Subjective Equivalence of Sound and Vibration in Vehicles

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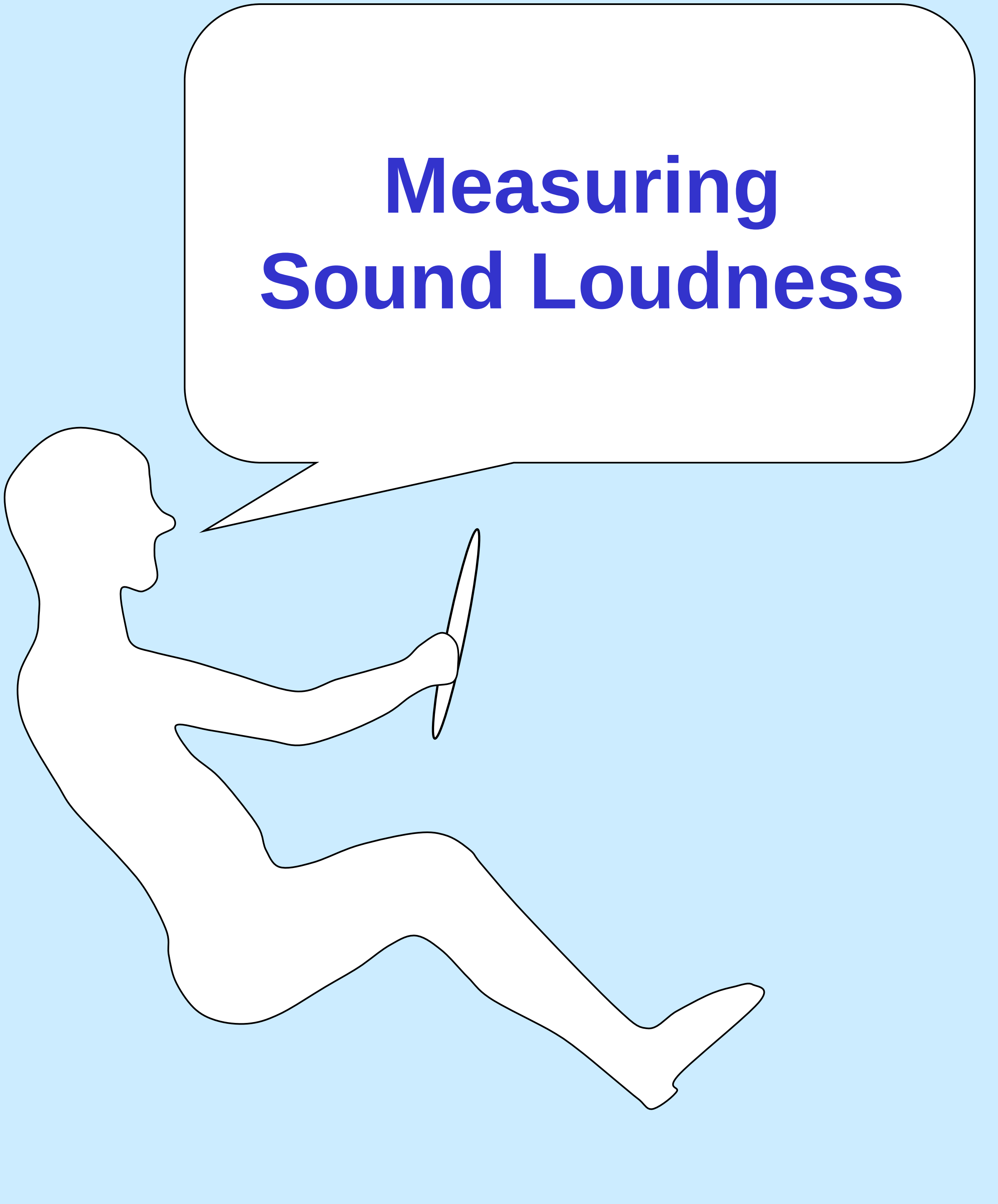

Measuring
Sound Loudness

Sound Loudness

Loudness is a complex subjective experience related to both the intensity and the frequency of the sound.

Much research has been performed over the years to develop loudness indices, two early attempts being the phon and the sone.

Phons

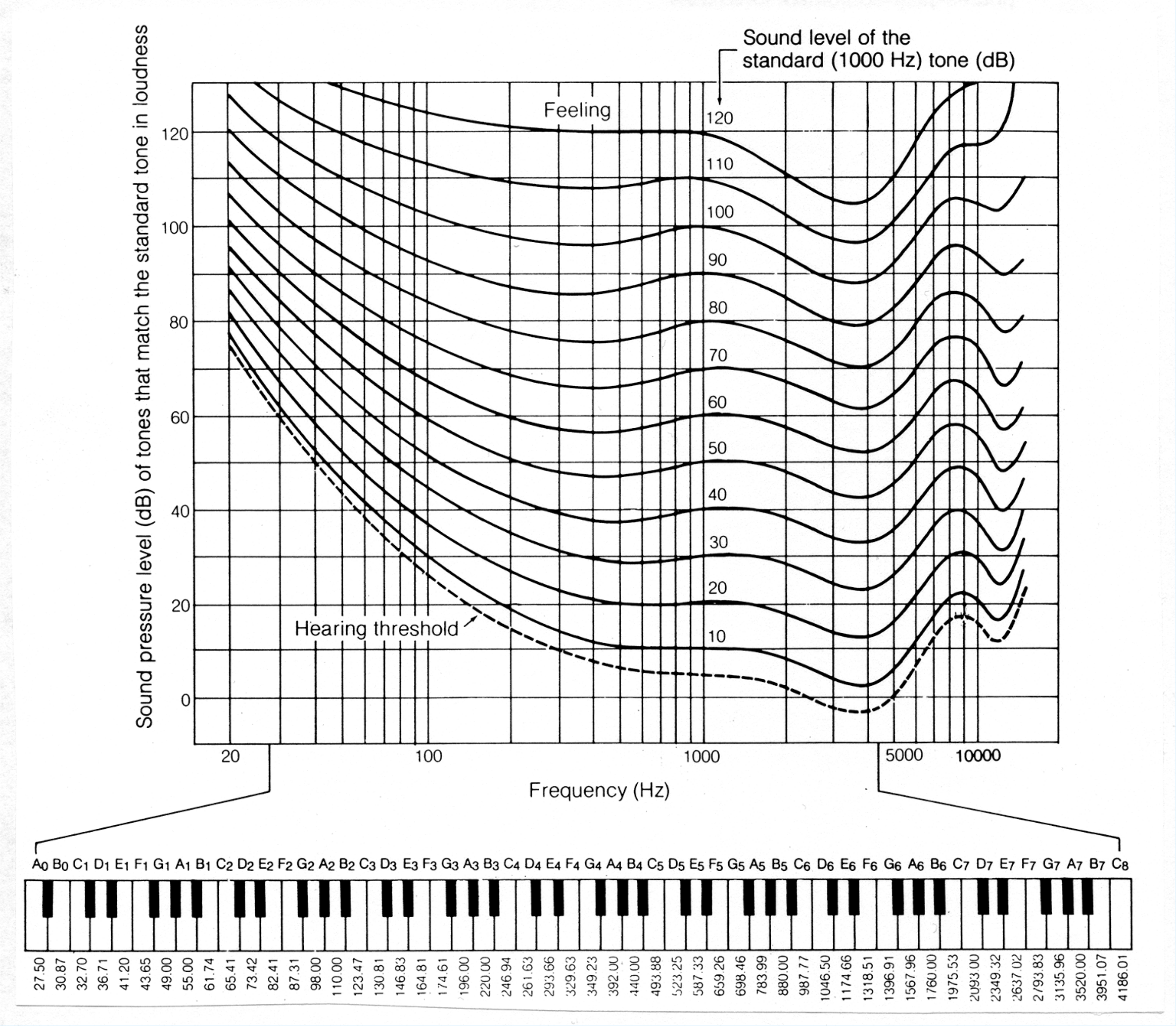
The phon was developed by experiments which used pure tone sound signals of fixed frequency and amplitude.

In each test the participant presented a 1000 Hz pure tone sound as a reference, then the sound frequency was changed and the participant was asked to adjust the amplitude of the new signal until it was of equal loudness.

By performing the test many times with different frequencies and different people it was possible to generate a set of equal-loudness curves.

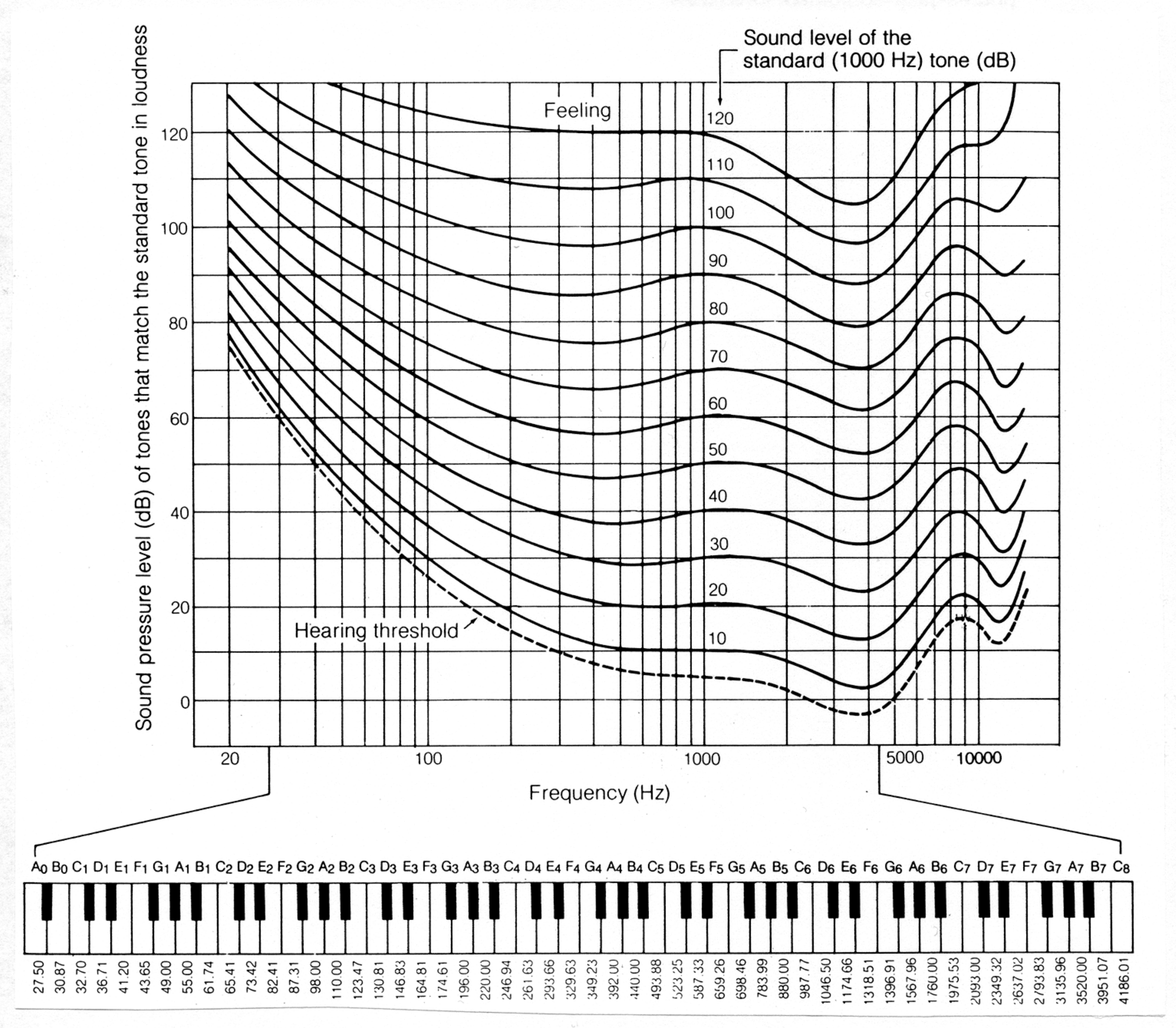
Phons

From the equal loudness curves it can be seen that human perception of loudness varies as a function of frequency. Humans are particularly sensitive to frequencies in the range from 1000 to 6000 Hz.



Phons

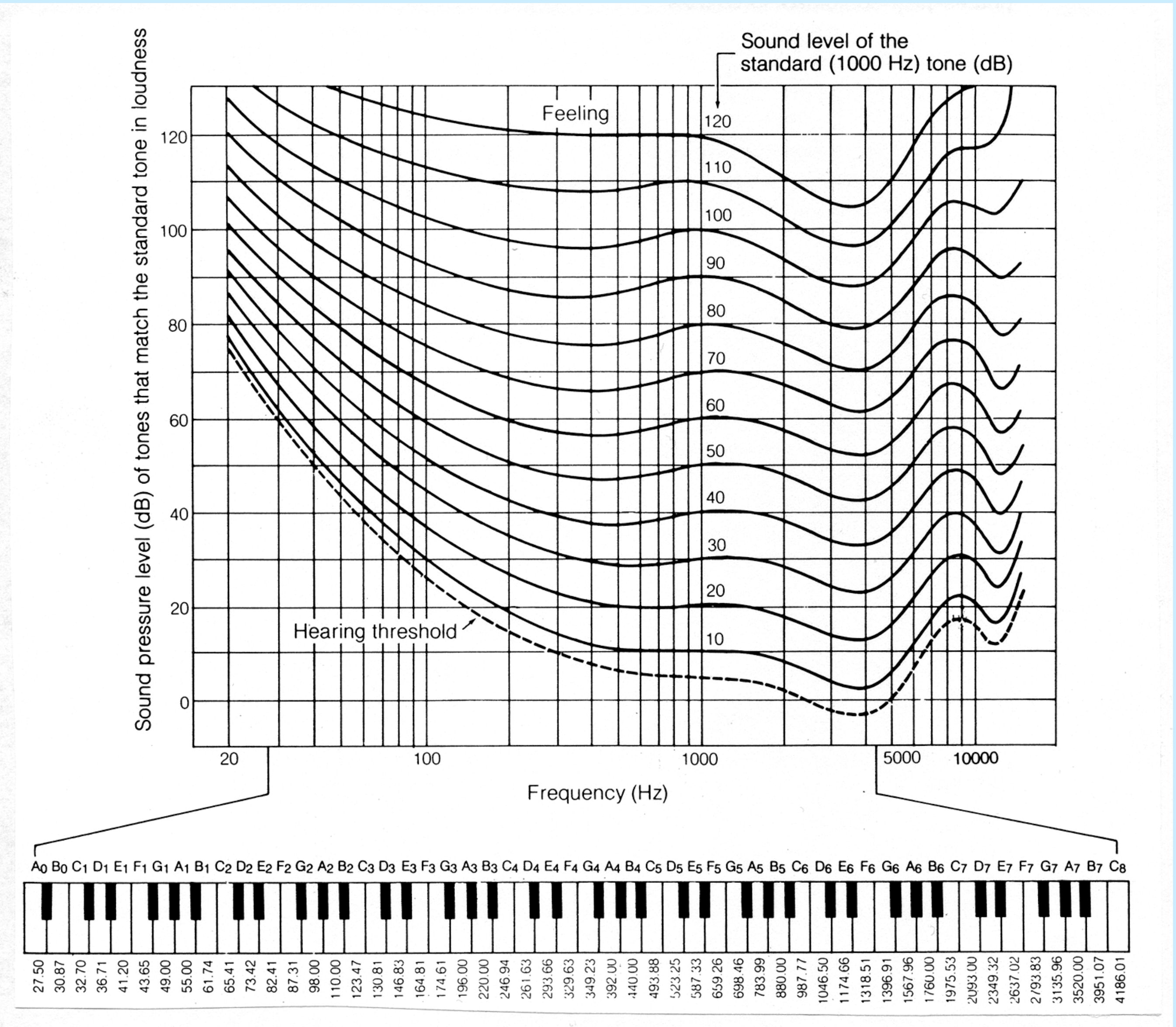
The phon was designated the unit of loudness and was set equal to the decibel level of the 1000 Hz reference tone. For example, all tones judged to be of equal loudness to the 60 dB reference tone are designated as having a loudness of 60 phons.



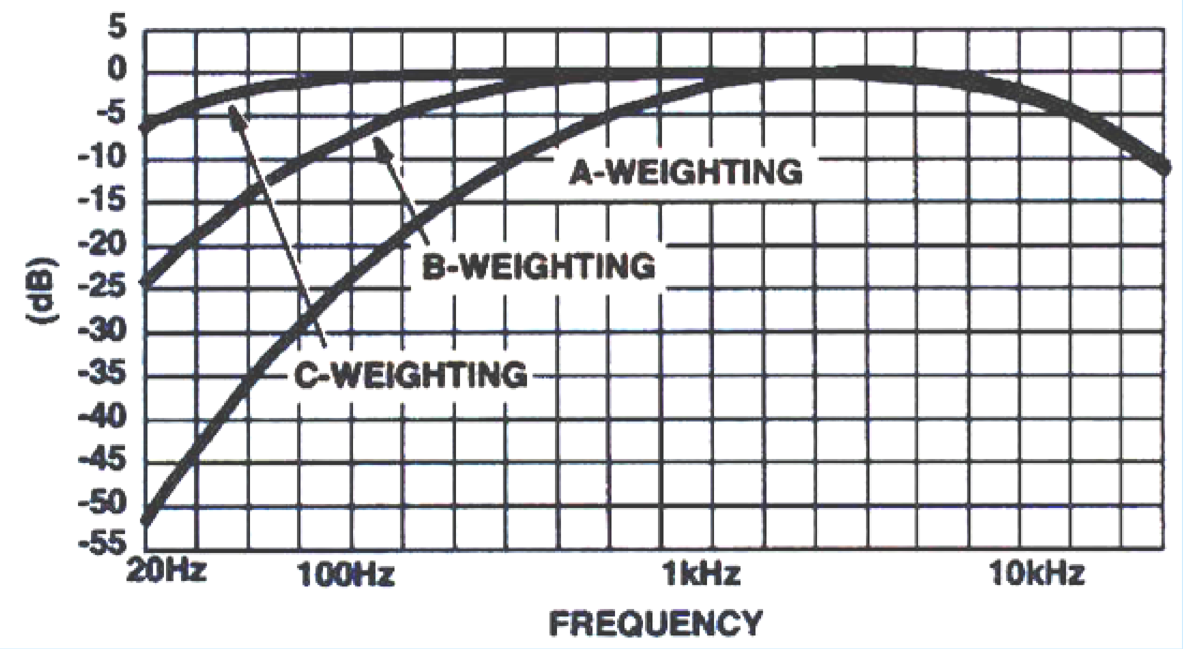
dB(A) Loudness

The frequency weighting networks used in sound level meters are based on the phon curves developed by Fletcher and Munson.

The A and B frequency weightings are the 40 and 70 phon contours, but with some minor modifications to simply the required electrical filter network.



dB(A) Loudness



The **A-weighted Sound Pressure Level L_A** is defined as

$$L_A = 10\,Log_{10}\left[\frac{p_A(t)}{p_{referecne}}\right]^2 \quad dB$$

Where $p_A(t)$ is the instantaneous sound pressure measured using the standard A scale frequency weighting shown below.

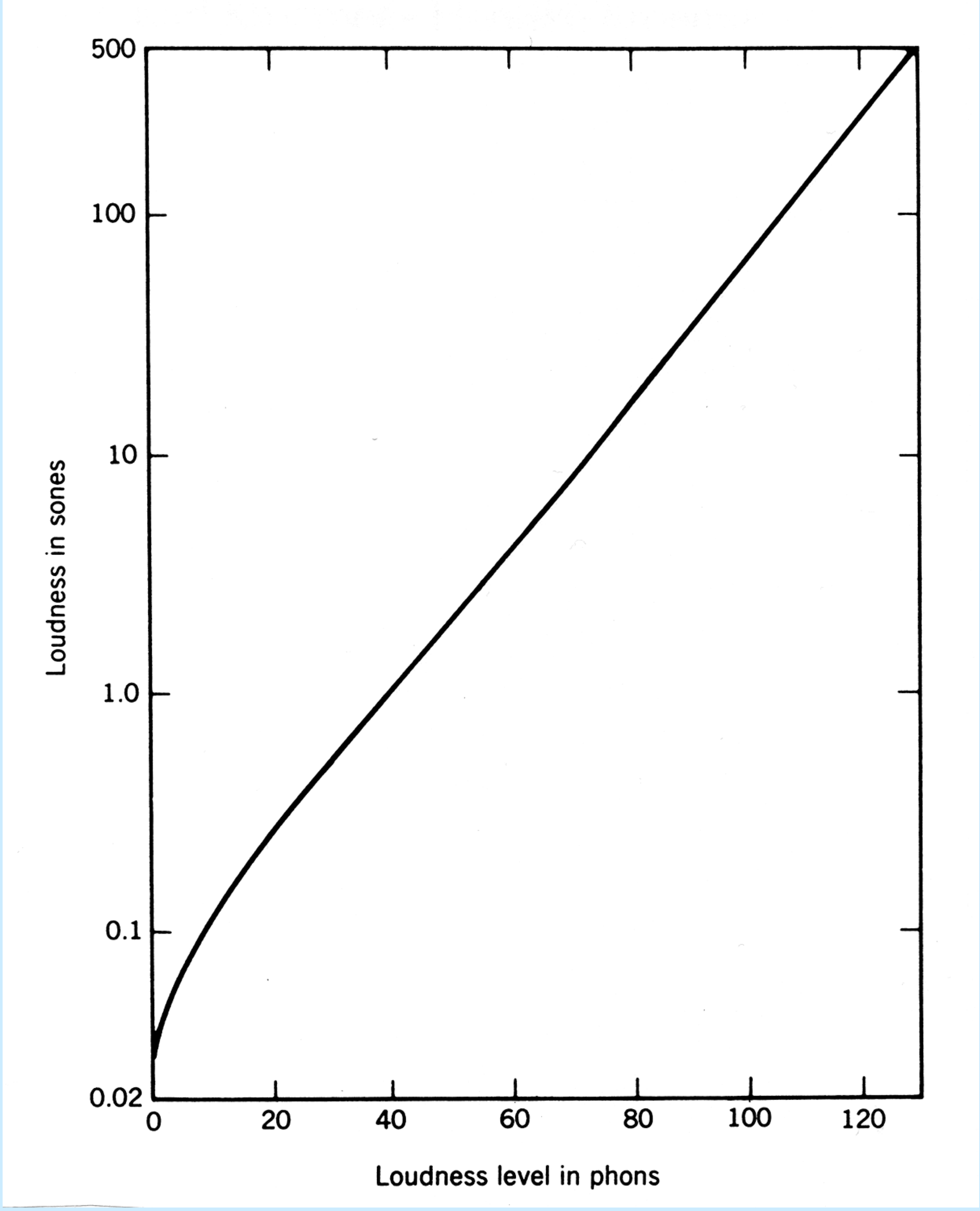
Sones

Phon curves provide information about the equivalence of sounds, but not about the absolute level of perceived loudness. We cannot say, for example, how many times louder a 40 phon sound is with respect to a 20 phon sound.

Fletcher and Munson therefore performed further tests with a rating scale which was later named the sone. One sone is defined as the loudness of a 1000 Hz tone of 40 dB (40 phons).

A sound which is judged to be twice as loud as the 1000 Hz standard reference tone has a loudness value of 2 sones, a sound judged three times as loud is 3 sones, etc..

Sones



The graph presents the relationship between the level in phons and the perceived loudness in sones for pure tone sounds. The perceived loudness grows rapidly with increasing sound pressure, particularly at lower levels.

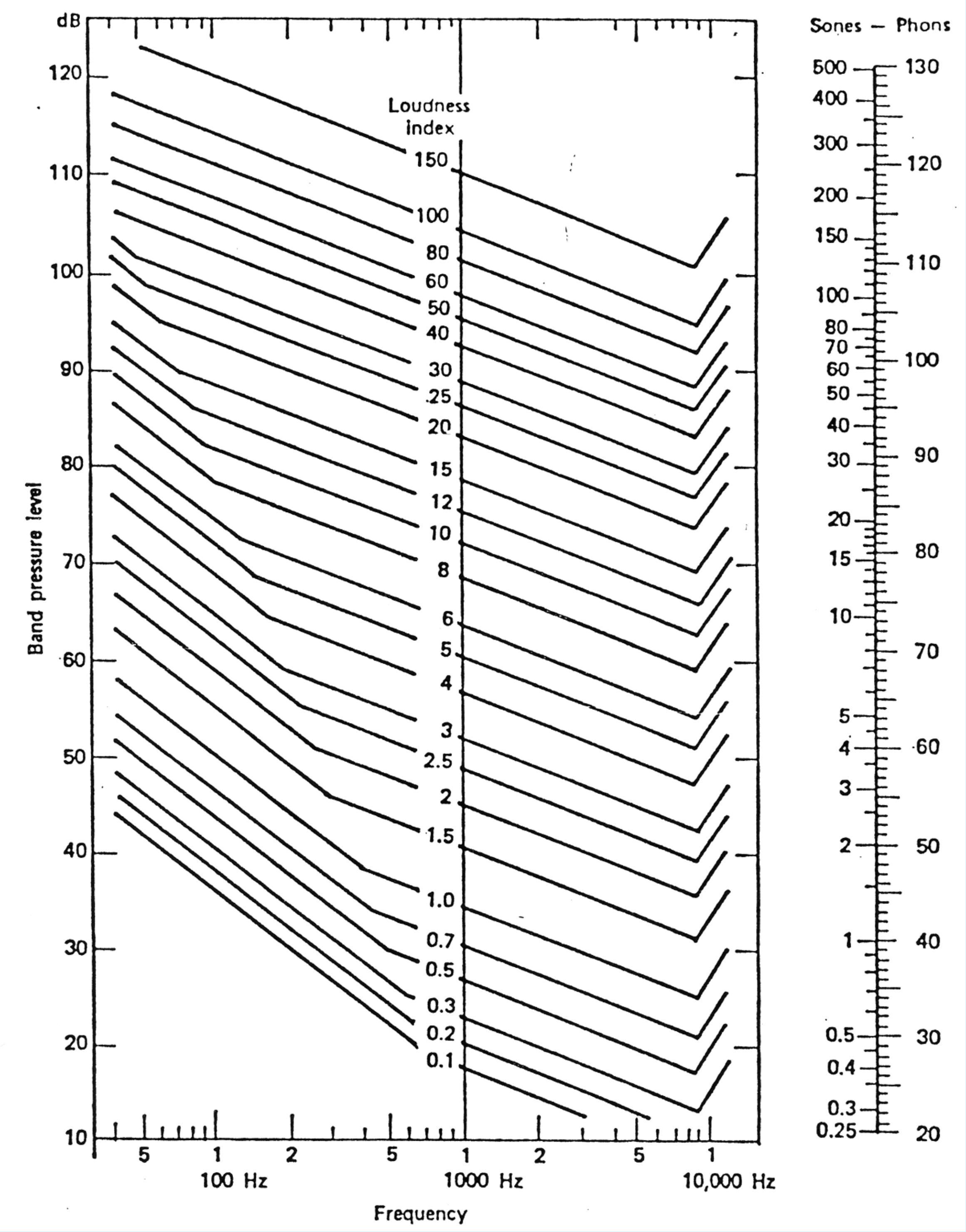
Stevens Loudness

The loudness of broadband sounds can be estimated by means of the Stevens Loudness Method (ISO 532A).

In this method the sound energy is first divided into octave or 1/3 octave bands. A loudness value for each band is then determined by means of a loudness nomogram.

The total loudness is then determined from the individual band values by means of a summation formula. The formula takes acoustic masking into account by weighting the loudness of the band with the greatest value about three times as much as the other bands.

Stevens Loudness



In the Stevens method a set of standard curves is used to determined a partial loudness value for each octave or third octave frequency band selected for analysis. The partial loudness values are expressed with respect to a reference octave or third octave random noise band at 1000 Hz.

Stevens Loudness

In the Stevens method the summation formula for obtaining the total sone loudness from the partial sone values of the individual bands is

$$s_t = s_m + F\left[\sum_{i=1}^{nbands} s_i - s_m\right]$$

where:

s_t = the total loudness in sones

s_m = the greatest of the partial loudness values (in sones)

$nbands$ = number of octave or 1/3 octave bands used

F = fractional loudness contribution factor reflecting masking effects. It is equal to 0.15 for 1/3 octaves.

Zwicker Loudness

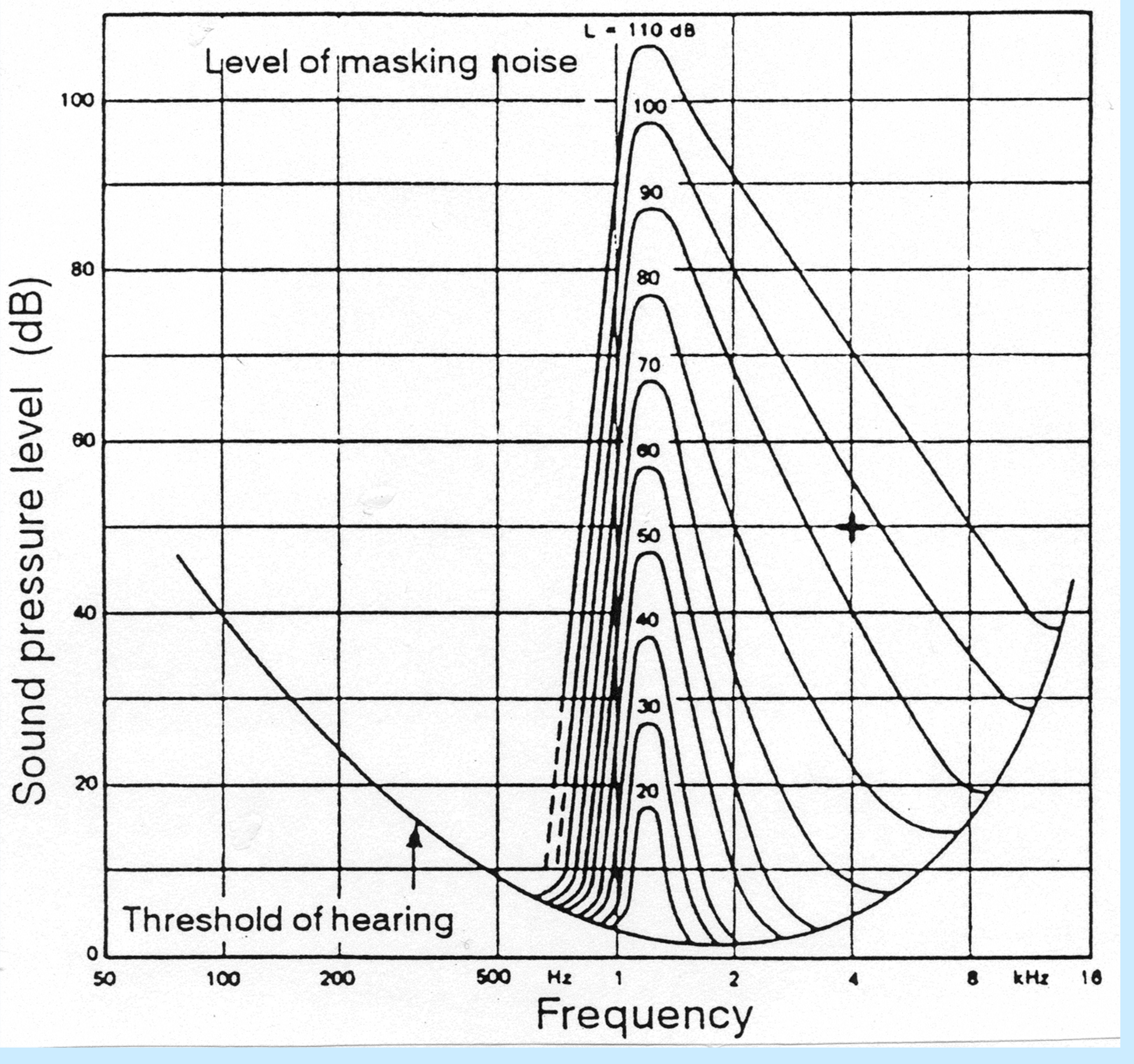
Another method for estimating total perceived sound loudness is the Zwicker method (ISO532B).

Like the Stevens method, the Zwicker method is based on the use of octave or 1/3 octave band analysis of the sound signal.

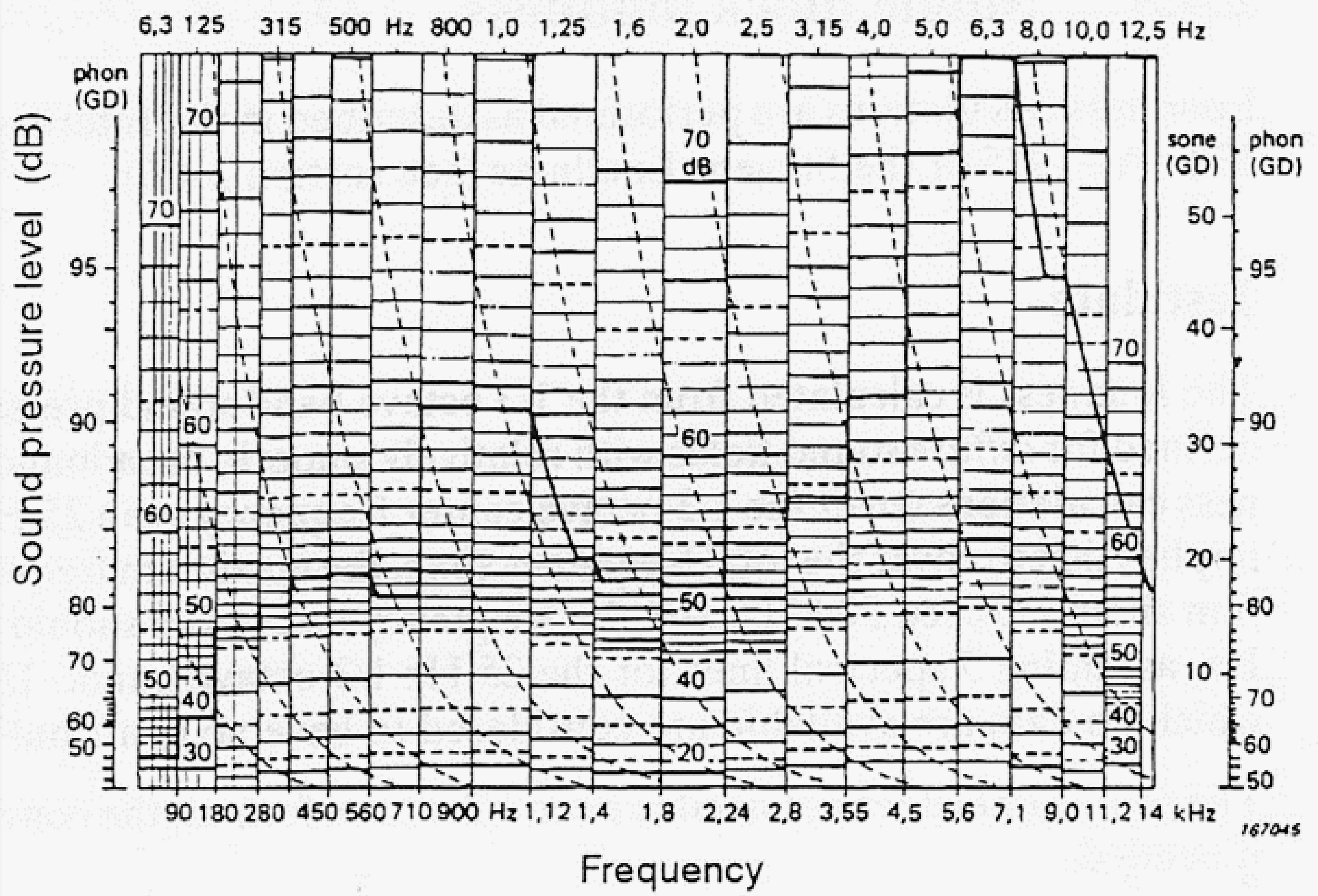
Zwicker Loudness

The Zwicker loudness method is more complex than the Steven loudness method because masking effects are considered. Masking occurs when a sound is not heard due to the presence of an intense sound at a nearby frequency.

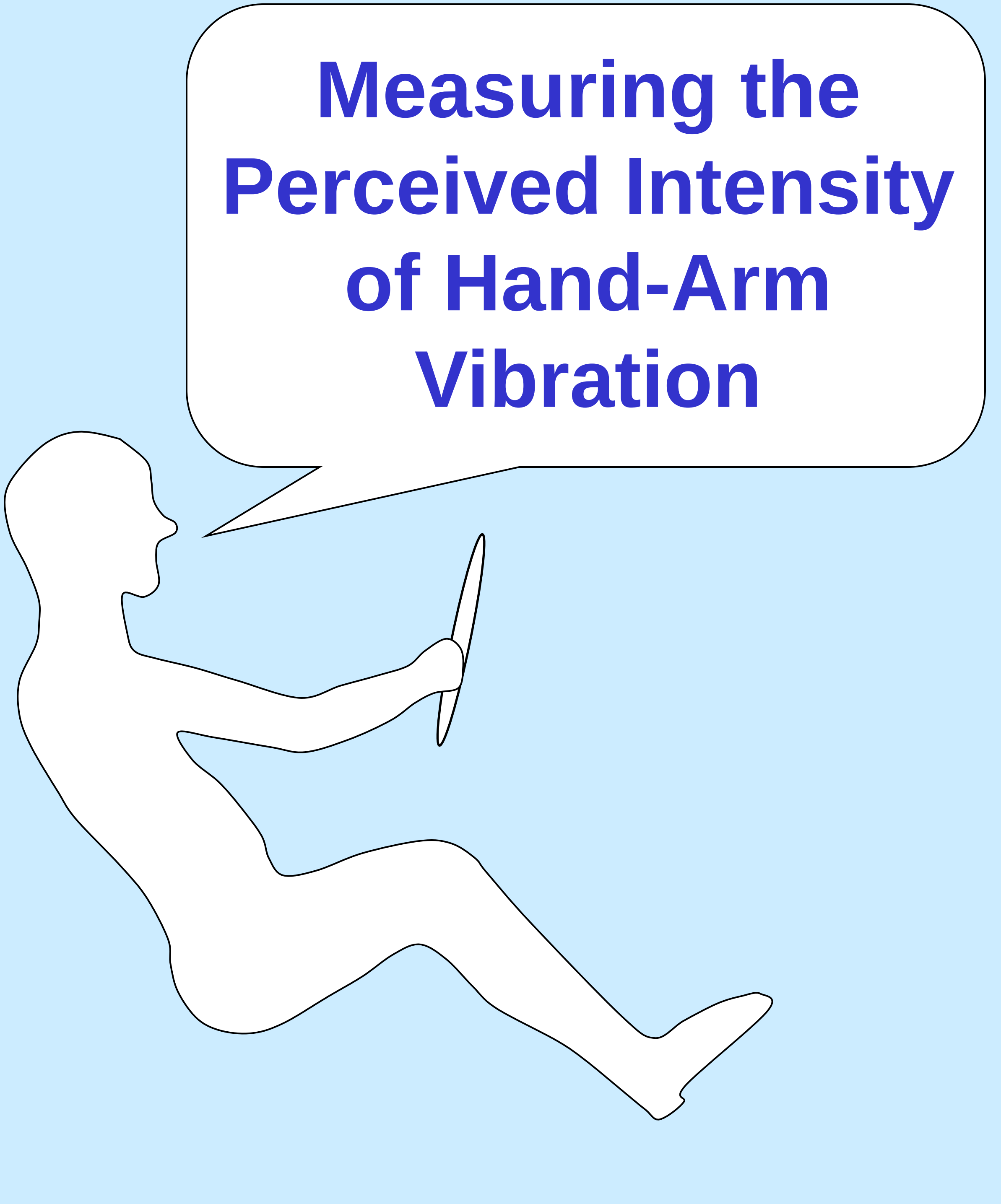
For example, a 50 dB tone at 4000 Hz will be completely masked by a 100 dB tone at 1200 Hz.



Zwicker Loudness

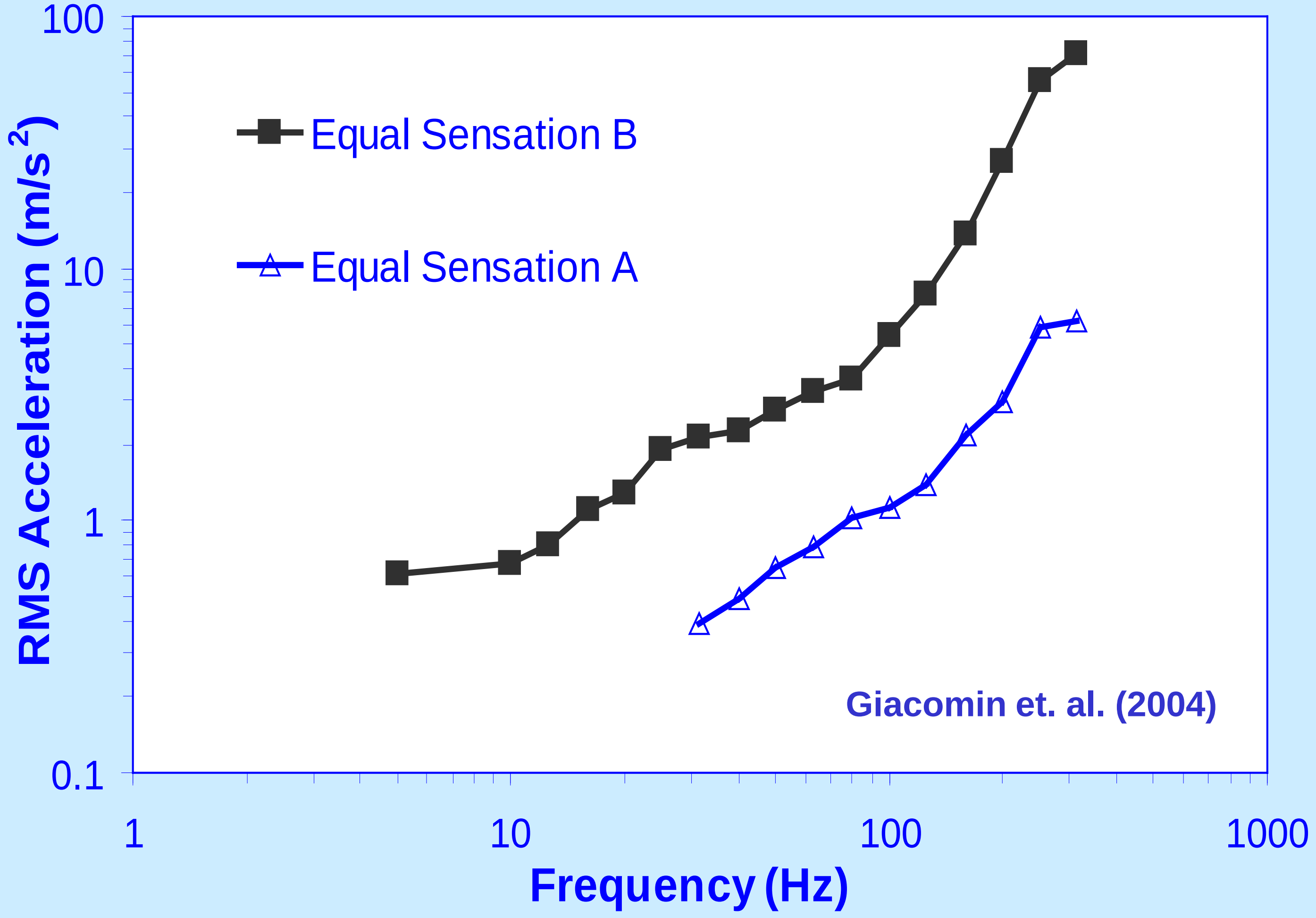


In the Zwicker loudness method the partial loudness value of each octave or third octave band is determined considering the possible masking effect of the sound energy occurring in the lower frequency bands to the left. The masking effects are summarised in the Zwicker nomogram by means of curving lines which are followed downwards from the masking band to the masked band.

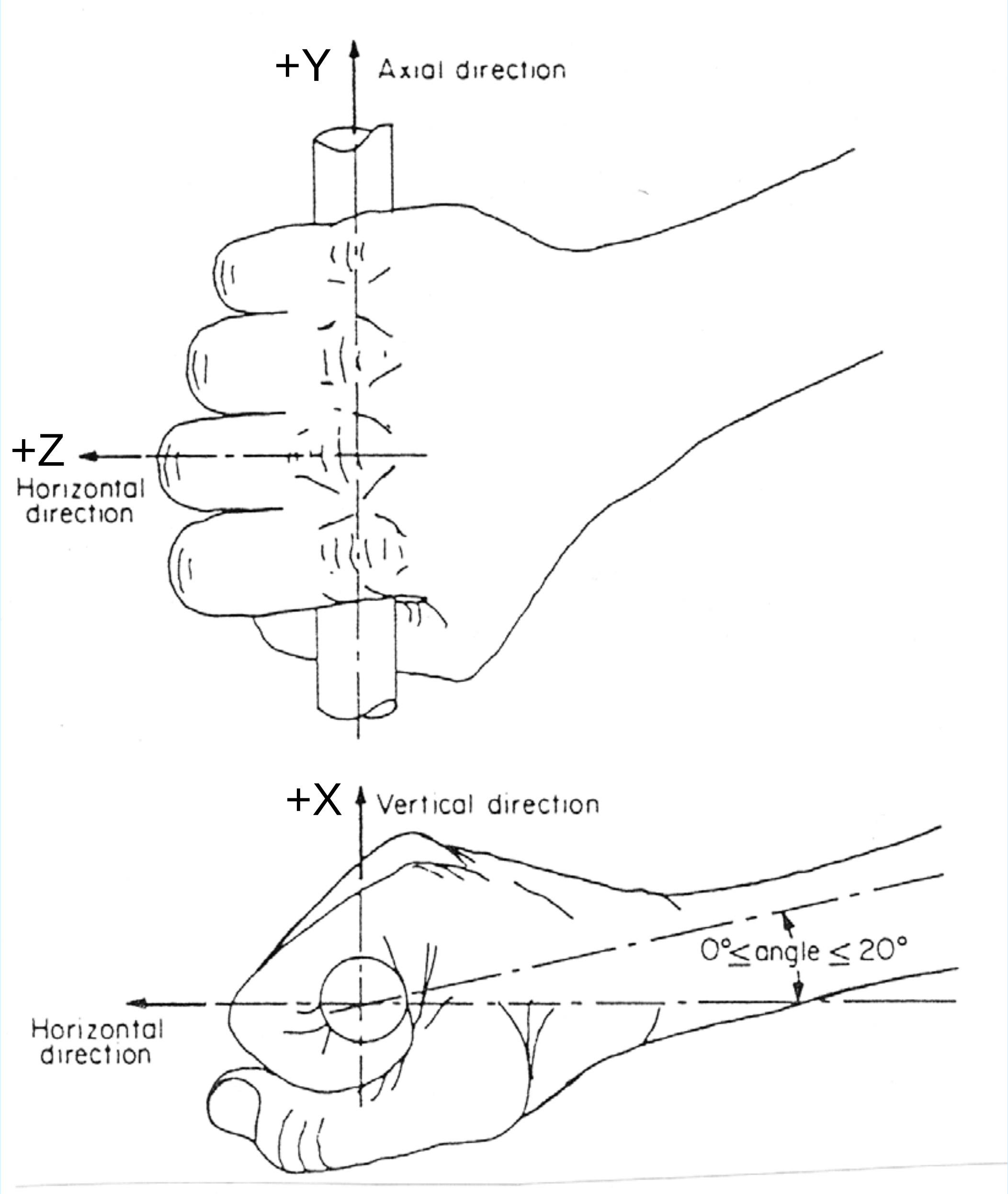

Measuring the Perceived Intensity of Hand-Arm Vibration

Perceived Vibration Intensity

In a manner similar to the research of Fletcher and Munson for sound, Miwa, Reynolds et. al. and Giacomin et. al. has defined equal-sensation curves for several forms of hand-arm vibration.

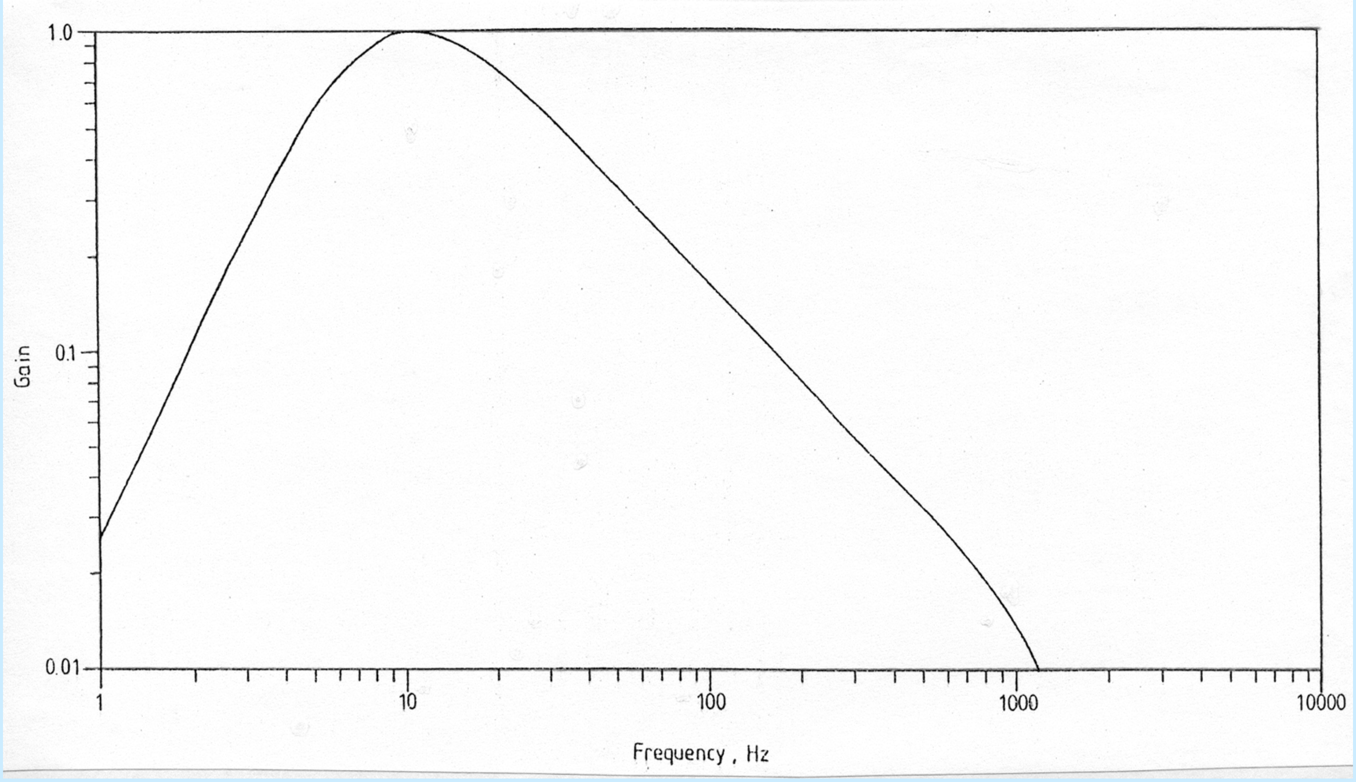


Perceived Vibration Intensity



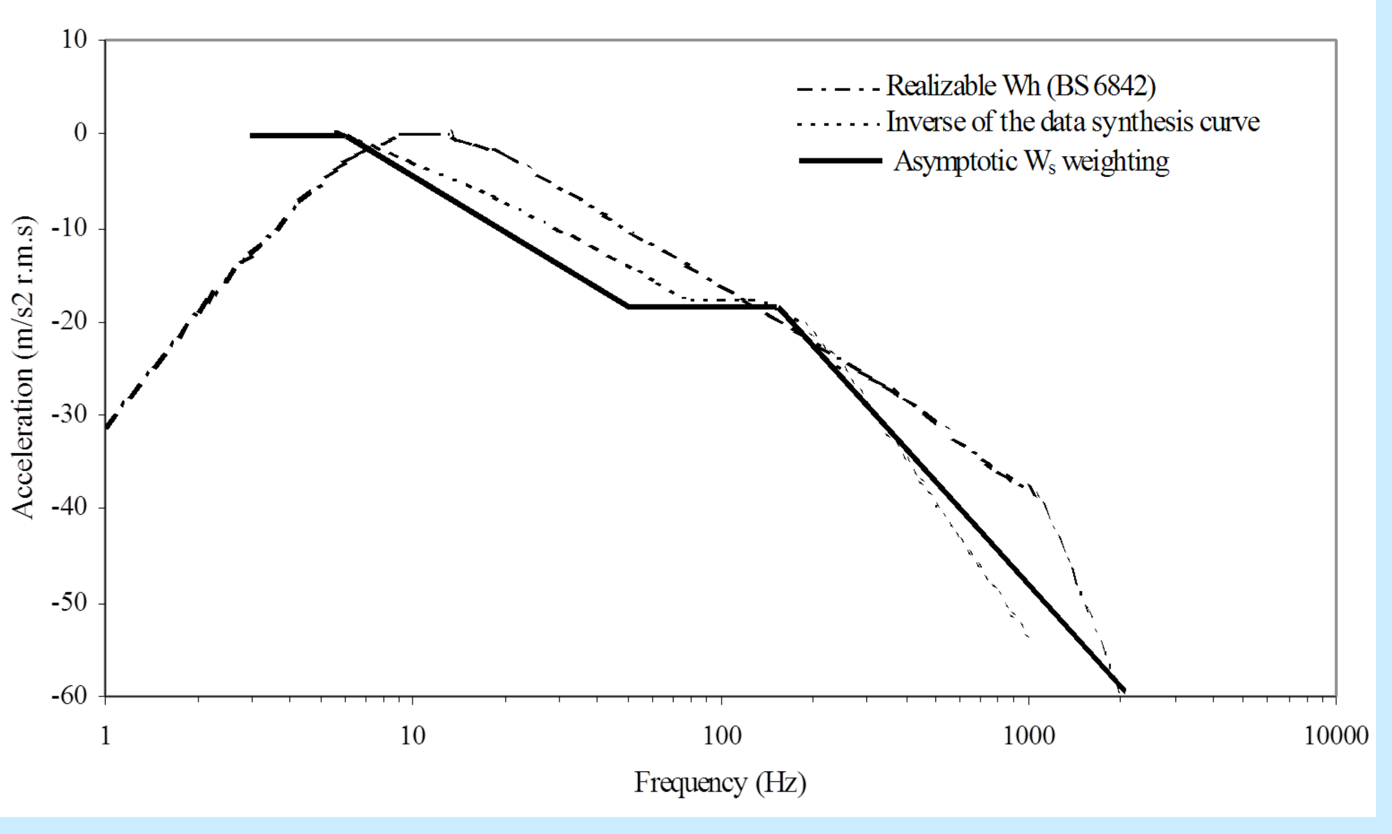
In a manner similar to the distinctions between free or diffuse fields made for sound, hand-arm vibration exposures are described in terms of the mechanical coupling (grip or press) and the vibration direction (x,y,z axis translations or rx, ry, rz axis rotations).

Frequency Weighting Wh



ISO 5349 and BS 6842 provide guidelines for the measurement and reporting of hand-arm vibration. Frequency weighting Wh is defined for use along three (x, y, and z) translational axis.

Frequency Weighting Ws



Giacomin et. al. have defined frequency weighting Ws for evaluating steering wheel rotational vibration. Further research is under way to validate Ws and to define a second weighting for use at lower vibration amplitudes.

Perceived Vibration Intensity

Frequency weightings are used to estimate the human perception of vibration. They convert measured acceleration signals into perceived acceleration signals.

Perceived Vibration Intensity

Frequency weightings convert acceleration signals into perceived acceleration signals. It is then necessary to quantify the intensity of the complete disturbance as a single number. Common indices include:

Root Mean Square Value

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

Root Mean Quad Value

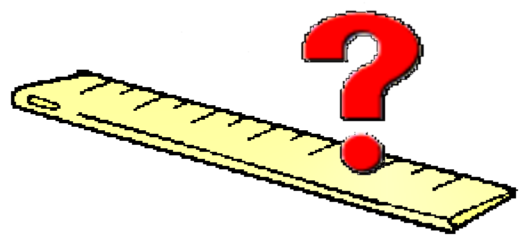
$$r.m.q. = \left[\frac{1}{T} \int_0^T a^4(t)\, dt \right]^{\frac{1}{4}}$$

Vibration Dose Value

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

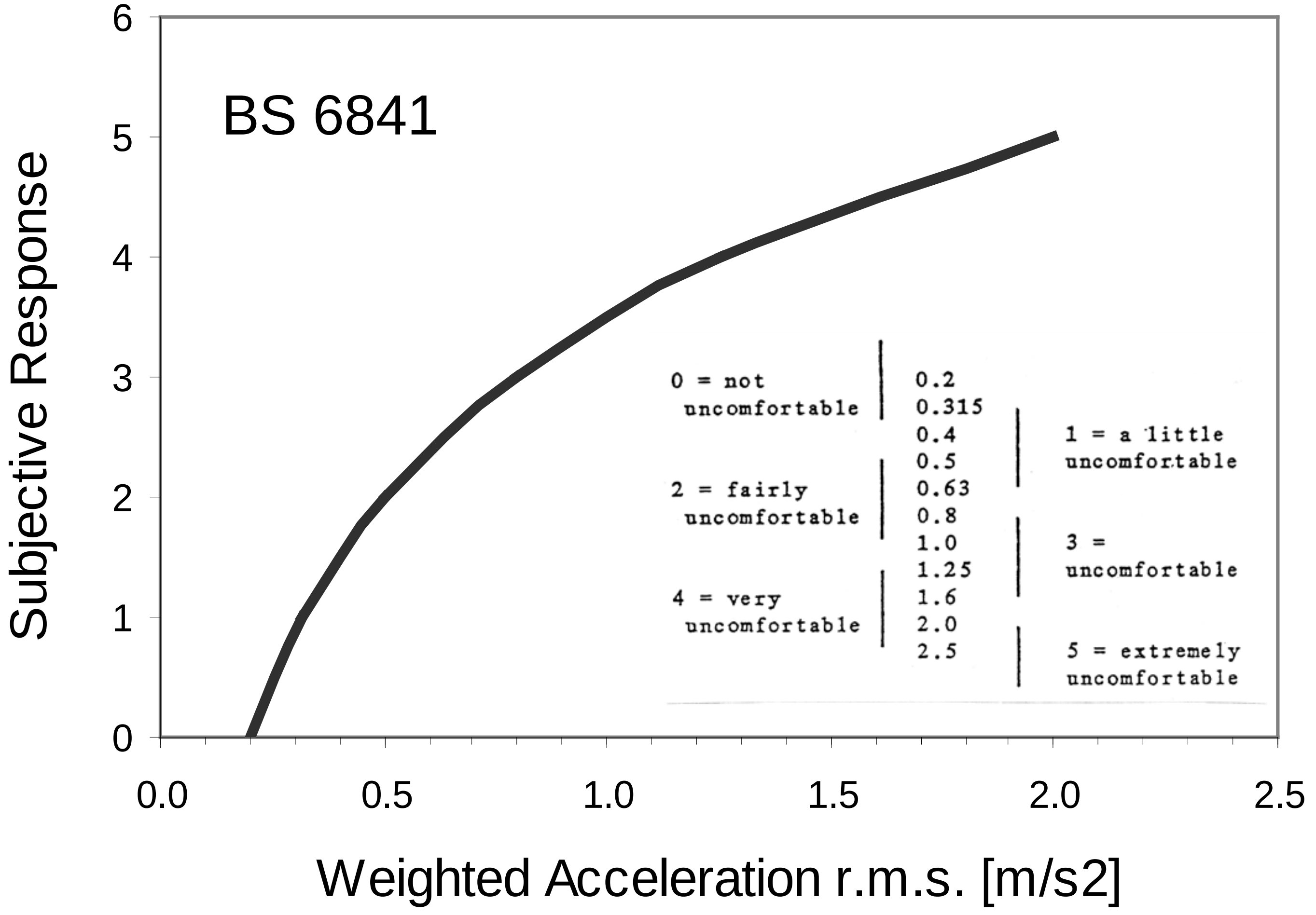
Scale of Perceived Intensity

Unlike whole-body vibration, where BS 6841 provides a scale for estimating the subjective response to vertical direction vibration, there is currently no generally accepted scale for estimating the subjective response to hand-arm vibration.



BS 6841	Weighted acceleration ms^{-2} r.m.s.	
0 = not uncomfortable	0.2	
	0.315	
	0.4	1 = a little uncomfortable
	0.5	
2 = fairly uncomfortable	0.63	
	0.8	
	1.0	3 = uncomfortable
	1.25	
4 = very uncomfortable	1.6	
	2.0	
	2.5	5 = extremely uncomfortable

Scale of Perceived Intensity



In a manner similar to sone curve from acoustics, the BS 6841 guideline suggests a negatively accelerating subjective response with increasing vibration level.

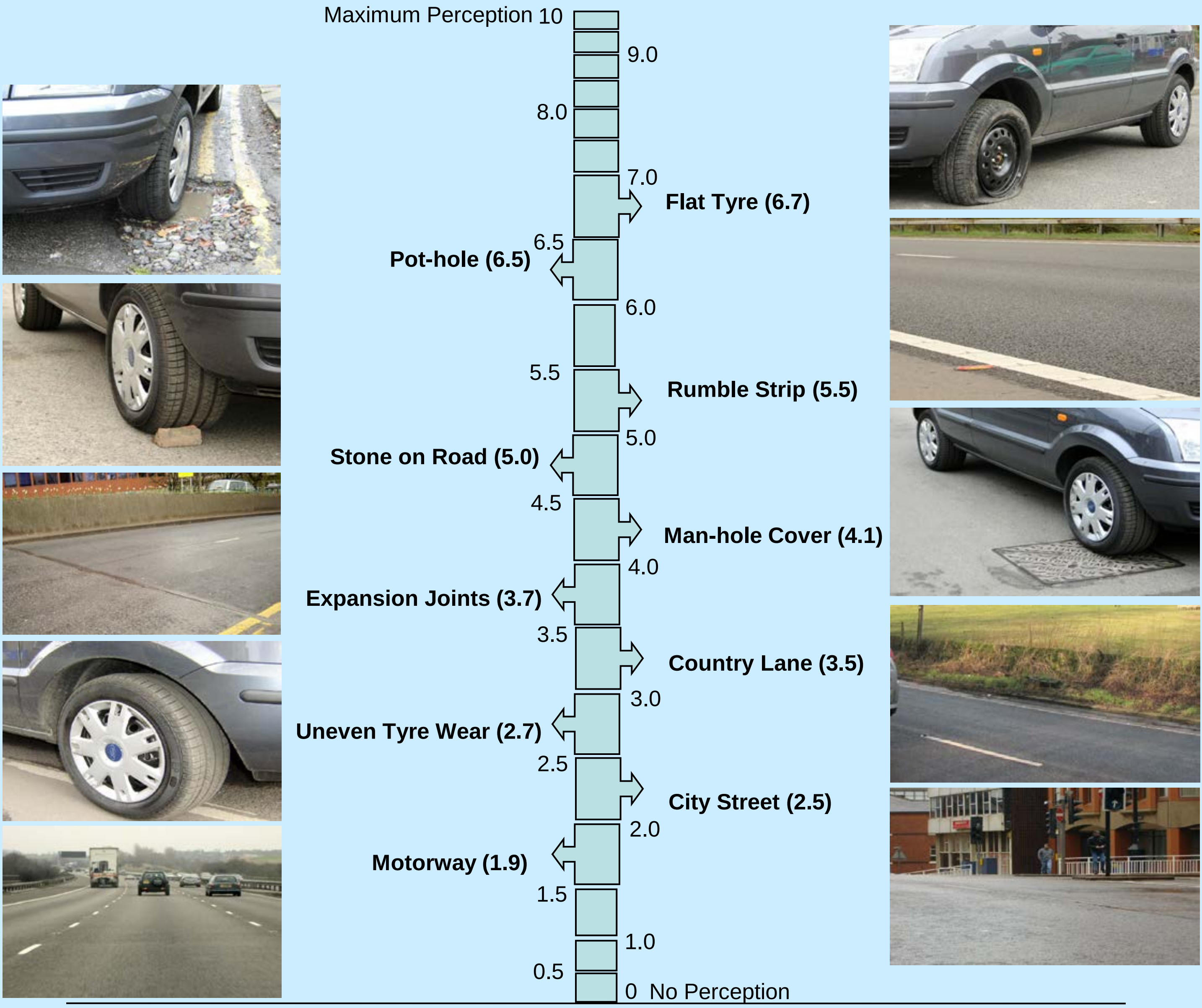
Borg CR-10 Scale

0	Nothing at all	"No P"
0.3		
0.5	Extremely weak	Just noticeable
1	Very weak	
1.5		
2	Weak	Light
2.5		
3	Moderate	
4		
5	Strong	Heavy
6		
7	Very strong	
8		
9		
10	**Extremely strong "Max P"**	
11		
↯		
●	Absolute maximum	Highest possible

An important response scale which has been developed over the last 30 years and which has ratio-scale properties is the Borg CR10 Scale.

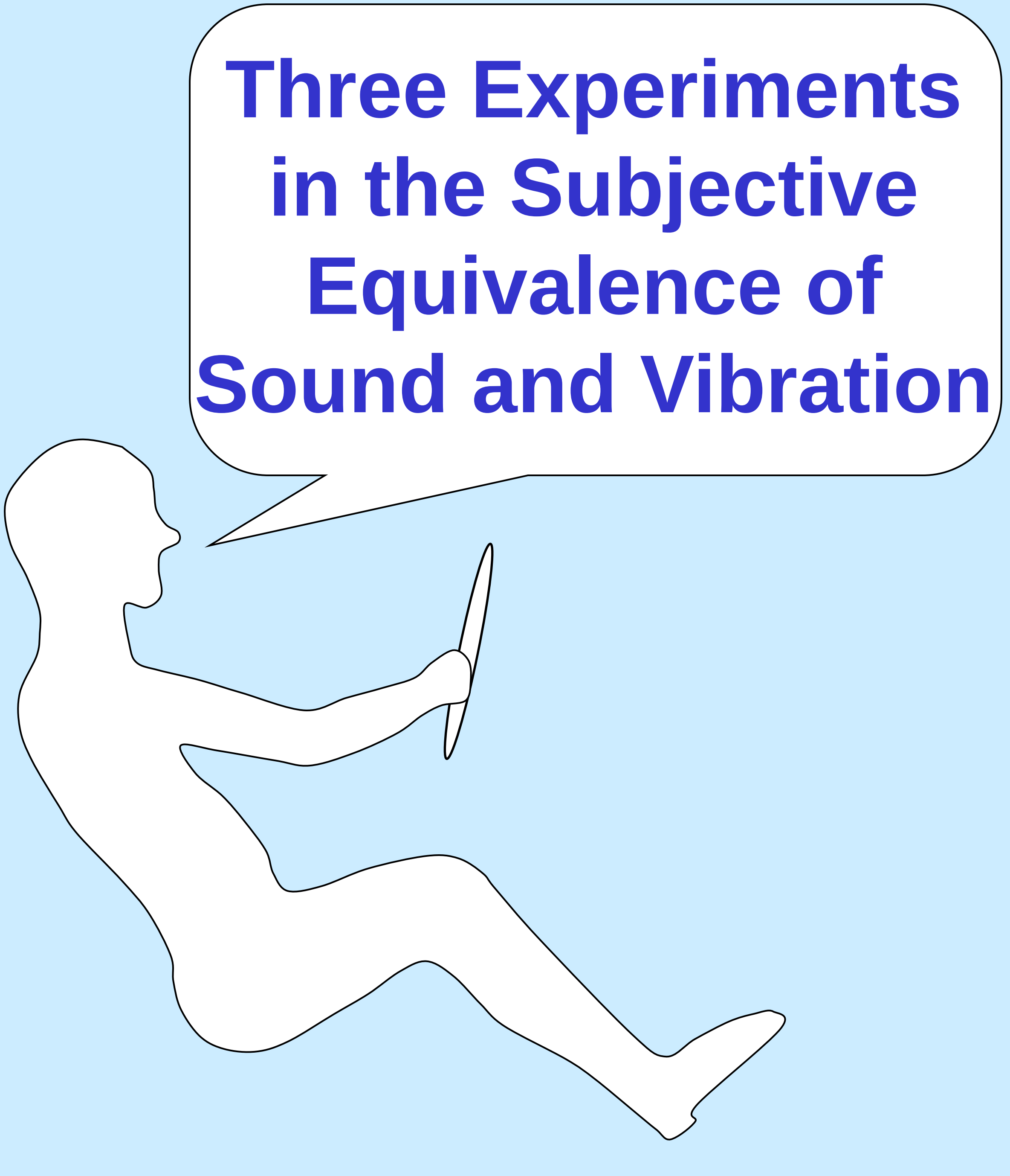
Scale of Perceived Intensity

In the Perception Enhancement Systems group research is under way to develop a response scale based on the use of a Borg CR-10 scale.



Perceived intensity estimated using a Borg CR10 Scale [n = 350 Drivers]

S.Gnanasekaran and J.A.Giacomin (2004), Steering Wheel Vibration Questionnaire, University of Sheffield.

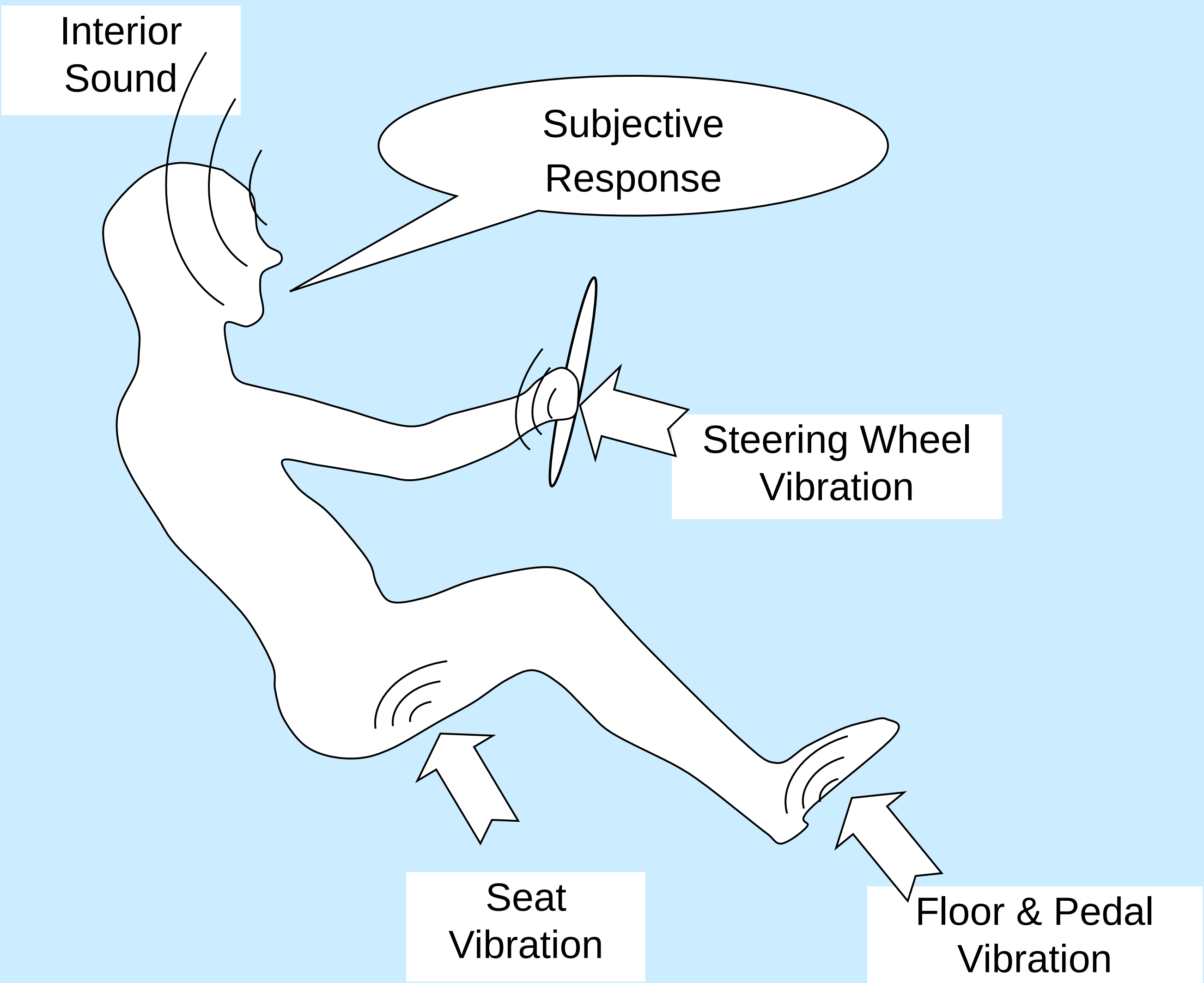

Three Experiments in the Subjective Equivalence of Sound and Vibration

Research Problem

When developing an automobile, a difficult task is the optimisation of its vibro-acoustic properties, particularly those in the immediate vicinity of the driver. The problem is complex because the vibro-acoustic stimuli effect:

- **comfort (causing fatigue)**
- **perceived quality (particularly sound quality)**
- **driver cognitive state (driving information)**

Sound and Vibration in Automobiles



An automobile driver experiences whole-body vibration due to contact with the supporting surfaces of the seat, and local vibration due to contact with the steering wheel, gear lever, pedals and floor. Sound emitted by the glass surfaces, trim and various body panels arrives at both ears.

Research Problem

The first question which comes to mind is which of the two stimuli, the sound or the vibration, is the greater problem ?

Research Objectives

Remaining in the domain of comfort, three experiments were performed. The research objectives included:

- To determine curves of subjective equivalence for three statistically different stimuli: driving over a course asphalt surface (random signal), driving over a 1.0 cm square metal bar (transient signal) and diesel idle (modulated signal).
- To evaluate the influence of the choice of sound and vibration intensity measurement metric on the equivalence relationship.
- To determine which stimuli, the sound or the vibration, is worse for a small set of common automobile operating conditions.

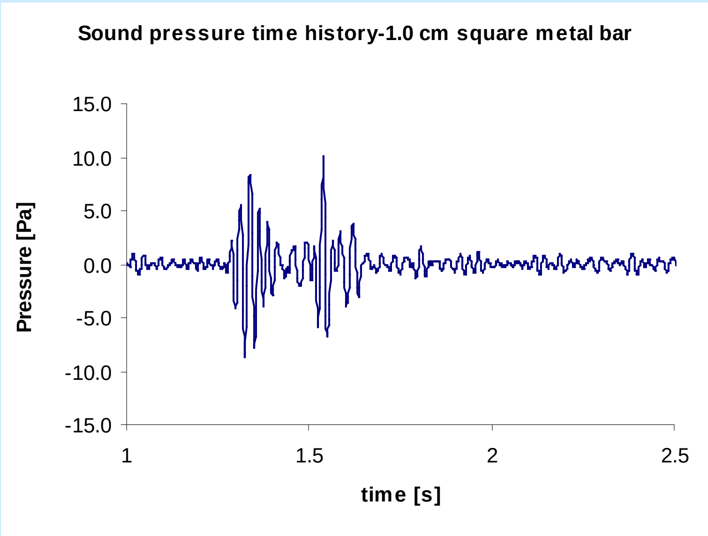
Test Stimuli

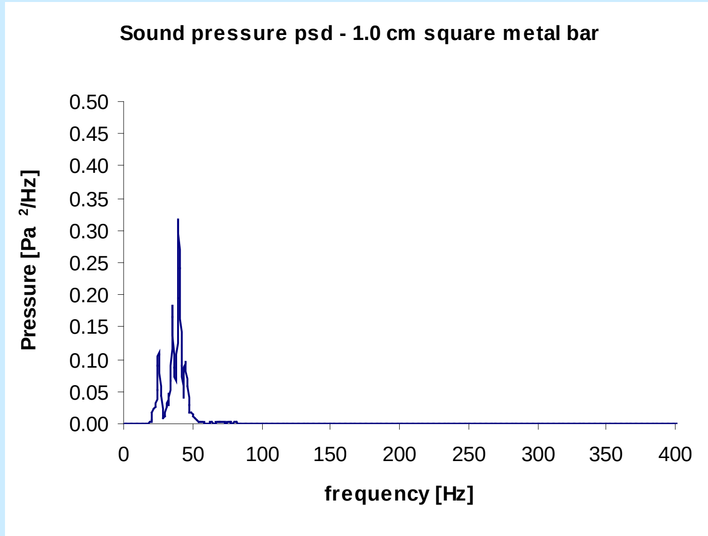
1.0 cm square
metal bar at 40 kph
(1 s segment)

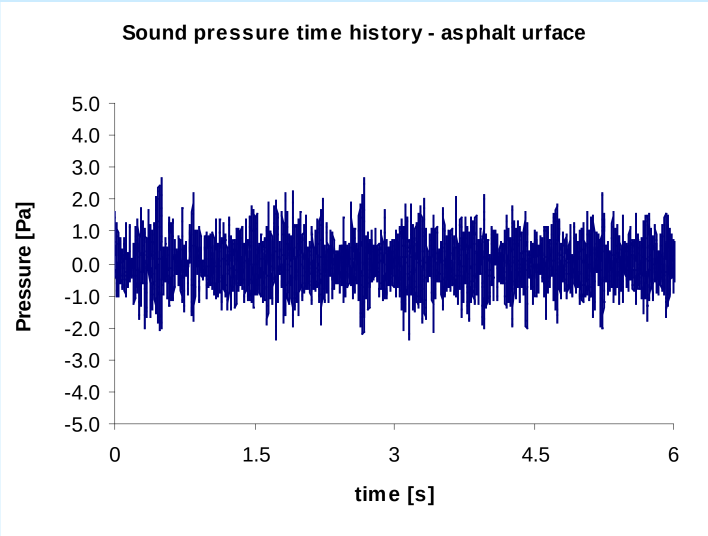
Course asphalt
surface at 80 kph
(15 s segment)

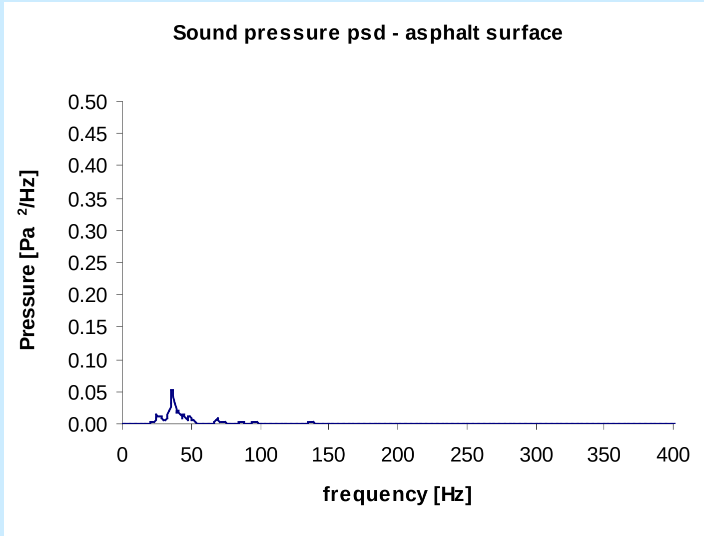
Diesel engine idle
(15 s segment)

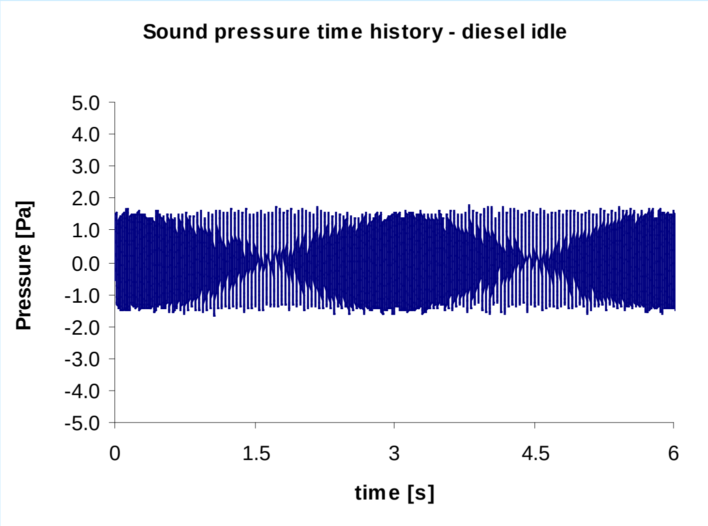
Test Stimuli : right ear sound

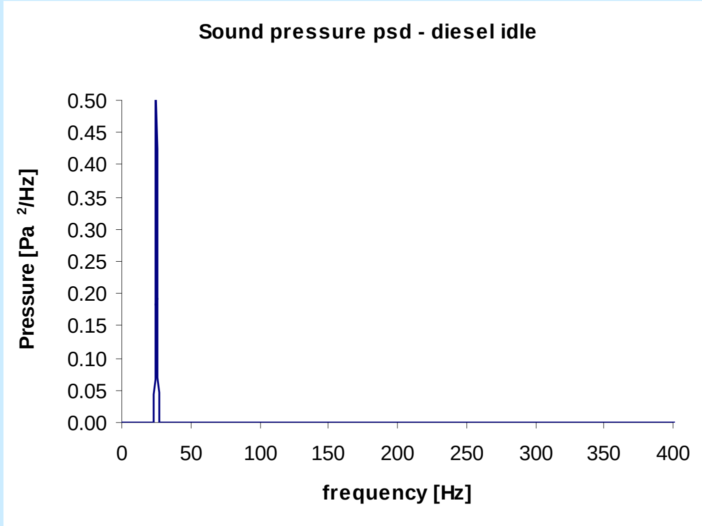




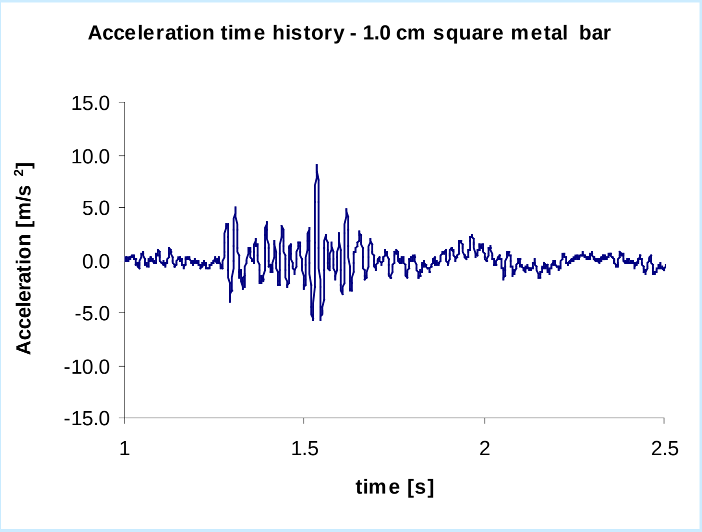


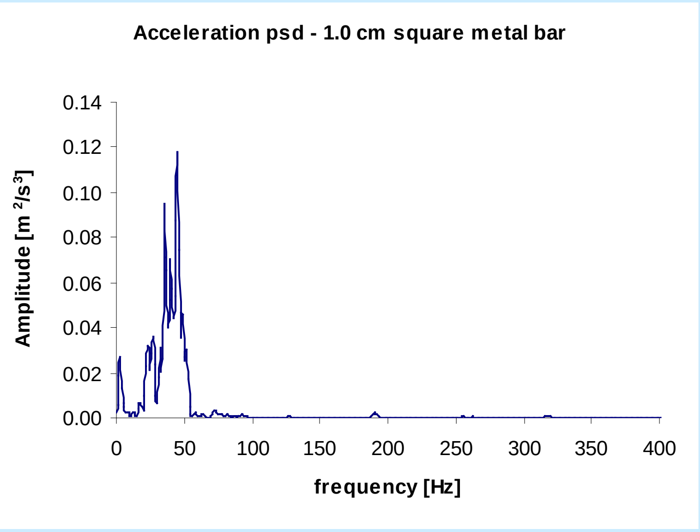


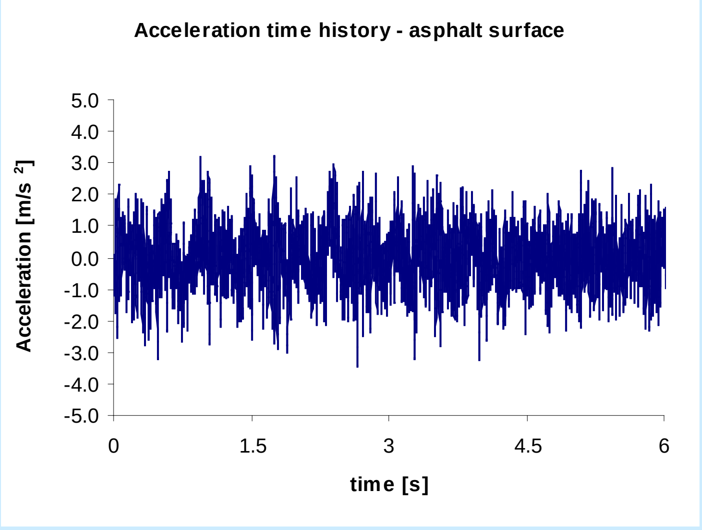


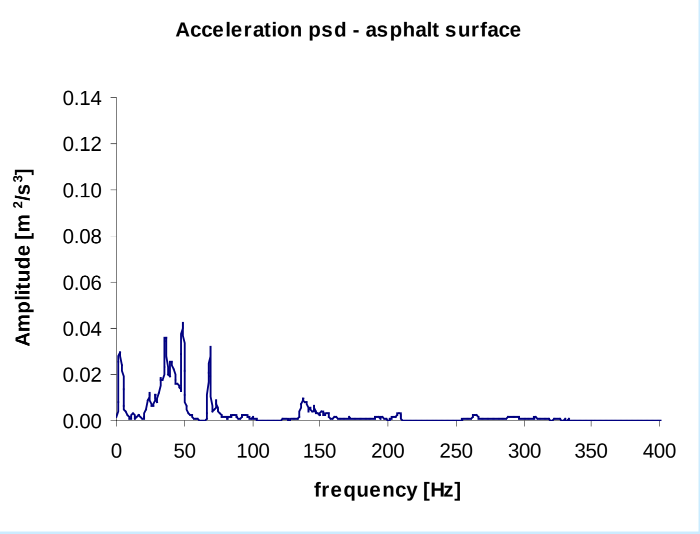


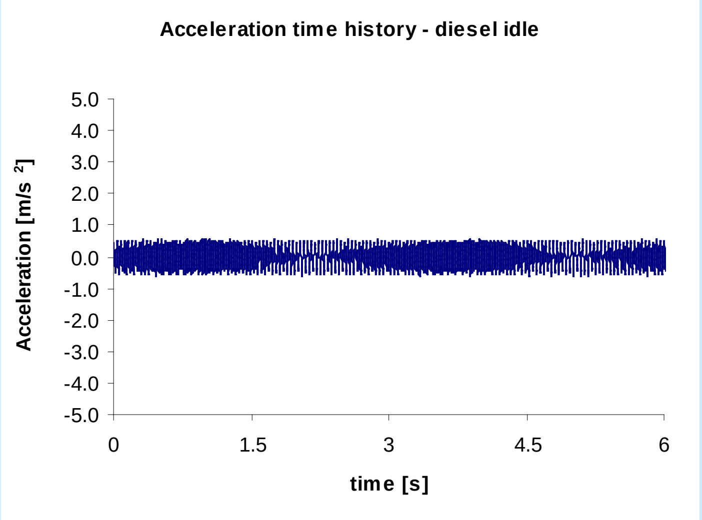
Test Stimuli : steering acceleration

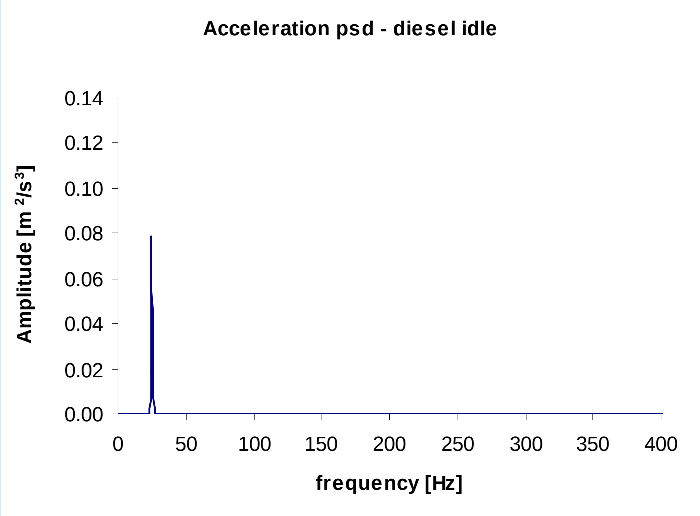












Test Stimuli

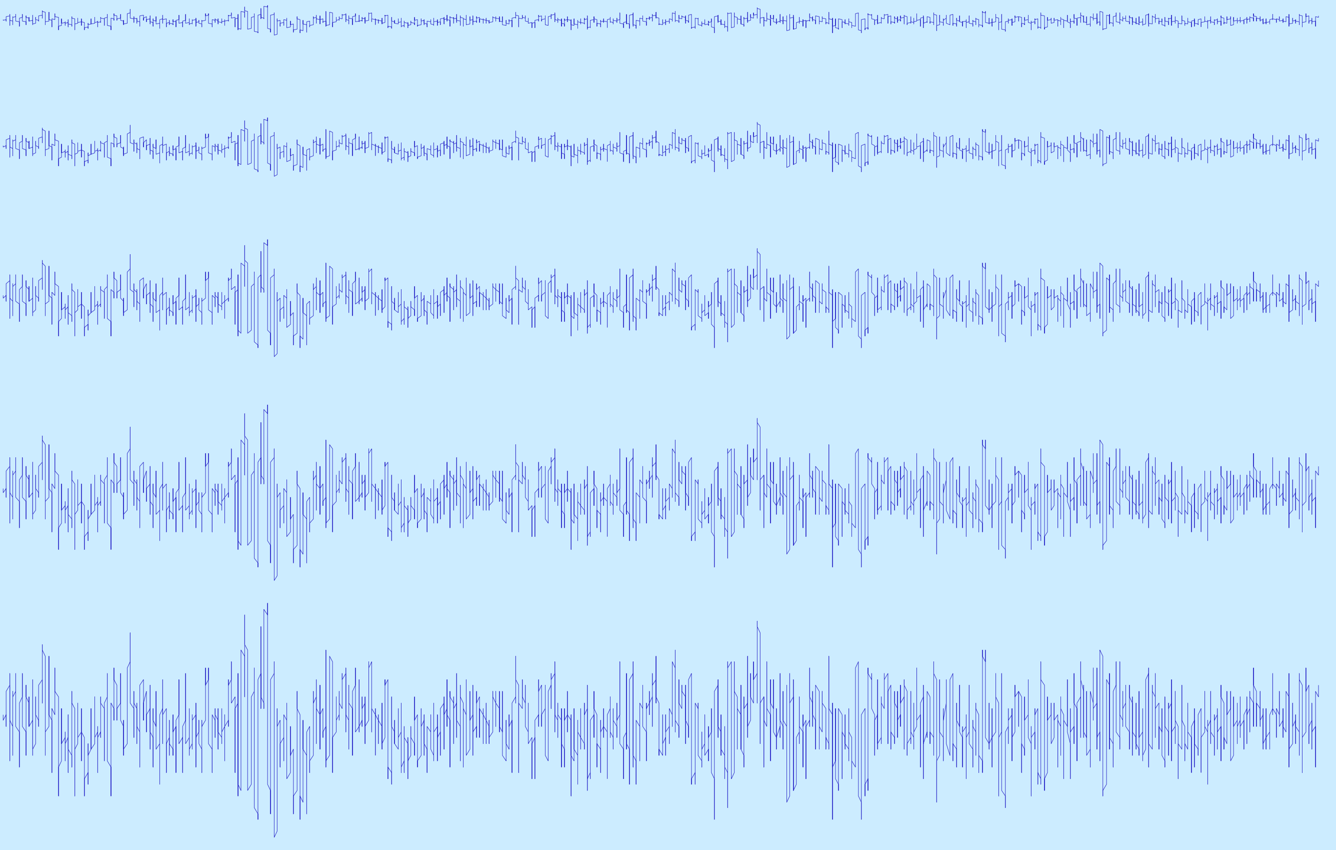
Sound pressure global statistical values

1.0 cm sqaure metal bar	Coarse asphalt	Diesel idle
r.m.s. = 1.46 Pa (97.3 dB)	r.m.s. = 0.77 Pa (91.7 dB)	r.m.s. = 1.07 Pa (94.6 dB)
kurtosis = 12.39	kurtosis = -0.09	kurtosis = -1.48
Crest Factor = 6.51	Crest Factor = 3.65	Crest Factor = 1.66

Steering acceleration global statistical values

1.0 cm sqaure metal bar	Coarse asphalt	Diesel idle
r.m.s. = 1.25 m/s^2	r.m.s. = 1.08 m/s^2	r.m.s. = 0.35 m/s^2
kurtosis = 14.36	kurtosis = 0.04	kurtosis = -1.42
Crest Factor = 8.99	Crest Factor = 3.81	Crest Factor = 1.95

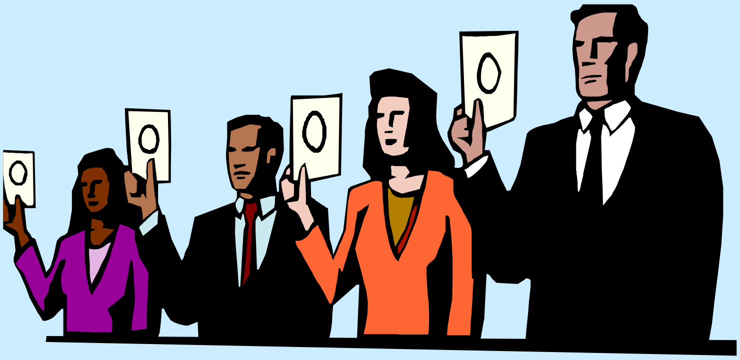
Test Stimuli



Eight copies of each of the three 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 three 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 stimuli pairs were produced for each of the three stimuli types.



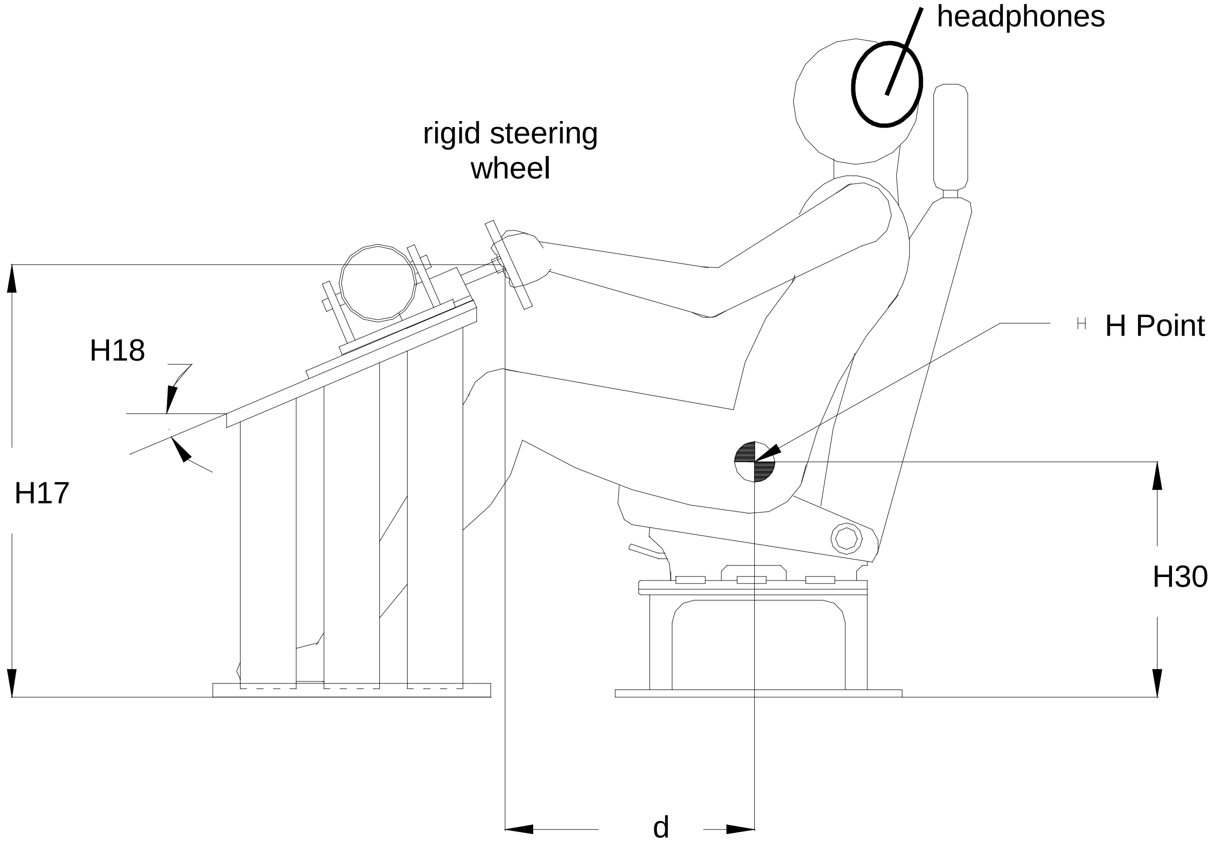
Test Participants

		Age [years]	Weight [kg]	Height [m]
Experiment 1 (course asphalt) (n=20, m=18, f=2)	Mean (SD)	**25.6 (4.6)**	**74.0 (12.5)**	**1.77 (0.07)**
	Minimum	**21**	**54.0**	**1.60**
	Maximum	**36**	**100.0**	**1.91**

Experiment 2 (cleat stimuli) (n=20, m=17, f=3)	Mean (SD)	**25.2 (4.6)**	**73.4 (12.3)**	**1.75 (0.09)**
	Minimum	**20**	**52.0**	**1.60**
	Maximum	**36.0**	**98.0**	**1.92**

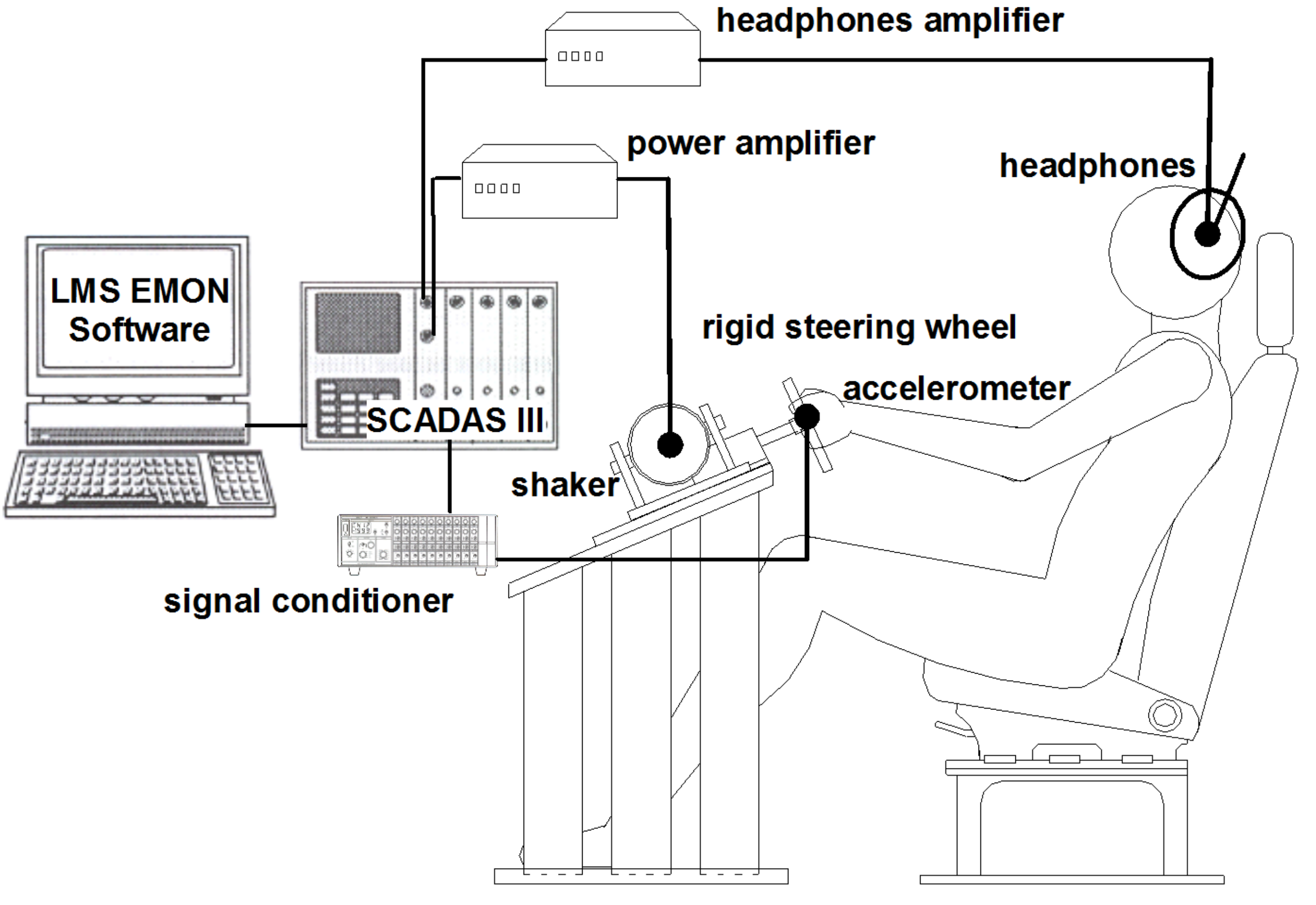
Experiment 3 (diesel idle) (n=20, m=14, f=6)	Mean (SD)	**27.1 (4.7)**	**71.0 (17.7)**	**1.72 (0.11)**
	Minimum	**20**	**45.0**	**1.50**
	Maximum	**42**	**110.0**	**1.88**

Steering Wheel Rotational Vibration Test Bench



Geometric Parameter	Value
Seat H point height from floor, h_1	275 mm
Horizontal distance adjustable from H point to steering wheel hub centre, d	390-550 mm
Steering wheel hub centre height above floor, h_2	710 mm
Steering column angle with respect to floor	23 º
Steering wheel handle diameter	12.5 mm
Steering wheel diameter	325 mm

Steering Wheel Rotational Vibration Test Bench



Test sequencing and control is performed by means of the LMS EMON software and a SCADAS III electronics frontend.

The G&W V20 electrodynamic shaker and Sennheiser HD 580 headphones are driven in open-loop using drive voltage signals defined using compensator filters which equalise the transfer function of the bench and the human test subject.

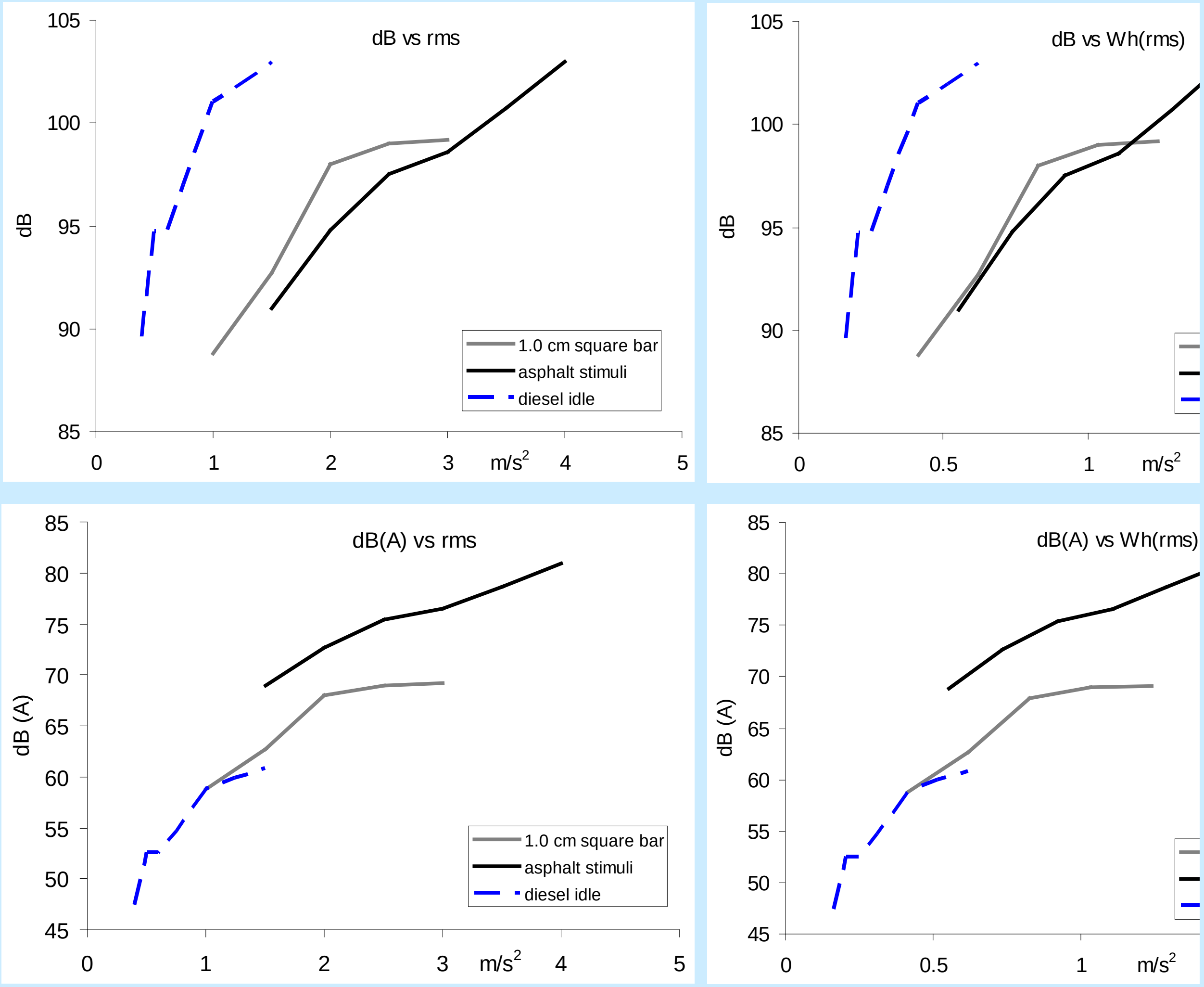
Steering Wheel Rotational Vibration Test Bench

Test Protocol

For each of the three signal types, the order of presentation of the 64 test stimuli was randomized in order to reduce learning and fatigue effects.

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”.

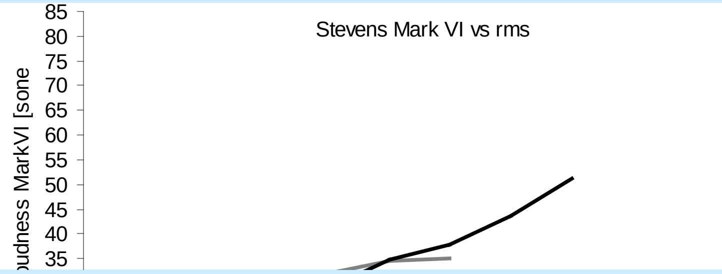
Results



Regardless of the choice of frequency-weighting for the steering vibration, unweighted sound pressure does not permit a simple definition of an equivalence relationship.

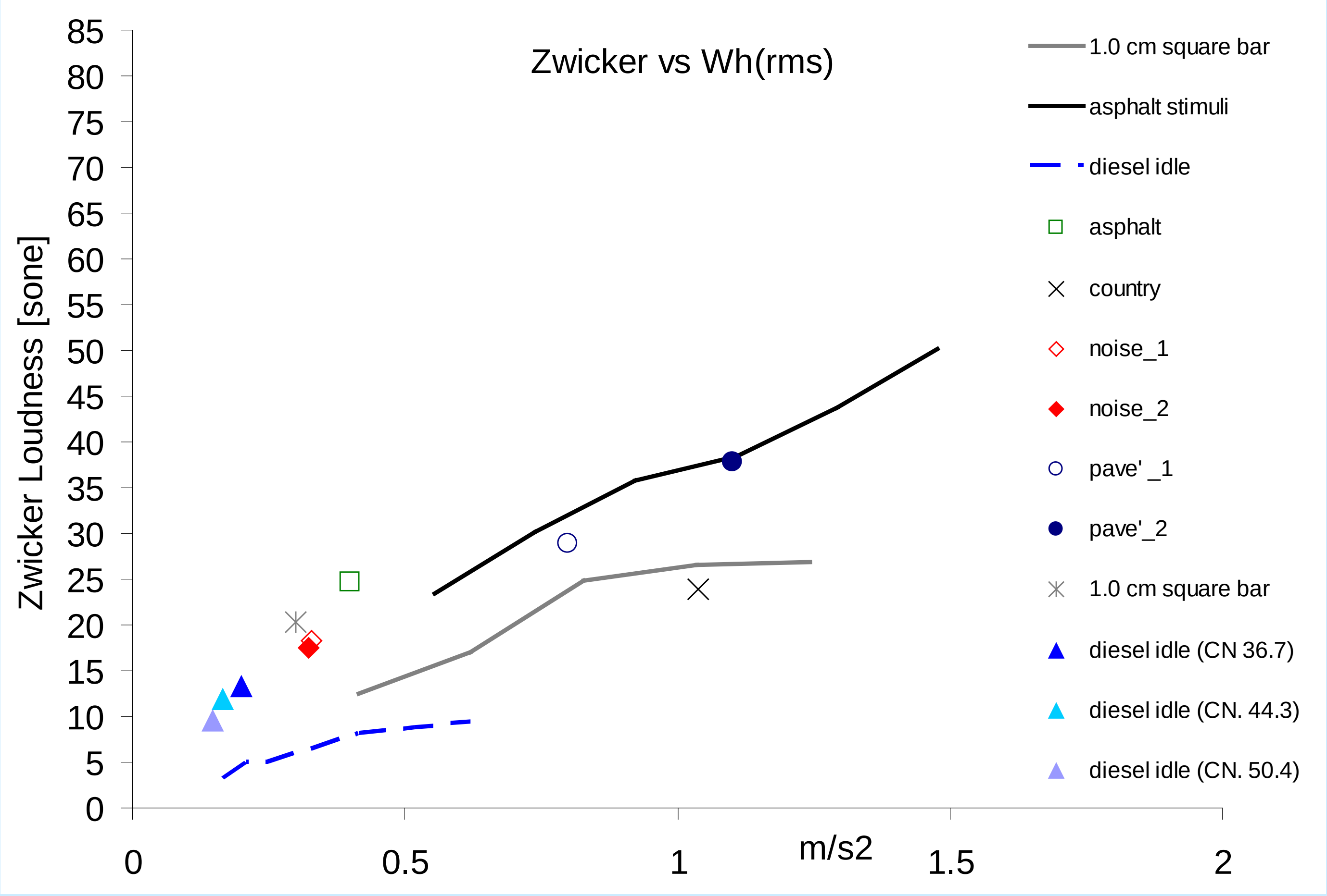
dB(A) provides a more promising representation, but the equivalence relationship remains highly nonlinear.

Results



The Stevens loudness VI procedure appears to offer the simplest equivalence relationship, but the result for the transient sound is questionable. Physiologically, human perception of sound transients of less than 1 second in duration is reduced with respect to similar-leveled stationary sounds.

Examples of Representative Automobile Operating Conditions



Plotting data points defined by the Zwicker loudness and the frequency-weighted steering acceleration for various operating conditions, it becomes clear that the sound is dominant in some conditions while vibration is dominant for others.

Conclusions

- Unweighted and A-weighted sound pressure level are not sufficiently accurate to permit the definition of a simple equivalence relationship between sound and steering wheel vibration.

- The Stevens Loudness method provides a simple equivalence relationship, but is suspect because the relationship leads to unrealistic results in the case of sound transients.

- Despite being the most complex sound loudness method, Zwicker Loudness did not provide an equivalence relationship which remained invariant under changes in signal statistics. Research is therefore required to establish if the discrepancies are caused by the Zwicker method or by the Wh hand-arm vibration frequency weighting.