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Effect of automobile operating condition on the subjective equivalence of steering wheel vibration and sound

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Abstract

For the manufacturers of automobiles, automobile components and fuels, subjective equivalence relationships between vibration and sound can be used as a reference against which to plot the results from simulations or tests of specific operational conditions. The research described here was performed to define curves of subjective equivalence between steering wheel rotational vibration and sound using stimuli from different automobile operating conditions. The steering wheel acceleration stimuli were summarised in terms of the unweighted and W_h weighted r.m.s. values, while the sound stimuli were summarised in terms of the unweighted SPL in decibels, the A-weighted SPL in decibels, the Stevens Mark VI loudness in sones, the Stevens Mark VII loudness in sones and the Zwicker loudness in sones. The results suggest that both the statistical properties of the stimuli, and the choice of metric, effect the shape of the equivalence curve. No single combination of vibration and sound metric produced a family of curves which were separated by less than a single psychophysical just noticeable difference.

Keywords: vibration, sound, psychophysics, perception, steering, automobile.

1 Introduction

The acceleration level and the spectral content of automobile steering wheel vibration depend on several factors including the nature of the road surface, the speed of the vehicle, the dynamic characteristics of the tyres, the nature of the engine, the design of the vehicle chassis, the design of the main suspension, the design of the steering mechanism and the vibration characteristics of the steering wheel. Vibration at the steering wheel can achieve root mean square (r.m.s.) acceleration levels of 5.0 m/s^2 (Giacomin *et al.*, 2004) and the spectral energy can reach frequencies of up to 300 Hz. 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 (Demers, 2001). The pressure level and the spectral content of the sound in the passenger cabin depend on many of the same factors as the steering vibration, with a large additional factor being the geometric and absorptive properties of the acoustical cavity of the cabin. Interior automobile sound levels are typically in the range from 60 to 106 dB and are characterized by large frequency components from 20 to 1000 Hz, with little energy normally present above 5000 Hz (Young and

Jordan, 1981). For the steering wheel an interesting question is which of the stimuli reaching the driver, the vibration or the sound, is more unpleasant. Knowing the relative importance can help to establish which of the two requires greater attention during the vehicle development programme.

Parizet *et al.* (2004) have studied the human perception of combined vibration and sound for diesel engine automobiles running at idle using a test rig which reproduced vertical direction seat vibration, fore-and-aft direction steering wheel vibration and interior sound. Measurements were recorded from six mid-sized automobiles equipped with 4-cylinder common rail diesel engines which had cubic capacities ranging from 1.7 to 2.1 litres. The test stimuli were 7 seconds in length and consisted of seat acceleration levels ranging from 0.1 to 0.8 r.m.s. m/s^2, of steering wheel ISO 5349-1 (2001) W_h weighted acceleration levels ranging from 0.7 to 3.0 r.m.s. m/s^2 and of headphone applied A-weighted sound pressure levels ranging from 51 to 60 dB(A). In the experiment, 34 participants were asked to indicate which stimuli, the vibration or the sound, was felt to be the “more comfortable” in a paired-comparison format. Regression lines describing the combined perception of vibration and sound were produced. The vibration was found to have only a slight effect on the perception of sound, with high levels of vibration influencing the perception of low levels of sound. The result was in agreement with those of Paulsen and Kastka (1995) and Howarth and Griffin (1991) for combined whole-body seat vibration and sound.

Amman *et al.* have investigated the human subjective response to combined vibration and sound experienced when driving over an obstacle (Amman *et al.*, 2005a) and when driving over a coarse road surface (Amman *et al.*, 2005b). In each experiment 24 participants were presented 62 pairs of simultaneous vibration and sound stimuli in a paired-comparison format, and were asked to select the stimulus that was “most preferred”. The experiments used an automobile simulator which reproduced seat vibration along six degrees-of-freedom, floor vibration along the vertical direction, steering wheel vibration along four degrees-of-freedom (vertical, lateral, fore-and-aft, and rotation) and binaural sound. The vibration test stimuli were band limited to the range from 3 to 100 Hz, whereas the sound stimuli contained spectral energy from 20 to 16,000 Hz. Unlike past studies performed using railway (Howarth and Griffin, 1991) or aircraft (Västfjäll *et al.*, 2003) whole-body vibration and sound, Amman *et al.*’s results showed no evidence of interaction between the two stimuli. Regression lines describing the combined perception of vibration and sound were produced, with both stimuli being found to contribute almost equally. The sound was found to be slightly more important in the case of the coarse road surface, whereas the vibration was found to have somewhat more influence in the case of the impact transient event.

Giacomin and Fustes (2005) investigated the human subjective equivalence between rotational steering wheel vibration and interior automobile sound in two experiments. Test stimuli used in the first experiment were scaled copies of a 15-second segment of a time history which had been measured in an automobile when driving at a constant speed of 80 km/h over a coarse asphalt road surface. Test stimuli used in the second experiment were scaled copies of a 1-second time history segment obtained when driving at a constant speed of 20 km/h over a 1.0 cm square metal bar. The acceleration time histories were scaled to eight root mean square 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 sound pressure level (SPL). In each experiment 20 participants were presented 64 pairs of simultaneous vibration and sound in a simulator which reproduced a driving posture. The test participants were asked to indicate which stimuli, the vibration or the sound, was felt to be the ‘‘more unpleasant’’. Curves of subjective equivalence were produced and the human response to the vibration was found to increase in relative importance with respect to the sound in the case of the short duration, transient, square metal bar stimuli.

An important scientific question which has not been fully addressed in the previous research is the question of which psychophysical metrics are the most efficient for representing each of the two stimuli. Intuitively, it might be expected that any quantifiable interrelation and interaction effects between vibration and sound will depend for their size and extent on the engineering metrics used to measure each individually. Measurement metrics introduce additional analytical transformations into the equivalence relationship, and thus should be chosen with care. There are currently, however, no standard metrics for quantifying the perceived intensity of vibration and sound when presented together as a combined stimuli.

In the case of the human perception of hand-arm vibration, both the unweighted acceleration and the W_h-weighted acceleration defined by International Organization for Standardization ISO 5349-1 are widely used to evaluate subjectively perceived intensity. While not originally intended as a measure of perceived intensity, the W_h frequency weighting does provide an approximate model of the nonlinear response of the hand-arm system over the frequency range from 8 to 1000 Hz (ISO5349-1, 2001). In the case of the human perception of sound, the A-weighted sound pressure level defined by international specification IEC 60651 (1979) and both the Stevens and the Zwicker loudness methods which are defined by International Organization for Standardization ISO 532 (1975) are regularly used to evaluate perceived intensity (Auken and Zellner, 1998; Quinlan, 1994). The A-weighting provides an approximate model of the nonlinear response of the human ear over the frequency range from 20 to 20,000 Hz. Being derived from the Fletcher-Munson 40-phon equal-loudness curve (Zwicker and Fastl, 1990), however, it varies only with frequency and not with pressure level. In contrast, the Stevens loudness and the Zwicker loudness methods both use a family of equal-loudness curves which vary with both frequency and sound pressure level. The Stevens method provides a linear scale of loudness in units of sones which is based on a calculation involving one-third octave bands from 5.0 to 10,000 Hz and a procedure for quantifying the effects of mutual masking among the spectral components. The method provides two loudness descriptors, called the Stevens Mark VI (Stevens, 1961) and the Stevens Mark VII (Stevens, 1971), which differ mainly in the shape of the equal loudness curves. The Zwicker method provides a linear scale in units of sones which is based on a calculation involving one-third octave bands from 25 to 12,500 Hz and on procedures for quantifying the effects of frequency masking. ISO standard 532 defines the Zwicker loudness method for use in the case of continuous, steady-state sounds. An additional procedure (Zwicker, 1977) is also available for quantifying simultaneously the effects of both frequency and temporal masking in the case of time-varying sounds.

The primary objective of the study described here was to define subjective equivalence relationships between rotational steering wheel vibration and sound for several automobile operating conditions. The secondary objective was to compare the equivalence relationships which arise from the use of the most commonly applied methods for estimating the human subjective response to vibration and sound stimuli.

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 325 mm diameter aluminium 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 LMS EMON software system (LMS International, 2002), coupled to a DIFA SCADAS III electronic front-end 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. The safety features of the rig and the acceleration levels used conform to the health and safety recommendations outlined by British Standards Institution BS 7085 (1989).

[insert Figure 1 here]   [insert Table 1 here]

Calibration tests were performed using three participants 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. 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.

2.2 Test stimuli

A set of four automotive test stimuli were chosen which had significantly different statistical properties. Figure 2 presents the steering wheel acceleration time histories and the power spectral densities of the four test stimuli, while Figure 3 presents the same quantities for the sound pressure time histories which were simultaneously recorded. Table 2 presents the summary of the global statistical properties of each test stimulus, together with those of the stimuli which were previously used by Giacomin and Fustes (2005). The steering wheel acceleration time histories were tangential direction stimuli at the 90 degree position along the wheel, while the sound pressure time histories were driver right ear stimuli.

[insert here Table 2]

The first test stimulus was measured in an automobile when driving at a constant speed of 80 km/h over a country lane road surface. A 15-second segment of a time history was used which had an r.m.s. acceleration level of 1.79 m/s^2 and a sound pressure level of 97.1 dB. From the power spectral densities and the global statistical values it can be seen that the first stimulus can be broadly classified as a coloured, broad-band random vibration (Erdreich, 1986). In particular, the skewness value of the acceleration and sound pressure signals are both close to 0.0 and the kurtosis values are close to 3.0, suggesting a Gaussian distributed process. The second test stimulus was measured in an automobile when driving at a constant speed of 20 km/h over a stone on the road. A 1-second segment of a time history was used which began at the start of contact between the front tyres and the stone and which ended when the vibration had decayed after contact with the rear tyres. The r.m.s. acceleration level was 0.72 m/s^2 and the sound pressure level was 89.8 dB. The second test stimulus can be broadly classified as a short duration impact transient. In particular, the skewness, kurtosis and crest factor values are much higher than those of a random process.

The third test stimulus was measured in a common rail diesel engine automobile which was at idle at 740 rpm, combusting a diesel fuel characterized by a cetane number of 50.4. A 15-second time history segment was used which had an r.m.s. level of 0.35 m/s^2 and an amplitude modulation depth m (Ajovalasit and Giacomin, 2005) of 0.3 for the acceleration, and a pressure level of 94.6 dB and modulation depth of 0.4 for the sound. The fourth test stimulus was measured in a mechanical rotary distributor equipped diesel engine automobile which was at idle at 800 rpm combusting the same diesel fuel. A 15-second time history segment was used which had an r.m.s. level of 0.21 m/s^2 and modulation depth m of 0.8 for the acceleration, and a pressure level of 92.2 dB and modulation depth of 0.6 for the sound. The third test stimulus provided a weakly modulated condition ($m<0.5$) while the fourth provided a strongly modulated condition ($m>0.5$) (Ajovalasit and Giacomin, 2005).

For the laboratory experiment, eight copies of each of the four acceleration time histories were constructed by rescaling the data such that the r.m.s. amplitudes were exactly 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5 and 4.0 m/s^2 for the two driving conditions and 0.4, 0.5, 0.6, 0.75, 1.0, 1.25, 1.5, 1.75 m/s^2 for the two idle conditions. Eight copies of each of the four 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 for both the driving and the idle conditions. By arranging all possible combinations of vibration and sound, a total of 64 pairs were produced for each of the four conditions. A check of stimuli reproduction accuracy was performed with 10 participants who were asked to adopt a realistic driving posture, and to grip the steering wheel using both hands, applying the grip strength that would be used when driving on a winding country road. 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 participant 10 applications of each stimuli pair were performed and the response measurements averaged. The maximum r.m.s. acceleration error was found to be 15 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.

[insert Figure 2 here]   [insert Figure 3 here]

2.3 Test protocol

Four experiments were performed. Each involved 64 stimuli pairs of combined steering wheel vibration and binaural sound. Experiment 1 reproduced stimuli from the country lane road surface, experiment 2 reproduced stimuli from the stone-on-road obstacle, experiment 3 reproduced stimuli from the common rail diesel engine idle weakly modulated condition, while experiment 4 reproduced stimuli from the mechanical rotary pump diesel engine idle strongly modulated condition. To minimise fatigue and learning effects, the order of presentation of the combined test stimuli was randomized for each participant. Except for the stimuli type and the total time duration, all other aspects of the four experiments were identical. Total time from when the test participant entered the laboratory to when he or she completed all testing was 38 minutes for experiments 1, 3 and 4, and 30 minutes for experiment 2. Room temperature was from 20 to 25° centigrade during all tests.

Twenty university students and staff participated in each experiment. Upon arriving in the laboratory each participant was issued an information and consent form. Age, gender, weight, and height data were then collected, and the participant was requested to state whether he or she had any physical or mental condition which might effect the 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. No participant from the four groups 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. The physical characteristics of the four groups of test participants are summarised in Table 3. In order to determine whether age, weight and height characteristics lead to any statistically significant difference between the experimental groups, a one-factor independent measures ANOVA test was applied to the data for each of the physical characteristics chosen as the dependent variable. At a 0.05 confidence level and for the sample size (n=20) considered, no significant differences were found between the groups with respect of each physical characteristic considered.

Before commencing testing 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 combined stimuli, which of the two he or she felt was the ”more unpleasant”. Two preliminary tests (whose data were 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 (0.5 m/s^2 and 88 dB). The facility and protocol were reviewed and found to meet University guidelines for good research practice.

[insert here Table 3]

3 Results

The steering wheel acceleration time histories used in the four experiments described above and in the two previous experiments reported by Giacomin and Fustes (2005) were analysed to determine the unweighted and W_h weighted r.m.s. values. The sound pressure time histories were also analysed to determine the unweighted sound pressure level in decibels, the A-weighted sound pressure level in decibels, the Stevens Mark VI loudness in sones, the Stevens Mark VII loudness in sones and the Zwicker loudness in sones. All vibration and sound the metrics were calculated using the LMS Cada-X 3.5 E software (LMS International, 2002), which contains a W_h frequency weighting which is based on ISO standard 5349-1, an acoustical A-weighting which is based on IEC 60651, and both Stevens and Zwicker loudness methods which are based on ISO standard 532. In the case of the Zwicker loudness, the LMS software implementation includes temporal masking effects (Zwicker, 1977). All Stevens and Zwicker loudness metrics were calculated using one third octave analysis and a diffuse field assumption.

The relative frequency, expressed as a percentage, that each sound stimulus was considered to be “the more unpleasant” was calculated for each vibration level for each of the 64 pairs of combined stimuli. In order to test internal consistency, a Chi-square X^2 test of independence (Hinton, 1999) was performed to verify if the pattern of frequencies observed at each vibration level was statistically different from that of the other vibration levels. Significant difference in the responses were found in all cases at a p=0.01 level of significance with a X^2 value of 84.5 obtained for experiment I, of 83.7 for experiment II, of 81.0 for experiment III and of 82.2 for experiment IV.

The calculation results were collected into ten datasets defined by all possible combinations of the two vibration metrics and the five sound metrics. For each of the ten datasets a cumulative normal distribution function (Montgomery and Runger, 1999) was then fitted at each r.m.s. acceleration amplitude in the dataset and used to estimate the 25th, 50th and 75th percentile preferences of sound as the “more unpleasant” stimuli. The 50th percentile values were used to define the points of subjective equivalence between the two stimuli. The difference between the 25th and 75th percentile values, which defined the inter-quartile-range (IQR), was used to provide a measure of the variability of the subjective equivalence points around the mean values. Table 4 presents the subjective equivalence values of sound and the inter-quartile-ranges for each of the acceleration stimuli for all six automobile operating conditions. Data are not provided for several acceleration amplitudes because at the amplitudes in question the statistical distributions deviated substantially from a Gaussian assumption due to the near-complete preference for one stimulus over the other.

[insert Table 4 here]

In Table 4 each row is relative to one of the six test stimuli while the columns contain the corresponding vibration and sound metrics, along with the associated inter-quartile-ranges. It can be seen that the numerical values of each column occupy different numerical intervals. For example, the use of the W_h frequency weighting for the steering wheel acceleration time histories reduces the numerical range of the root mean square acceleration by approximately half, while the use of the Stevens or Zwicker loudness reduces the maximum numerical value of the sound metric by more than half with respect to the unweighted sound pressure level. Further, when expressed as inter-quartile-range, the data of Table 4 suggests that the range of variability of each of the points of the subjective equivalence across the different automobile operating conditions occupies almost similar numerical intervals of variation around the means for each of the five sound intensity metric used. The different numerical ranges occupied by the various metrics have obvious implications on any functional relationships which are to be determined from the data.

Figure 4 presents the 10 sets of subjective equivalence curves which are obtained by plotting each of the five sound metrics as a function of each of the two vibration metrics. Each plot contains the subjective equivalence curves obtained for each of the six test stimuli. All data sets suggest monotonically increasing relationships, however differences appear among the data sets depending on which metrics are used. The use of some combinations of the vibration and sound metrics suggests a large change in the points of subjective equivalence with changes in the statistical properties of the stimuli (for example dB and unweighted r.m.s.), while other combinations appear less subject to variation (for example Stevens Mark VI and unweighted r.m.s.). Further, the achievement of a linear expression of subjective equivalence appears to be facilitated by the use of the Stevens and Zwicker loudness methods, independent of the choice of the vibration metric.

[insert Figure 4 here]

Tables 5 and 6 present the differences between the lowest and the highest subjective equivalence values among the six test stimuli curves found at each unweighted r.m.s. amplitude, and each W_h-weighted r.m.s. amplitude, respectively. The difference values are expressed both in the original units of the metric and as a percentage of the largest values found for the metric in the dataset. With the possible exception of the sound pressure level in unweighted units of decibels, most data in Tables 5 and 6 suggest the hypothesis that the use of the W_h frequency weighting increases the sensitivity of the subjective equivalence curve to the statistical properties of the stimuli (i.e., increases the sensitivity to the automobile operating condition). When expressed as a percentage of the maximum value found in the dataset, the data of Tables 5 and 6 also suggest the hypothesis that the use of any of the three most complex loudness estimation procedures, i.e. the Stevens Mark VI, the Stevens Mark VII and the Zwicker methodologies, leads to increases in the relative differences between the subjective equivalence curves obtained from the different test stimuli.

[insert Table 5 here]   [insert Table 6 here]

4 Discussion

The results obtained in the current investigation show that the relationship of subjective equivalence between steering wheel vibration and sound is dependent on the statistical properties of the two stimuli. As an example, the transient stimuli of the stone-on-road and the 1.0 cm metal bar driving conditions were found to produce equivalent sound values which were generally lower than the values obtained for the steady-state conditions. This occurred despite the fact that, theoretically, the stimuli should have been accurately quantified by the Zwicker loudness method due to its algorithms for both frequency and temporal auditory masking. In addition, the inter-quartile-ranges of variability calculated for each point of the subjective equivalence curves of the six stimuli suggest that the individual variation of the subjective equivalence values are generally smaller than the differences found between the curves obtained using the different stimuli.

The results obtained in the current investigation also suggest that the statistical differences associated with differences in automobile operating condition are important in psychophysical terms. As an example, the differences between the curves of subjective equivalence reached values of more than 5 dB when expressed in terms of the unweighted sound pressure level or the A-weighted sound pressure level. Such differences are larger than the well-known human just-noticeable difference (Zwicker and Fastl, 1990) value of approximately 1 dB needed to detect the smallest perceptible change in sound. When quantified using the Stevens or Zwicker loudness methods, differences of 3 to 32 sones occurred between the lowest and the highest subjective equivalence data points. These values are greater than the value of the just noticeable difference reported in the case of refrigerator noise (Jeon *et al.*, 2006) of 0.5 sone determined using the Zwicker loudness method, and are also greater than the maximum permissible sound quantisation error of from 0.8 to 6.4 sones (at amplitudes from 40 to 70 dB) which has been found to lead to severe reductions in speech intelligibility (Mannell, 1991).

For the manufacturers of automobiles, automobile components and fuels, subjective equivalence relationships between vibration and sound can serve a useful purpose during product design since the relationship can be used as a background against which to plot the results from simulation or test of specific operational conditions. Equivalence curves can provide a simple ruler against which to judge the balance of the two stimuli. The distance of a specific operational condition from the curve of subjective equivalence, in units of perceived intensity, provides a measure of which of the two stimuli types is the most prominent.

The possibility of using these relationships in such ways raises, however, questions regarding the invariance and accuracy of the equivalence relationship, and regarding the most convenient technical measurement methods to adopt. In the case of the vibration experienced by the driver due to the movement of the automotive steering wheel, the most commonly used metrics of perceived intensity are the unweighted and the W_h weighted root mean square acceleration. Neither measure is rigorously applicable to the task of perceived intensity estimation, but the W_h weighting has been shown to provide more accurate estimates (Bellmann *et al.*, 2001) than its unweighted counterpart. In recent years proposals have been put forward for a new hand-arm frequency weighting derived from psychophysical test results with rotating steering wheels (Amman *et al.*, 2005c; Giacomin *et al.*, 2004), but such developments are still in their infancy. In the case of sound, the research literature provides evidence that the use of the popular acoustical A-weighting underestimates the loudness of perceived sound due to its inability to represent the nonlinear response characteristics of the human ear (Quinlan, 1994). In the automotive industry several studies (Banovese and Gibian, 1985) have raised uncertainty about the use of this metric for the subjective evaluation of the loudness of interior sound. Automotive research (Auken and Zellner, 1998) has also suggested that Zwicker loudness correlates best with the subjective judgments of automobile interior sound.

The current study has directly applied the most commonly used vibration and sound perceived intensity metrics to the task of defining subjective equivalence. The results suggest that both the statistical properties of the stimuli, and the choice of metric, affect the shape of the equivalence curve. No single combination of sound and vibration metric produced a family of curves which were separated by less than a single psychophysical just noticeable difference. Further, the results suggest greater separation of the curves when passing from unweighted to frequency weighted acceleration, and when adopting sound metrics characterised by increasing ability to correctly represent frequency and temporal auditory masking. The more sophisticated perceptual metric, the less likely it appears that a single equivalence curve can be defined which is applicable to all operating conditions. Therefore, the current results would suggest a trade-off between the accuracy of the human perception metric and the ability of defining a single curve of subjective equivalence.

5 Conclusions

Subjective equivalence relationships between steering wheel vibration and sound have been developed for six automobile operating conditions by means of laboratory tests performed using a steering rotational vibration test rig. The relationships have been developed using ten different formats, determined by all possible combinations of two perceived vibration intensity metrics and five perceived sound intensity metrics. The results suggest that both the statistical properties of the stimuli, and the choice of metric, affect the shape of the equivalence curve. No single combination of sound and vibration metric produced a family of curves which were separated by less than a single psychophysical just noticeable difference. Further, the results suggest an increased divergence of the curves when passing from unweighted to frequency weighted acceleration, and when adopting sound metrics characterised by increasing ability to correctly represent frequency and temporal auditory masking.

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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 handle diameter	12.5 mm
Steering wheel diameter	325 mm

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

					Vibration signal statistics				Sound signal statistics			
Operating contidion	Vehicle / Engine speed	Type of stimuli	Duration [s]	Main frequency range [Hz]	r.m.s. [m/s^2]	Skewness	Kurtosis	Crest factor	Sound pressure level [dB]	Skewness	Kurtosis	Crest factor
Country lane driving	80 km/h	steady-state random	15	10-300	1.79	0.02	3.26	3.94	97.10	0.00	3.61	4.18
Coarse asphalt driving (Giacomin and Fustes, 2005)	80 km/h	steady-state random	15	10-300	1.12	-0.02	3.04	3.81	91.80	0.02	2.91	3.65
1.0 cm sqaure metal bar driving (Giacomin and Fustes, 2005)	40 km/h	transient	1	10-60	1.28	0.67	14.36	8.99	97.30	0.14	12.39	6.51
Stone on road driving	20 km/h	transient	1	10-60	0.72	-0.11	11.27	6.15	89.80	0.35	21.70	8.51
Diesel engine idle	740 rpm (idle)	weak amplitude-modulation, m<0.5	15	18-30	0.35	-0.10	1.60	1.90	94.60	0.00	1.52	1.70
Diesel engine idle	800 rpm (idle)	strong amplitude-modulation, m>0.5	15	20-33	0.21	-0.35	1.92	2.18	92.20	0.56	1.86	1.75

Table 2) Global statistical properties of the four acceleration and sound stimuli used in the laboratory experiments and the two stimuli previously used by Giacomin and Fustes (2005).

		Age [years]	Weight [kg]	Height [m]
Experiment 1 (country lane) (n=20, m=15, f=5)	Mean (SD)	29.6 (6.8)	78.40 (16.8)	1.71 (0.1)
	Minimum	22.0	47.0	1.50
	Maximum	47.0	104.0	1.86
Experiment 2 (stone on road) (n=20, m=15, f=5)	Mean (SD)	29.8 (6.1)	75.4 (16.1)	1.72 (0.1)
	Minimum	22.0	48.0	1.55
	Maximum	45.0	98.0	1.80
Experiment 3 (diesel engine idle - weak amplitude modulation) (n=20, m=14, f=6)	Mean (SD)	27.1 (4.7)	71.0 (17.7)	1.72 (0.1)
	Minimum	20.0	45.0	1.50
	Maximum	42.0	110.0	1.88
Experiment 4 (diesel engine idle - strong amplitude modulation) (n=20, m=15, f=5)	Mean (SD)	30.1 (8.0)	74.4 (15.5)	1.70 (0.1)
	Minimum	22.0	44.5	1.52
	Maximum	55.0	100.0	1.90

Table 3) Physical characteristics of the four groups of test participants involved in the laboratory experiments.

Operating contidion	Unweighted vibration level [m/s^2 r.m.s.]	W_h frequency-weighted vibration level [m/s^2 r.m.s.]	Sound pressure level [dB]	A-weighted sound pressure level [dBA]	Stevens loudness Mark VI [sone]	Stevens loudness Mark VII [sone]	Zwicker loudness [sone]
Country lane driving	0.5	0.28	——	——	——	——	——
	1.0	0.56	90.3 (9.3)	62.3 (8.1)	15.5 (10.0)	13.3 (11.8)	11.2 (8.2)
	1.5	0.84	97.9 (5.6)	69.9 (5.7)	25.9 (10.7)	26.2 (12.7)	20.1 (8.1)
	2.0	1.12	101.3 (4.4)	73.3 (4.2)	33.2 (9.6)	35.3 (13.3)	25.5 (7.7)
	2.5	1.41	105.5 (7.7)	77.6 (7.7)	45.7 (11.7)	50.6 (14.0)	34.8 (17.0)
	3.0	1.69	105.6 (5.9)	77.7 (6.1)	45.8 (9.5)	51.2 (13.4)	35.0 (13.3)
	3.5	1.97	106.0 (7.6)	78.0 (7.8)	47.2 (10.8)	53.0 (15.3)	36.0 (18.5)
	4.0	2.25	——	——	——	——	——
Coarse asphalt driving (Giacomin and Fustes, 2005)	0.5	0.18	——	——	——	——	——
	1.0	0.37	——	——	——	——	——
	1.5	0.55	91.0 (9.0)	68.9 (9.0)	22.5 (13.0)	28.3 (18.7)	23.4 (13.5)
	2.0	0.74	94.8 (8.9)	72.7 (8.9)	29.0 (14.2)	38.0 (17.2)	30.1 (14.6)
	2.5	0.92	97.5 (9.0)	75.4 (9.0)	34.8 (18.8)	46.9 (19.5)	35.8 (18.3)
	3.0	1.11	98.6 (2.7)	76.5 (2.7)	37.8 (7.1)	51.8 (11.5)	38.5 (6.5)
	3.5	1.29	100.8 (6.4)	78.7 (6.4)	43.8 (15.6)	61.3 (18.3)	43.8 (17.7)
	4.0	1.48	103.0 (3.2)	80.9 (3.2)	51.1 (12.0)	73.0 (14.8)	50.1 (10.1)
1.0 cm sqaure metal bar driving (Giacomin and Fustes, 2005)	0.5	0.21	——	——	——	——	——
	1.0	0.41	88.8 (7.3)	58.8 (7.3)	16.6 (9.7)	13.0 (10.4)	12.5 (8.2)
	1.5	0.62	92.7 (7.0)	62.7 (5.7)	22.0 (9.3)	18.8 (9.7)	17.0 (7.4)
	2.0	0.83	98.0 (6.8)	68.0 (6.4)	32.0 (10.2)	29.5 (11.1)	24.8 (10.4)
	2.5	1.04	99.0 (7.2)	69.0 (8.9)	34.5 (13.4)	32.7 (14.5)	26.6 (13.8)
	3.0	1.24	99.2 (2.7)	69.1 (2.7)	35.0 (4.4)	33.2 (7.9)	26.9 (5.0)
	3.5	1.45	——	——	——	——	——
	4.0	1.66	——	——	——	——	——
Stone on road driving	0.5	0.32	——	——	——	——	——
	1.0	0.64	91.0 (8.6)	61.0 (8.6)	19.0 (11.5)	17.2 (11.8)	11.4 (6.8)
	1.5	0.96	93.1 (10.1)	63.1 (9.9)	21.1 (18.3)	17.5 (13.6)	11.6 (10.8)
	2.0	1.28	97.9 (5.5)	67.8 (5.3)	30.0 (11.4)	27.0 (12.8)	16.8 (6.8)
	2.5	1.60	99.4 (3.2)	69.3 (3.2)	33.3 (7.4)	31.0 (8.8)	18.7 (4.4)
	3.0	1.92	99.5 (2.8)	69.4 (2.7)	33.5 (6.3)	31.2 (7.7)	18.8 (3.6)
	3.5	2.24	——	——	——	——	——
	4.0	2.56	——	——	——	——	——
Diesel engine idle (weak amplitude modulation)	0.4	0.26	89.6 (7.2)	47.4 (7.2)	9.3 (5.7)	3.2 (3.3)	3.3 (2.4)
	0.5	0.32	94.8 (10.6)	52.5 (10.6)	13.3 (8.3)	5.5 (4.8)	5.0 (3.4)
	0.6	0.38	94.6 (9.6)	52.5 (9.6)	13.3 (10.1)	5.5 (6.6)	5.0 (4.1)
	0.75	0.48	97.0 (14.9)	54.8 (14.9)	15.7 (15.6)	7.1 (10.4)	6.1 (6.0)
	1.0	0.64	101.0 (4.7)	58.8 (4.7)	21.6 (7.5)	11.4 (5.8)	8.2 (2.6)
	1.25	0.80	102.0 (3.9)	59.9 (3.9)	23.5 (7.7)	13.0 (6.6)	8.8 (3.4)
	1.5	0.96	103.0 (7.9)	60.8 (7.8)	25.1 (16.7)	14.3 (14.0)	9.4 (8.1)
	1.75	1.12	——	——	——	——	——
Diesel engine idle (strong amplitude modulation)	0.4	0.24	——	——	——	——	——
	0.5	0.30	——	——	——	——	——
	0.6	0.36	90.8 (6.8)	55.6 (7.2)	11.3 (5.0)	6.2 (3.9)	6.1 (2.9)
	0.75	0.44	92.5 (8.0)	56.9 (7.9)	12.8 (6.2)	7.4 (4.6)	7.1 (3.6)
	1.0	0.59	99.8 (10.9)	64.2 (12.5)	21.8 (14.0)	15.0 (10.0)	12.5 (8.3)
	1.25	0.74	100.3 (9.8)	65.0 (9.3)	23.0 (17.0)	16.3 (15.1)	13.0 (9.9)
	1.5	0.89	100.8 (5.3)	65.4 (5.3)	23.8 (9.2)	16.9 (8.3)	13.7 (5.2)
	1.75	1.04	101.2 (7.3)	65.5 (7.4)	24.4 (12.3)	17.4 (11.0)	13.8 (7.1)

Table 4) Subjective equivalence values between steering wheel tangential acceleration and binaural sound for six automobile operating conditions. Data in parentheses are the inter-quartile-range (IQR) calculated as the difference between the 25th and 75th percentile values. Each test involved 20 human participants (n=20).

Unweighted vibration level [m/s^2 r.m.s.] Equivalence sound value	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
Sound pressure level [dB]	—	12.2 (11.5%)	12.0 (11.3%)	6.4 (6.1%)	8.0 (7.5%)	7.0 (6.6%)	5.3 (5.0%)	—
A-weighted sound pressure level [dBA]	—	5.5 (6.7%)	9.2 (11.3%)	5.5 (6.8%)	8.6 (10.6%)	8.6 (10.6%)	0.7 (0.8%)	—
Stevens Mark VI loudness [sone]	—	6.3 (12.3%)	4.8 (9.4 %)	4.2 (8.2%)	12.4 (24.3%)	12.3 (24.1%)	3.5 (6.8%)	—
Stevens Mark VII loudness [sone]	—	5.8 (7.9%)	14.0 (19.2%)	11.0 (15.1%)	19.6 (26.9%)	20.6 (28.2%)	8.3 (11.3%)	—
Zwicker loudness [sone]	—	4.3 (8.6%)	14.0 (28.0%)	13.3 (26.5%)	17.1 (34.0%)	19.7 (39.3%)	7.8 (15.5%)	—

Table 5) Difference values in units of perceived acoustical intensity between the lowest and the highest subjective equivalence curves for each unweighted r.m.s. stimuli amplitude. Data in parentheses are the percentage difference values normalized to the highest equivalent sound value in the dataset.

W_h weighted vibration level [m/s^2 r.m.s.] Equivalence sound value	0.3	0.5	0.8	1	1.2	1.5	1.7	2
Sound pressure level [dB]	—	7.1 (6.7%)	10.0 (9.4%)	7.4 (7.0%)	5.8 (5.5%)	6.5 (6.1%)	6.1 (5.8%)	—
A-weighted sound pressure level [dBA]	—	5.1 (6.3%)	13.5 (16.7%)	12.3 (15.2%)	11.0 (13.6%)	8.6 (10.6%)	8.3 (10.3%)	—
Stevens Mark VI loudness [sone]	—	3.9 (7.6%)	11.0 (21.5%)	13.8 (27.0%)	13.0 (25.4)	13.4 (26.2%)	12.4 (24.3%)	—
Stevens Mark VII loudness [sone]	—	7.8 (10.7%)	28.0 (38.4%)	31.8 (43.6%)	31.9 (43.7%)	21.2 (29.0%)	20.4 (27.9%)	—
Zwicker loudness [sone]	—	7.9 (15.8%)	23.2 (46.3%)	24.6 (49.1%)	25.5 (50.9%)	16.7 (33.3%)	16.3 (32.5%)	—

Table 6) Difference values in units of perceived acoustical intensity between the lowest and the highest subjective equivalence curves for each W_h weighted r.m.s. stimuli amplitude. Data in parentheses are the percentage difference values normalized to the highest equivalent sound value in the dataset.

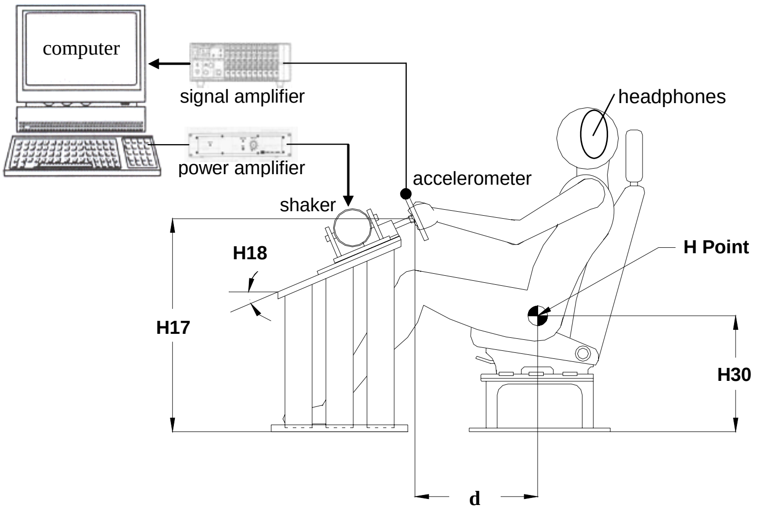

Figure 1) Schematic representation of the steering wheel rotational vibration test rig and associated electronics.

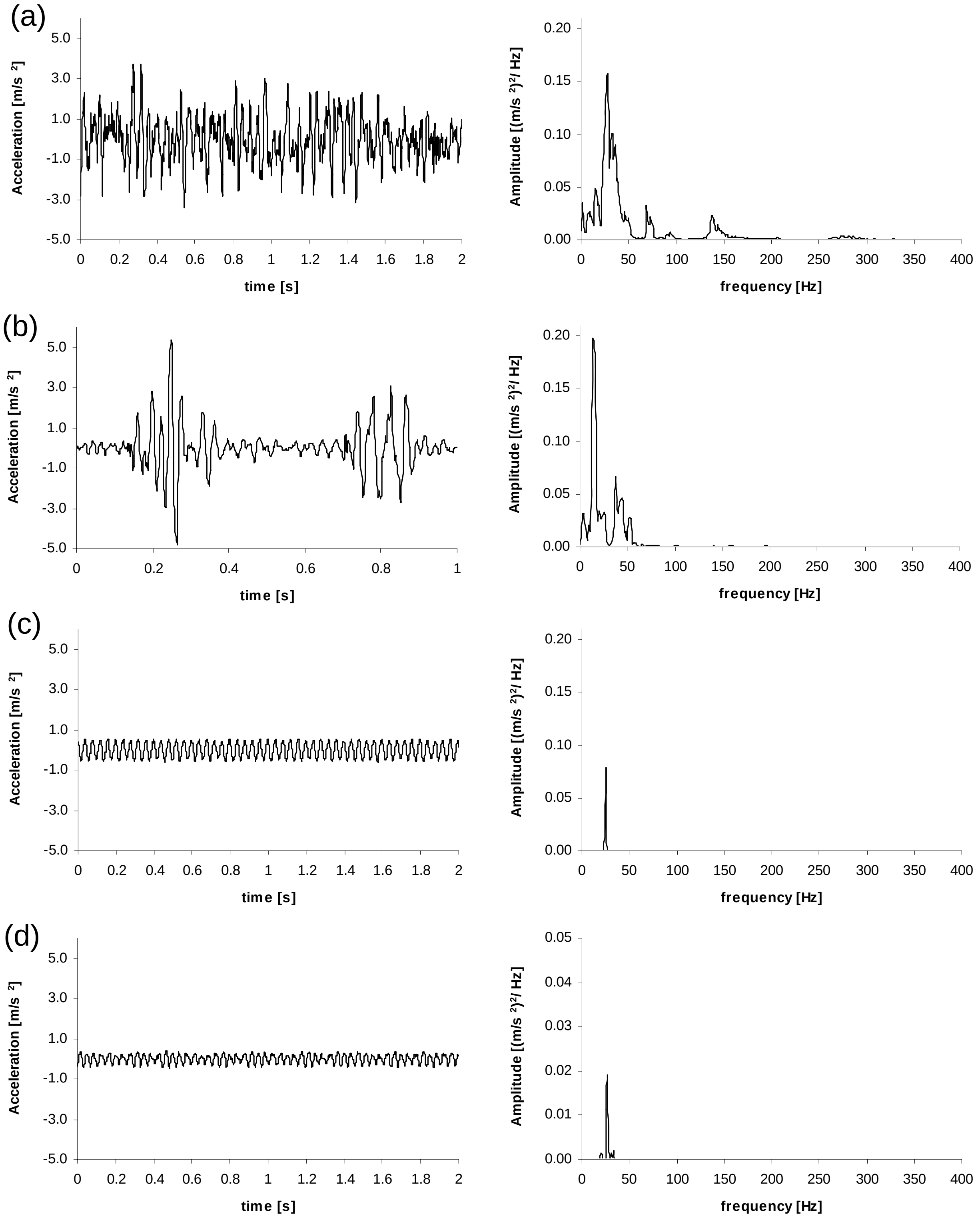

Figure 2) Acceleration time histories and power spectral densities of the four test stimuli.

(a) Country lane steering wheel tangential acceleration (80 km/h).

(b) Stone on road steering wheel tangential acceleration (20 km/h).

(c) Diesel engine idle weak amplitude modulation (m<0.5) steering wheel tangential acceleration.

(d) Diesel engine idle strong amplitude modulation (m>0.5) steering wheel tangential acceleration.

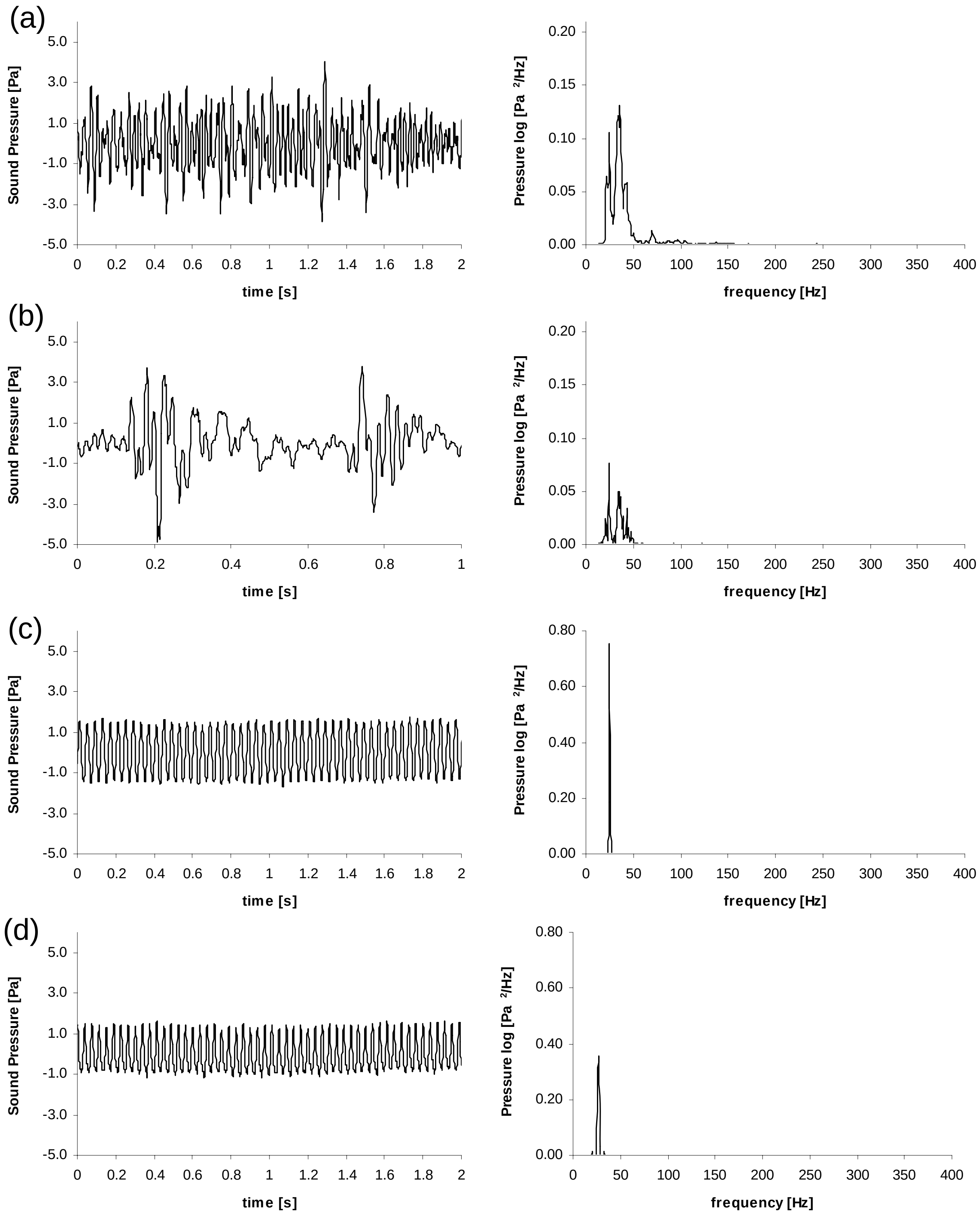

Figure 3) Sound pressure time histories and power spectral densities of the four test stimuli.

(a) Country lane interior sound at driver's right ear (80 km/h).

(b) Stone on road interior sound at driver's right ear (20 km/h).

(c) Diesel engine idle weak amplitude modulation (m<0.5) interior sound at driver's right ear.

(d) Diesel engine idle strong amplitude modulation (m>0.5) interior sound at driver's right ear.

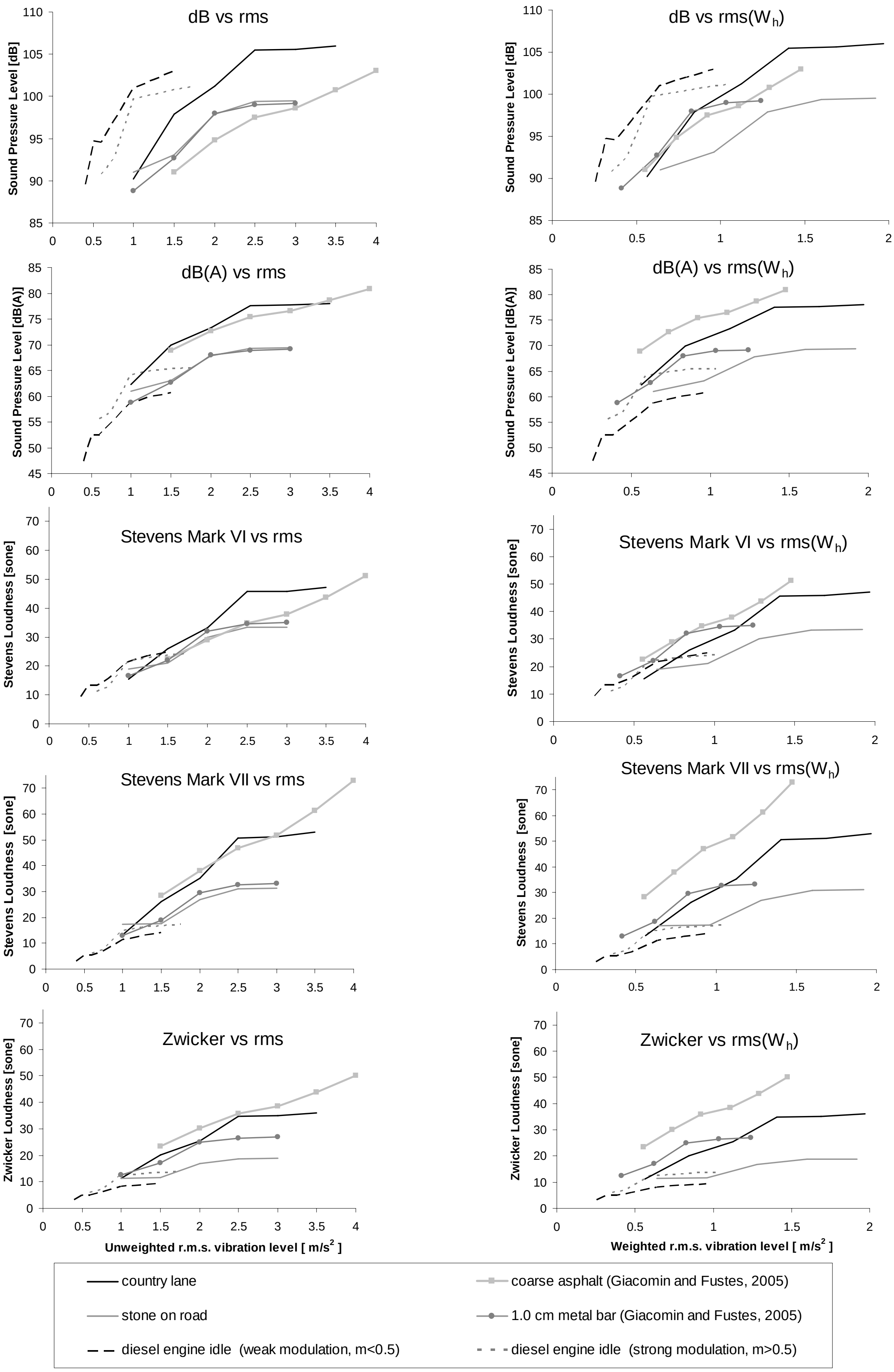

Figure 4) Subjective equivalence between steering wheel tangential acceleration and binaural sound for six automobile operating conditions. The 10 plots are all the combinations of the two perceived vibration intensity metrics and the five perceived sound loudness metrics.