research of Peruzzetto (1988) in which hand-arm vibration was found to cause similar levels of discomfort to whole-body vibration when approximately 5 to 7 times greater in level.

A further point of note is that there exists a potential difficulty associated with the choice of data format for quantifying human subjective response to combined sound and vibration. Whereas the equivalent sound levels for the square metal bar stimuli were found to be higher than those of the coarse asphalt stimuli in terms of unweighted sound pressure level (Figures 4 and 5), the opposite is true when decibel A-weighting is performed (Figure 6) on the sound pressure data. The problem of data presentation is illustrated in Figure 7 where the equivalence curves are plotted in both unweighted, and decibel A-weighted, sound pressure values and in terms of both r.m.s. and VDV vibration level. Figure 7 suggests that performing A-weighting can greatly increase the apparent difference in human response to stimuli having different statistical properties. While not possible to fully demonstrate here, A-weighting of sound pressure levels may be insufficiently accurate for the purposes of measuring vehicle transient sound stimuli.

5.0 Conclusions

This study investigated the subjective equivalence between rotational steering wheel vibration and sound. In one experiment the stimuli used were scaled copies of a sound pressure and of an acceleration time history measured in an automobile when driving over a coarse asphalt surface. In a second experiment the stimuli were from a test in which the automobile was driven over a 1.0 cm square metal bar. In each experiment 20

test subjects were asked to indicate for each of 64 stimuli pairs which of the two, the sound or the vibration, was felt to be the "more unpleasant".

Regression expressions were developed for both stimuli in both the unweighted (dB SPL versus r.m.s. acceleration amplitude) and frequency-weighted (dB(A) versus VDV) forms. The slopes of the regression equations were in the range from 23.8 to 26.8, similar to data reported for whole-body vibration in previous studies. Unlike the previous studies, the constant offsets were lower, being in the range from 56.6 to 88.8. The equivalent sound levels for the 1.0 cm square metal bar stimuli were from 1 to 3 dB SPL higher than those obtained using the coarse asphalt stimuli. All other conditions remaining equal, the findings suggest that the human subjective response to vibrational disturbances increases in relative importance for short duration, transient, stimuli with respect to steady-state conditions.

Comparison of the current results for hand-arm vibration to previously reported results for whole-body vibration suggests that the point of subjective equivalence is from 5 to 15 dB(A) lower for the coarse asphalt stimuli, and from 15 to 25 dB(A) lower for the square metal bar stimuli.

6. Acknowledgements

7. References

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Geometric Parameter	Value
Steering column angle (H18)	23°
Steering wheel hub centre height above floor (H17)	710 mm
Seat H point height from floor (H30)	275 mm
Horizontal distance adjustable from H point to steering wheel hub centre (d=L11-L51)	390–550 mm
Steering wheel tube diameter	12.5 mm
Steering wheel diameter	325 mm

Table 1   Geometric dimensions of the steering wheel rotational vibration test rig.

vibration level [m/s^2 r.m.s.]	Coarse Asphalt Stimuli Sound Pressure Level [dB]	Cleat Stimuli Sound Pressure Level [dB]
0.5	-	-
1.0	-	88.8
1.5	91.0	92.7
2.0	94.8	98.0
2.5	97.5	99.0
3.0	98.6	99.1
3.5	100.7	-
4.0	103.0	-

Table 2   Subjective equivalence values determined from the course asphalt and cleat stimuli tests.

Test Stimuli	Data Form	Expression	r^2
coarse asphalt	unweighted	dB = 26.8 Log$_{10}$(r.m.s.) + 86.4	0.99
coarse asphalt	weighted	dB(A) = 26.8 Log$_{10}$(VDV) + 64.8	0.99
Cleat	unweighted	dB = 24.6 Log$_{10}$(r.m.s.) + 88.8	0.94
Cleat	weighted	dB(A) = 23.8 Log$_{10}$(VDV) + 56.6	0.94

Table 3   Subjective equivalence expressions between sound and steering wheel vibration determined from linear regression. Expressions provided for both the coarse asphalt and the cleat stimuli in both unweighted and frequency-weighted forms.
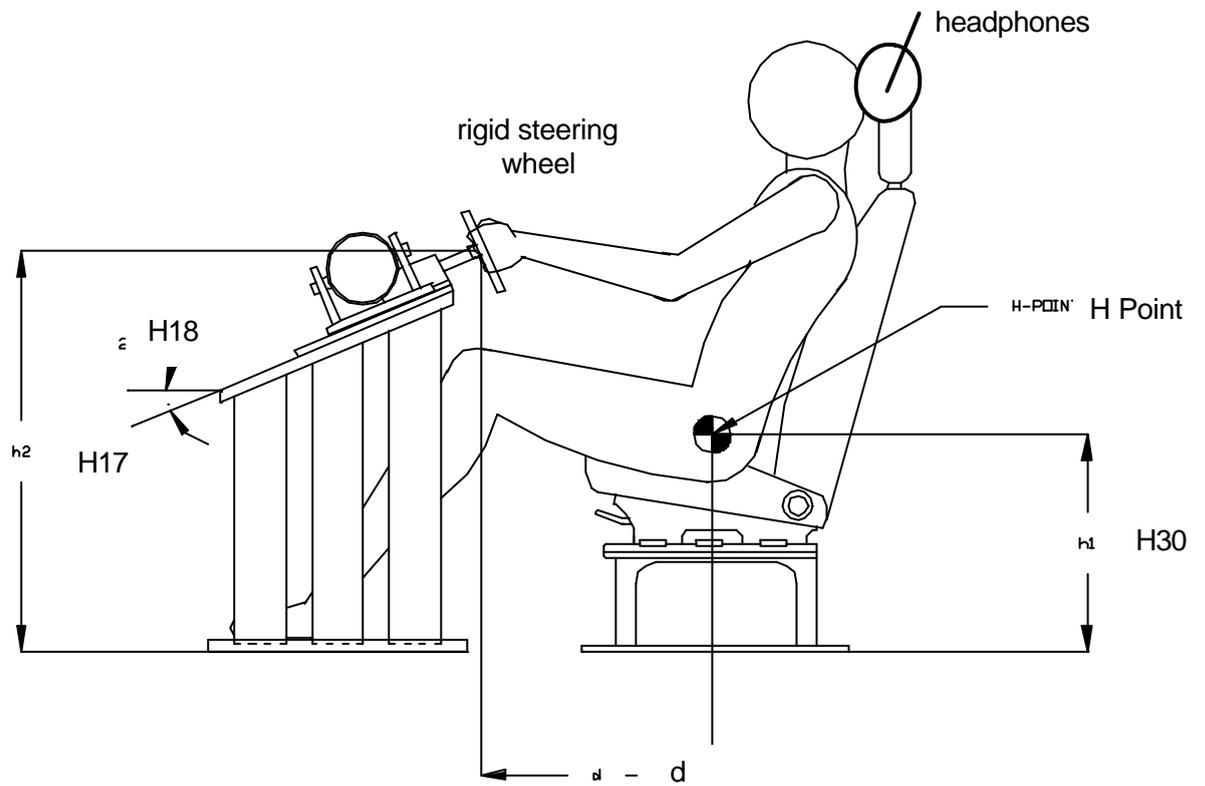
Figure 1   Steering wheel rotational vibration test rig.
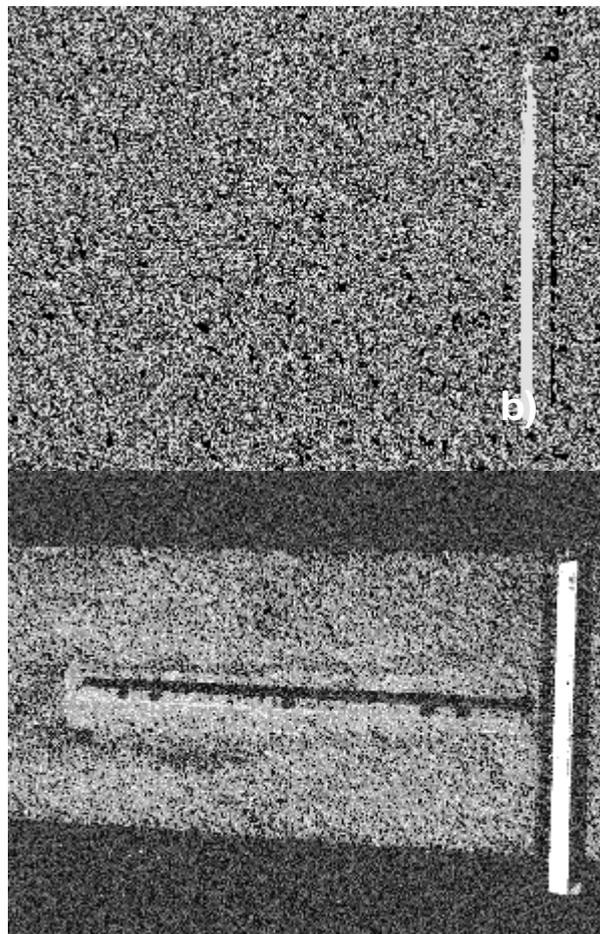
Figure 2   Road surfaces whose sound and vibration stimuli were chosen for
          use in the laboratory tests. Scale indicated by a 30 cm ruler.
          a)   coarse asphalt (vehicle driven at 80 km/h)
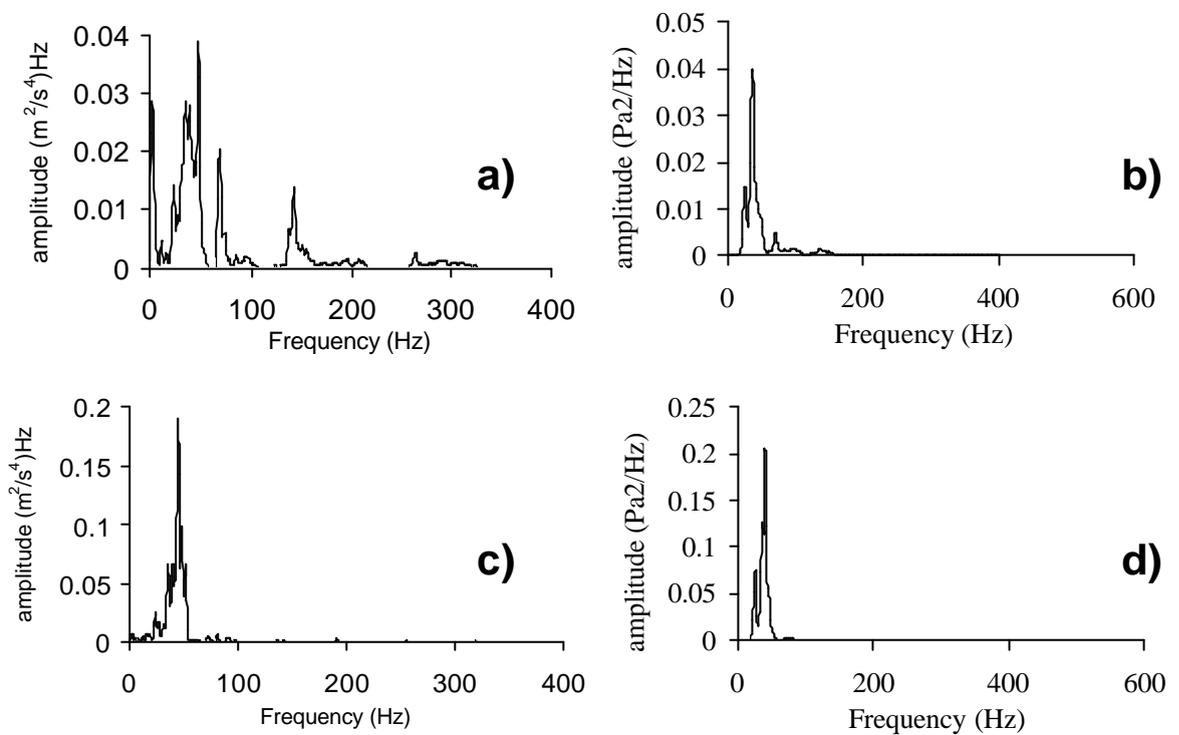   b) 1.0 cm square metal bar (vehicle driven at 40 km/h)

Figure 3   Power spectral densities of the test stimuli.
a) course asphalt tangential acceleration at steering wheel (80 km/h)
b) coarse asphalt sound at ear (80 km/h)
c) 1.0 cm square metal bar tangential acceleration at steering wheel (40 km/h)
d) 1.0 cm square metal bar sound at ear (40 km/h)
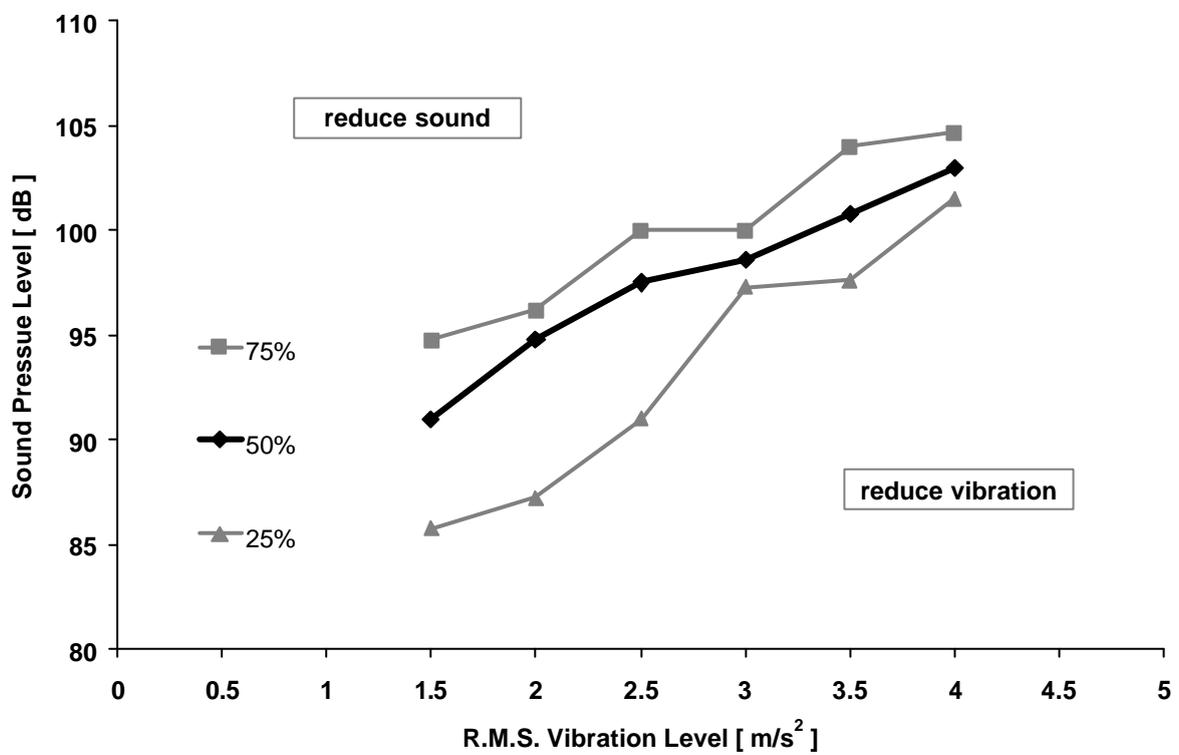
Figure 4   Percentages of the 20 test subjects who indicated that they preferred the sound stimuli reduced for the given vibration level of the coarse asphalt stimuli.
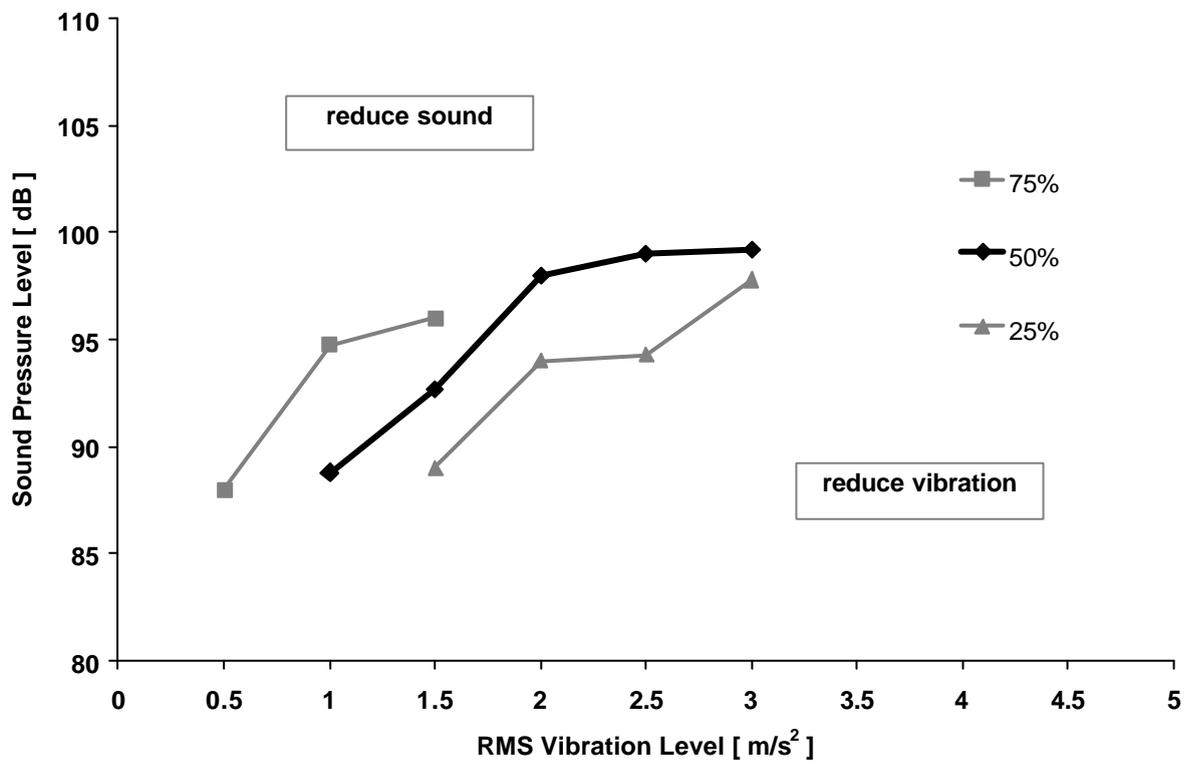
Figure 5   Percentages of the 20 test subjects who indicated that they preferred the sound
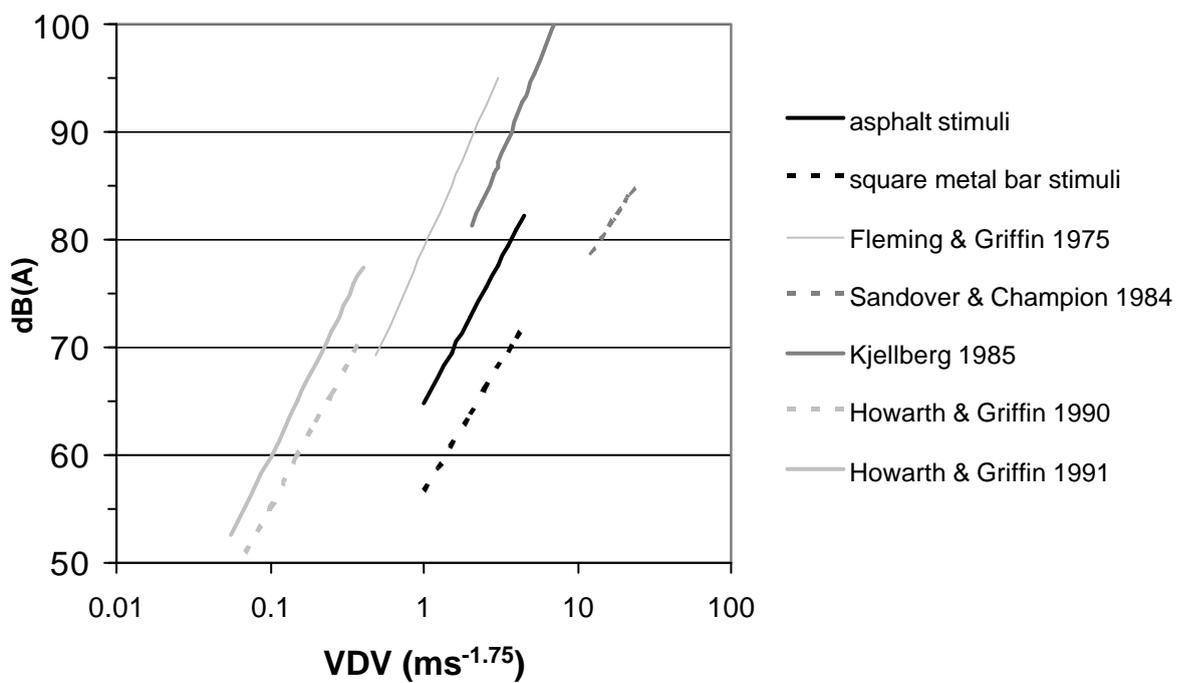stimuli reduced for the given vibration level of the 1.0 cm square metal bar stimuli.

Figure 6   Equivalence between sound and steering wheel rotational vibration from the current study and equivalence lines for seated vertical whole-body vibration reported in the literature.
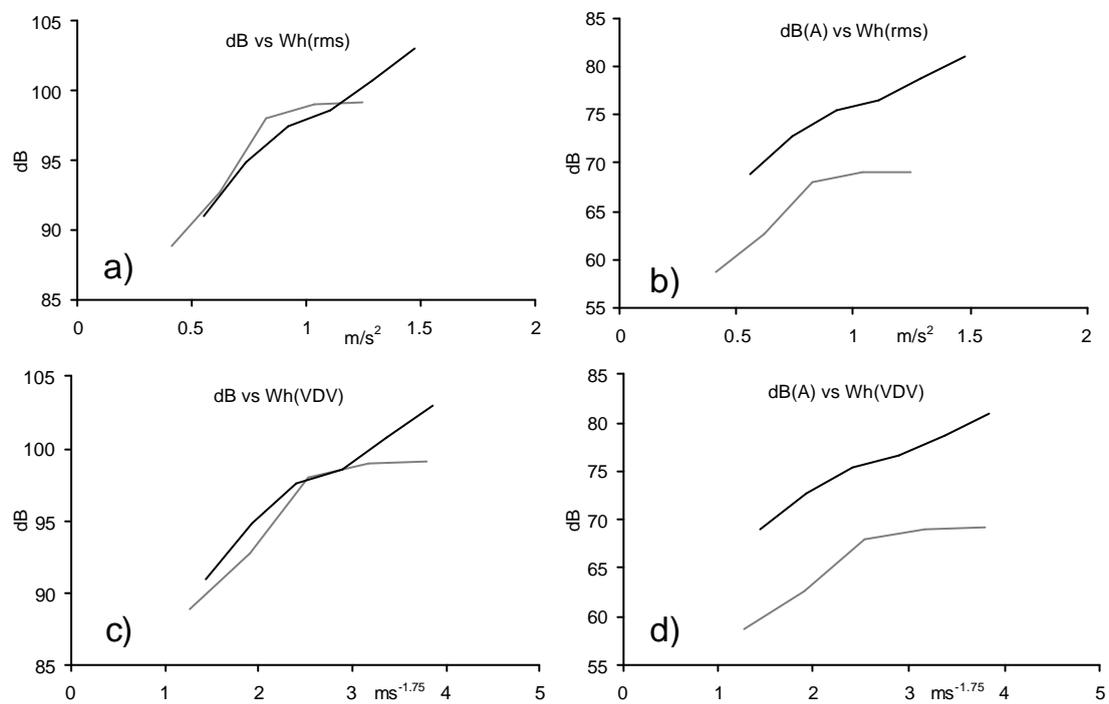
Figure 7   Influence of the decibel-A frequency weighting on the subjective equivalence curves
determined from the data for the coarse asphalt and the 1.0 cm square metal bar stimuli.
a) unweighted sound pressure level versus Wh weighted r.m.s. acceleration level
b) A-weighted sound pressure level versus Wh weighted r.m.s. acceleration level
c) unweighted sound pressure level versus Wh weighted vibration dose value
d) A-weighted sound pressure level versus Wh weighted vibration dose value