Human subjective response to steering wheel vibration caused by diesel engine idle

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Abstract: This study investigated the human subjective response to steering wheel vibration of the type caused by a 4-cylinder diesel engine idle in passenger cars. Vibrotactile perception was assessed using sinusoidal amplitude modulated vibratory stimuli of constant energy level (0.41 r.m.s. m/s^2) having a carrier frequency of 26 Hz (i.e. engine firing frequency) and modulation frequency of 6.5 Hz (half engine order). Evaluations of seven levels of modulation depth parameter m (0.0, 0.1, 0.2, 0.4, 0.6, 0.8, 1.0) were performed in order to define the growth function of human perceived disturbance as a function of amplitude modulation depth. Two semantic descriptors were used (unpleasantness and roughness) and two test methods (Thurstone paired comparison and Borg CR-10 direct evaluation scale) for a total of four tests. Each test was performed using an independent group of 25 individuals. The results suggest that there is a critical value of modulation depth m = 0.2 below which human subjects do not perceive differences in amplitude modulation and above which the stimulus-response relationship increases monotonically with a power function. Stevens' power exponents suggest that the perceived unpleasantness is nonlinearly dependent on modulation depth m with an exponent greater than 1 and that the perceived roughness is dependent with an exponent close to unity.

Keywords: vibration, engine, idle, subjective, perception, modulation

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NOTATION

$A(t)$	*instantaneous amplitude of modulated signal [m/s^2]*
a	*acceleration value [m/s^2]*
CR	*Category-Ratio*
f_c	*carrier frequency [Hz]*
f_m	*modulation frequency [Hz]*
H_i	*engine harmonic [order]*
m	*modulation depth*
*m**	*modulation index equal to* m-m_{th}
m_{th}	*amplitude modulation detection threshold*
MTF	*modulation transfer function*
p	*significance level*
PSD	*power spectral density*
RMS	*root mean square acceleration value [m/s^2]*
rpm	*revolution per minute*
SD	*standard deviation*
VDV	*vibration dose value [m/s$^{1.75}$]*

1. INTRODUCTION

Amplitude modulation is a commonly observed phenomenon in the vibro-acoustic signatures of many types of mechanical systems **(1)**. Amplitude modulation is present in the vibration measured at the steering wheel of road vehicles at idle due to the rotational irregularity of the engine **(2-4)**. For a 4-cylinder, 4-stroke engine at idle amplitude modulation occurs due to the action of the half order engine harmonic on the second order engine harmonic **(5-7)**. Comprehensive analytical treatment of the spectral contents of multi-cylinder engines can be found in reference **(7)**. What follows here is a brief description of the 4-cylinder case.

The half order harmonic of a 4-cylinder, 4-stroke engine is due to there being only a single power stroke occurring in each cylinder every two crankshaft revolutions. For an automobile engine the crankshaft rotational speed when at idle is typically in the range from 600-840 rpm, corresponding to linear frequencies of from 10 to 15 Hz. The half order harmonic originating from combustion forces in the cylinder is therefore in the range from 5 to 7 Hz, as shown by the experimental measurements performed by Dixon *et. al*. **(5)**.

The second (H_2) and the other even order harmonics (H_4, H_6, etc.) are caused instead by mechanical unbalance **(6-8)**. The reciprocating motion of the pistons and of the connecting rods, combined with the rotational motion of the crankshaft, generate inertial forces which act on the engine block. At low engine speeds the combustion gas forces are greater than the mechanical inertial forces, but at high speeds the opposite is true. In 4-cylinder, 4-stroke engines the first-order inertial forces are normally well balanced since the crankshaft is balanced and the piston pairs move in opposite directions. Vertically acting second-order forces and their multiples are produced, however, because the two descending pistons in a four-cylinder engine travel further at a given crankshaft angle than the two ascending pistons since lateral movement of the connecting rods accelerates the descending pistons while delaying the ascending pistons. The centre of gravity of the ascending and descending masses therefore varies, producing a resultant force which varies periodically twice per crankshaft revolution. Laterally acting second-order forces and their multiples also occur due to the angle between the connecting rod and the cylinder. Lateral gas and inertial forces vary periodically twice per crankshaft revolution due to the change in direction of the connecting rod. For an idle speed in the range from 600-840 rpm, the corresponding linear second order linear frequencies are from 20 to 28 Hz.

Amplitude modulation of the form described above is conveniently and compactly represented by means of the modulation depth parameter m. This parameter is defined as the amount of change in the amplitude of the waveform, and which is expressed as a proportion:

$$m = \left(A_{\max} - A_{\min}\right) / A_{\max} \qquad (1)$$

Thus a value of m = 1.0 describes an amplitude variation of the carrier sinusoid from zero to a maximum, whereas a value of m = 0.0 describes the unmodulated version of the carrier signal (i.e. a pure sine wave). Due to combustion irregularity an engine tends to run “rough” and stall much more easily at lower idle speeds **(4)**. Also, anecdotal evidence suggests that even slight fluctuations of engine idle can cause unpleasant vibrations leading to lower customer satisfaction. Since smooth idle is an important vehicle attribute perceived by customers **(9)**, identification of an acceptance level of amplitude modulation index m can provide valuable information to vehicle designers.

For the human hand-arm system considerable psychophysical research has been performed to investigate how the amplitude and the frequency of a vibrotactile stimulus affects detection threshold **(10-11)** and difference threshold **(12)**. Results of vibrotactile discrimination tests performed using two-superimposed sinusoids at low-frequency (10Hz+30Hz) **(13)** presented to the fingertip suggest that the tactile system utilises a temporal code for amplitude discrimination on the basis of uniformity or nonuniformity of the sequences of perceived peaks within stimulus cycles. Studies of temporal sensitivity in the tactile system performed by Weisemberger **(14)** defined a modulation transfer function (MTF) that related modulation depth thresholds to the frequency of modulation. MTF can be used to predict the depth of modulation necessary to just allow discrimination between a modulated and an unmodulated waveform. In Weisemberger’s experiments the modulated signal was frequently reported as feeling “rougher” than the unmodulated signal. Lamoré et al. **(15)** found that high-frequency (1000-2000 Hz) sinusoidal vibrations of the skin induced maximum sensitivity when amplitude modulation is applied at modulation frequencies between 100 and 300 Hz. The use of high-frequency stimuli makes this an atypical study, being outside the frequency range, up to about 350Hz **(10)**, to which the tactile system is maximally responsive. No data regarding the human response to amplitude modulated vibration of the type caused by engine idle is available in the scientific literature.

Psychophysical methods developed for the scaling of sensory attributes such as perceived roughness **(16)** or perceived intensity **(17)** can measure human subjective response to many forms of nonmetric (i.e. stimuli that can be arranged only on a nominal scale) and metric stimuli. The end objective of such tests is the establishment of some form of metric scale which describes the relationship between the physical properties of the stimulus and the subjective characteristics of the human response. In many applications the relationship can be compactly summarized by means of the well known Stevens' power law which relates human response to numerous environmental stimuli. The psychophysical test protocols themselves can be divided into two major classes, those involving indirect rating of the stimuli by means of paired comparisons and those in which a test subject directly provides an estimate of his or her response by means of a fixed scale. Unfortunately, the scientific literature provides little conclusive evidence **(18-19)** of the superiority of one protocol with respect to the other. It is therefore good practice to evaluate the potential differences that can occur due to the choice of psychophysical test protocol.

This paper presents an investigation of the growth in the human subjective response to amplitude modulated steering wheel idle vibration stimuli as a function of the modulation depth m. Both an indirect and a direct scaling method have been used to assess stimuli under two sensory attributes (unpleasantness and roughness) in order to evaluate possible differences. Psychophysical response scales were constructed by means of Thurstone's Law of Comparative Judgment **(20)** which provided an indirect scaling method, and the category-ratio Borg CR-10 scale **(21)** which is a direct scaling method.

2. TESTING OF HUMAN RESPONSE TO AMPLITUDE- MODULATED STEERING WHEEL VIBRATION STIMULI

2.1. Experimental apparatus

A test facility for applying rotational vibration to a seated test subject was used in this study. A schematic representation of the steering wheel test rig and associated data conditioning and acquisition systems are shown in Fig.1.

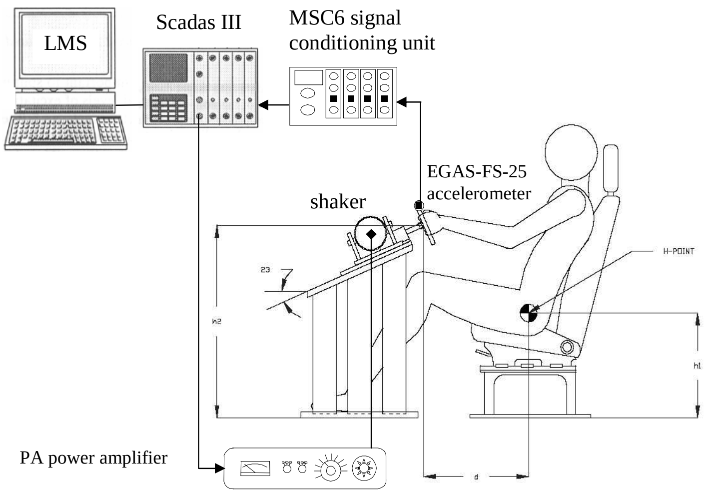

Fig. 1 - Steering wheel rotational vibration test rig and associated electronics.

The rotational steering system consists of a 325mm diameter aluminium wheel connected to a steel shaft which is mounted onto two high precision bearings. The shaft is connected to a G&W V20 electrodynamic shaker and associated PA 100 power amplifier by means of a steel stinger rod. Bench control and data acquisition were performed by means of LMS Cada-X 3.5 E software and a 12-channel Difa Systems Scadas III front-end unit. The acceleration obtained at the steering wheel was measured using an Entran EGAS-FS-25 accelerometer located on the top left side of the wheel. The acceleration was measured in the tangential direction. The accelerometer signal was amplified by means of an Entran MSC6 signal-conditioning unit. Table 1 presents the rig main geometric dimensions, which were chosen based on data from a small European automobile. The seat, taken from a small European automobile, was fully adjustable in terms of horizontal travel and backrest inclination.

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

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

The test bench had a first resonance frequency of 350 Hz. When loaded by a human hand-arm system and tested using sinusoidal excitation at frequencies of 4.0, 8.0, 16.0, 31.5, 63.0, 125 and 250 Hz at amplitudes of 0.2, 2.0 and 20.0 m/s^2 RMS the bench provided a maximum total harmonic distortion (THD) of 15% at 4 Hz and 20 m/s^2 **(22)**. 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. During the same tests, a linear fore-and-aft direction acceleration measurement was also performed at the same point on the rigid wheel. Fore-and-aft acceleration was found to be no greater than –50 dB with respect to the tangential acceleration in all cases measured.

Pretesting using amplitude modulated test stimuli showed that the dynamic response of the test bench produced unequal harmonic sidebands due to the frequency response of the shaker. Compensated drive voltage signals were therefore defined which included the effect of shaker frequency response. Figure 2 presents the power spectral density (PSD) of the target test stimuli and of the bench response signals at a modulation depth of m = 1.0 for both the uncompensated (Fig. 2a) and compensated (Fig. 2b) drive voltage signals. With frequency compensation the modulated acceleration stimuli were reproduced at the human test subject with RMS errors of less than 5%.

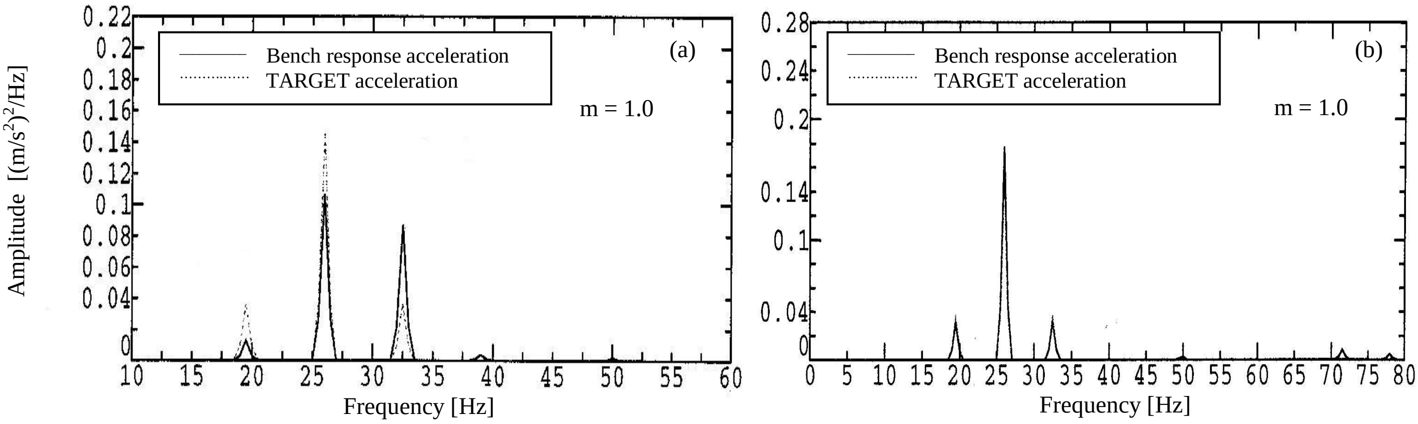

Fig. 2 – Test signals: (a) comparison between target and bench response acceleration before compensation; (b) comparison between target and bench response acceleration after compensation.

2.2. Test signals

Engine idle vibration occurring at the steering wheel of road vehicles was simulated by means of amplitude modulated acceleration time histories. Sinusoidal carriers were chosen as the best reproduction of the steering wheel idle vibration signals based on previous research by the authors **(2)**. The instantaneous amplitude $A(t)$ of a sinusoidal amplitude modulated signal is given by:

$$A(t) = A_0\left[1 + m\sin\left(2\pi\, f_m\, t + \varphi\right)\right] * \sin\left(2\pi f_c\, t + \theta\right) \quad (2)$$

where A_0 is the amplitude of the carrier signal, m is the modulation depth, f_m is the modulation frequency, f_c is the carrier frequency, t is a time increment, and φ and θ are the phases of the modulating and carrier signals respectively. In all the experiments presented here the phase of both the carrier and the modulating waves were chosen equal to zero for simplicity ($\varphi = 0$, $\theta = 0$). The frequency spectrum of the amplitude modulated waveform described by equation (2) consists of a component at the carrier frequency, and modulation components (sidebands) that are above and below the carrier.

For a 4 cylinder diesel engine idle at 780 rpm **(2)** the firing frequency harmonic of 26 Hz can be considered as the carrier frequency f_c and a one-half order of 6.5 Hz can be considered as the modulation frequency f_m. Figure 3 presents two steering wheel idle vibration signatures measured along the vertical (z) direction in terms of both the time history and its relative power spectral density for two different fuel conditions. The spectra, obtained using a Hanning window and a frequency resolution of 0.5 Hz, illustrate how the energy conveyed to the steering wheel normally covers only the low frequency range up to 200 Hz. The second harmonic H_2 (at about 26 Hz) and its modulation sidebands can be seen to be prominent. With respect to similar measurements performed at the engine itself, the even-order harmonics H_4 (52 Hz), H_6 (78 Hz) and higher orders are attenuated in the path through the mechanical component of steering system. Test results from a fuel having a higher cetane number (52.9) are presented in Fig. 3a and 3b while results from a fuel having a lower cetane number (44.7) are presented in Fig. 3c and 3d. Comparison of both the time histories and the PSD suggests that the amplitude modulation of the firing frequency is characteristic of deteriorated fuel conditions.

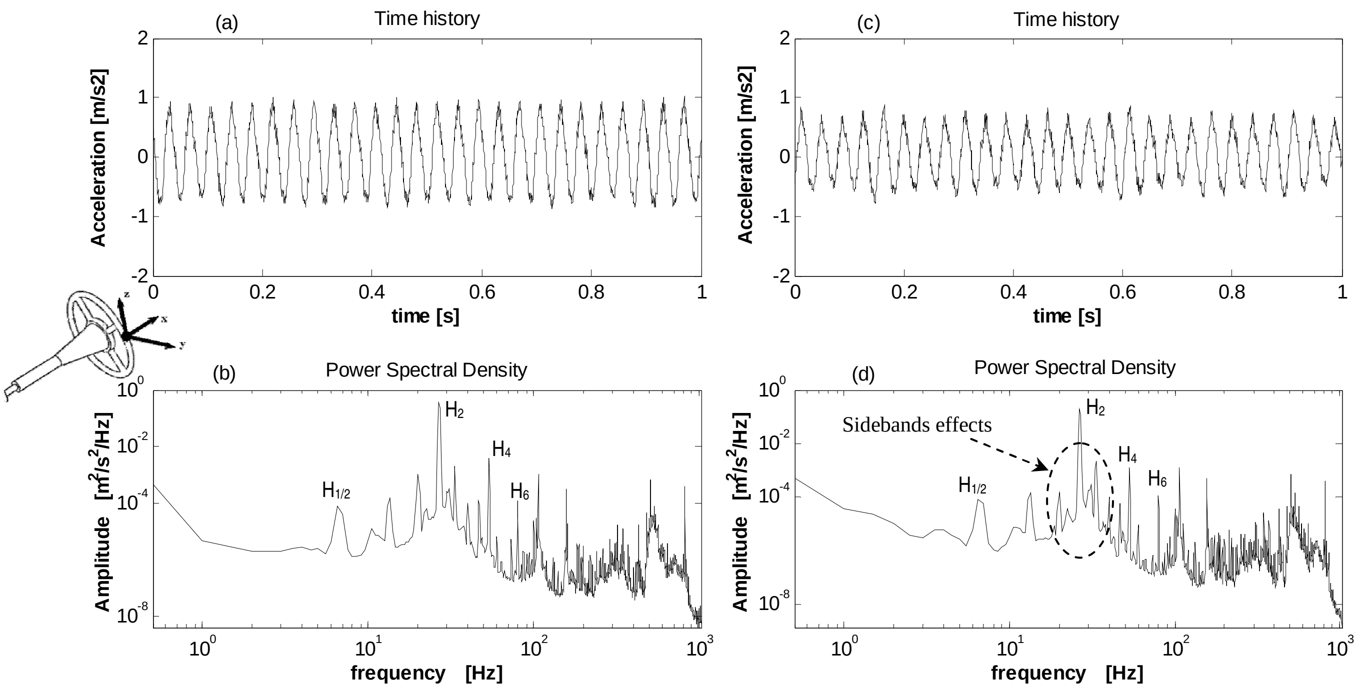

Fig. 3 Steering wheel idle vibration signature along the vertical (z) axis. Weakly modulated condition: (a) time history and (b) its relative PSD. Strongly modulated condition: (c) time history and (d) its relative PSD.

In the present experiment the test stimuli consisted of amplitude modulated sinusoids with a 26 Hz carrier frequency and a modulation frequency of 6.5, producing sideband components at 19.5 Hz and 32.5 Hz. A sampling rate of 512 Hz was chosen to generate the signals since the typical range of engine idle speeds of road vehicles is from 600 to 840 rpm, leading to firing frequencies ranging from 20 to 28 Hz and higher harmonics up to 100 Hz. Seven different values of modulation depth parameter m equal to 0.0, 0.1, 0.2, 0.4, 0.6, 0.8, 1.0

were chosen. Since the average power of a signal is increased when the carrier is modulated **(23)** all the seven stimuli were scaled to have equal average power in order to eliminate changes in overall perceived intensity with changes in modulation depth. Average power was quantified by means of root-mean-square (RMS) acceleration defined by:

$$RMS = \left[\frac{1}{T} \int_0^T a^2(t)\, dt \right]^{\frac{1}{2}} \tag{3}$$

where T is the duration over which the RMS value is measured, $a(t)$ is the acceleration value and t is a time increment. The reference RMS acceleration chosen for all stimuli was the average RMS value measured from the steering wheel idle vibration time histories recorded from a Ford Focus test vehicle for 12 different fuel conditions **(2)**. The RMS values for the 12 fuel conditions ranged from 0.31 to 0.43 rms m/s^2 with an average value of 0.41 m/s^2. Thus the value of the amplitude of the test carrier signal was calculated to be $A_0 = \sqrt{2} * RMS = \sqrt{2} * 0.41 = 0.58\ m/s^2$. The duration of each test signal was chosen to be 4 seconds based on the knowledge that the tactile system of the hand does not present temporal integration properties below approximately 40 Hz **(24)** and based on the results of experiments reported by Miwa **(25)** who suggested that for vibration in the range 2-60 Hz there may be no further increase in discomfort sensation for stimuli durations greater than approximately 2 seconds.

In addition to the RMS measure, the vibration dose value (VDV) was also calculated for all the seven signals by integrating the fourth power of the acceleration $A(t)$ of equation (2) as defined in British Standard BS 6841 **(26)**:

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

where T is the duration over which the VDV value is measured and $A(t)$ is the instantaneous acceleration amplitude of the signal. The VDV value provides a cumulative measure of the vibration exposure, and being a fourth power method it accounts more accurately for the greater effect on human response to vibration of high amplitude peaks which occur in the time history **(27)**. Figure 4 presents the seven time history test signals used in all experiments.

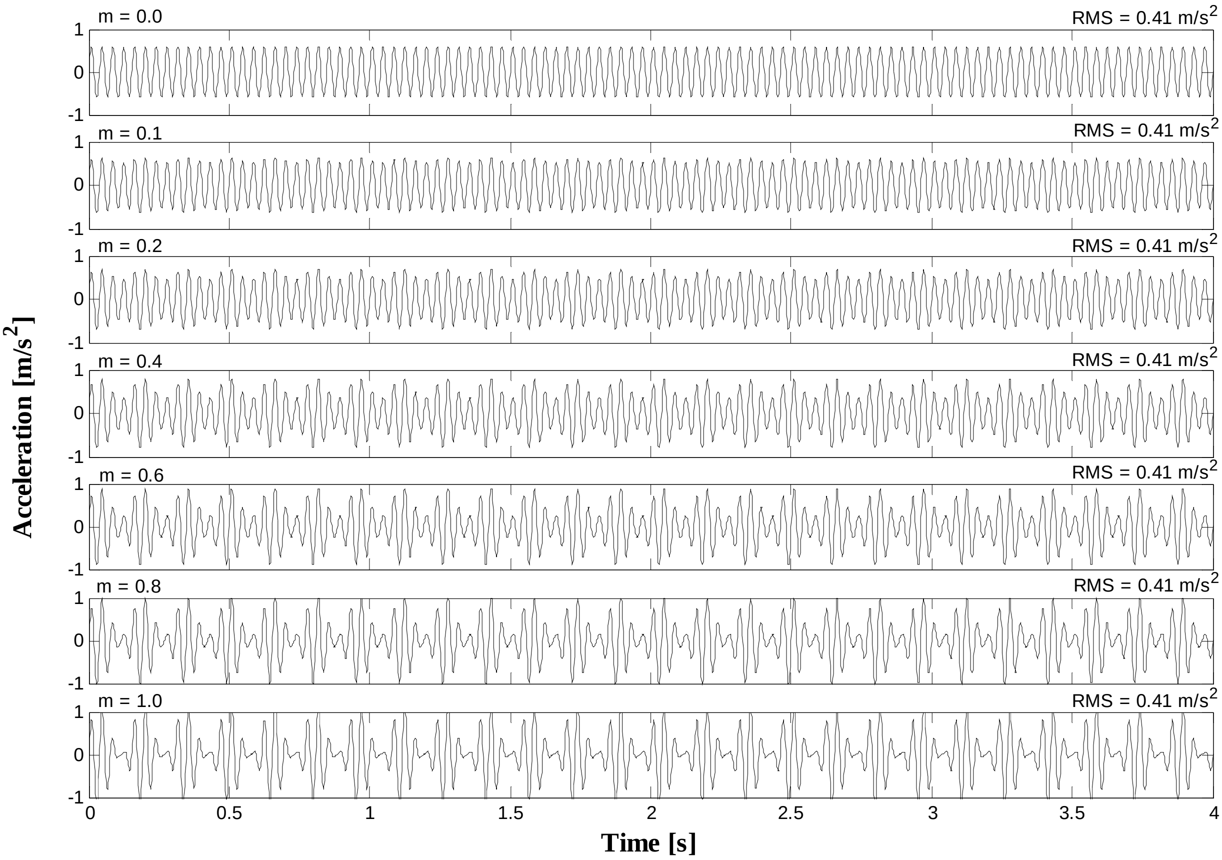

Fig. 4 - Test signals used in all experiments.

2.3. Test methodology

Four experimental conditions, determined by the combination of two subjective descriptors and two test methods, were conducted to examine the human subjective response to steering wheel idle vibration. The semantic attributes of unpleasantness and roughness were chosen as descriptors of the human response to idle vibration since they have been found to be used by drivers to describe vehicle idle quality **(9)**. In addition the sensory attribute of roughness was also chosen based on the feeling "rougher" reported in Wiesenberger's experiments **(14)**. Experiments I and II used the scaling method of Thurstone's Law of Comparative Judgement (Case III). Experiments III and IV used the category-ratio Borg CR-10 scale under the same sensory attributes of perceived unpleasantness and perceived roughness.

In experiments I and II all possible pairings of the 7 test signals were used in order to fully counterbalance the test **(28)**. The result was a total of 42 paired comparisons. In order to reduce testing time no stimulus was presented with its duplicate as a pair. Each subjective evaluation consisted of a 4-second test signal followed by a 2-second gap followed by the other 4-second test signal. Each paired comparison therefore required 10 seconds, a duration which was chosen to keep the stimulus short enough to permit both signals to remain in human short-term memory for tactile stimuli **(29)**. To reduce learning and fatigue effects the order of presentation of the 42 comparisons was randomized for each test subject. After presenting each stimuli pair the test subject was asked to indicate which stimuli they considered to be “more unpleasant” in experiment I or the “rougher” in experiment II. The complete paired comparison test (all 42 pairs) lasted 16 minutes for each test subject.

In experiments III and IV perceived unpleasantness and perceived roughness of the vibration were assessed using the Borg CR-10 scale following the instructions provided by Borg **(21)** for the scale’s administration. The Borg CR-10 scale (shown in Fig. 5) consists of a numerical scale from 0 (nothing at all) to 10 (extremely strong) with nine verbal anchors placed along the scale in an approximately logarithmic fashion. The test subjects were asked to judge each test stimuli on its own merits, independent of preceding stimuli. At the start of testing a familiarization period was used to acquaint the subject with the use of the scale by means of practice ratings using a non-vibrational stimuli (acidity rating of common foods) and a dummy test involving two vibrational stimuli selected from the test set. The same seven signals used in the experiments I and II were employed for the direct Borg CR-10 scaling method. All the stimuli had the same time duration of 4 seconds as in the pair-comparison tests. In order to assess the individual’s ability to rate stimuli using the Borg’s scale each of the seven exposures was repeated four times giving a total of 28 assessment trials. In order to minimize any possible bias resulting from learning or fatigue effects the order of presentation of the test signals was randomized for each subject. A break of 10 seconds after the presentation of each set and a break of 5 seconds between each trial were allowed to avoid annoyance effects. Total testing time for a single test subject amounted to 13 minutes.

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

Fig. 5 - Borg's category ratio CR-10 scale (adapted from Borg **(18)**).

2.4. Test subjects and test protocol

An independent group of 25 individuals was tested for each of the four test conditions. Upon arrival in the laboratory each participant was given an information sheet and a consent form describing the purpose, procedure, risks and time commitment for the research project. After providing written consent, subjects were given a verbal description of the experiment and a short questionnaire regarding their physical characteristics, health, driving experience and history of previous vibration exposure. The test groups consisted of Sheffield University students and staff, whose age, height and weight characteristics are summarised in Table 2. On average 88% of the subjects drove 2 to 10 hours daily and all declared that they were in good physical and mental condition. Before commencing testing each subject was asked to remove any coats, watches or jewellery, then to adjust the seat position and backrest angle so as to simulate a driving task as realistically as possible. Subjects were required to maintain a constant palm grip **(30)** on the steering wheel using both hands, as when driving on a winding country road. They were asked to wear ear protectors to avoid audio cues. During the paired comparison experiment they were also asked to wear opaque glasses and to close their eyes to avoid any visual distractions, whereas during the Borg CR-10 scale experiments they were encouraged to focus their eyes on a placard representing the perceived rating Borg scale placed about 1 meter ahead at eye level. Room temperature was maintained in the range from 20 to 25 ºC so as to avoid significant environmental effects on the skin sensitivity **(31)**. The test facility and test protocol were reviewed and found to meet the University of Sheffield guidelines for good research practice.

Table 2 - Physical characteristic of the four groups of test subjects

Group I (n=25)		Age [years]	Height [cm]	Mass [kg]
Perceived Unpleasantness (Pair Comparison)	Mean (SD)	**27.4 (7.93)**	**1.7 (0.08)**	**70.4 (14.10)**
	Minimum	**20.0**	**160.0**	**45.0**
	Maximum	**56.0**	**190.0**	**100.0**
Group II (n=25)				
Perceived Roughness (Pair Comparison)	Mean (SD)	**29.3 (5.12)**	**1.7 (0.09)**	**74.1 (16.39)**
	Minimum	**22.0**	**160.0**	**48.0**
	Maximum	**41.0**	**188.0**	**111.2**
Group III (n=25)				
Perceived Unpleasantness (Borg CR10 Scale)	Mean (SD)	**28.5 (5.04)**	**1.7 (0.08)**	**75.8 (14.30)**
	Minimum	**22.0**	**160.0**	**53.0**
	Maximum	**42.0**	**185.0**	**107.0**
Group IV (n=25)				
Perceived Roughness (Borg CR10 Scale)	Mean (SD)	**29.4 (6.55)**	**1.8 (0.107)**	**76.0 (15.69)**
	Minimum	**22.0**	**160.0**	**50.0**
	Maximum	**48.0**	**201.0**	**115.8.0**

3. RESULTS

From the average test results for each test group of 25 subjects an interval scale was constructed according to Thurstone's comparative judgement from experiments I and II, and a ratio scale was constructed according to the direct scaling method using the Borg CR-10 scale from experiments III and IV. The mean scale values obtained for each value of modulation depth in each of the four experiments is provided in Table 3, along with the standard deviation (SD) values. Thurstone's method produces as output a scale difference between the means of the stimulus responses, locating the stimuli on the interval scale with respect to one another. Direct rating by means of the Borg CR-10 scale produces a subjective value for each stimulus placing it along a scale which is claimed to have ratio scale properties. The mean scale values and the standard deviation values are presented for each of the four experiments in Fig. 6.

Table 3 - Subjective raw scale mean values and standard deviations (SD) for the seven test stimuli

Stimuli			**Thurstone scale values**				**Borg scale values**			
			Experiment I		**Experiment II**		**Experiment III**		**Experiment IV**	
Modulation depth, m	**RMS [m/s^2]**	**VDV [m/s$^{1.75}$]**	**Relative Unpleasantness**		**Relative Roughness**		**Perceived Unpleasantness**		**Perceived Roughness**	
m = 0.0	0,41	0,640	0	(0.338)	0	(0.982)	2.38	(1.212)	2.45	(0.708)
m = 0.1	0,41	0,644	-0.302	(0.288)	-0.054	(0.913)	2.42	(1.087)	2.75	(0.792)
m = 0.2	0,41	0,658	-0.077	(0.386)	0.287	(1.098)	2.48	(1.080)	2.78	(0.915)
m = 0.4	0,41	0,707	0.3	(0.414)	1.113	(1.419)	3.06	(1.225)	3.37	(0.973)
m = 0.6	0,41	0,773	0.895	(0.343)	1.853	(1.256)	3.44	(1.398)	4.03	(1.186)
m = 0.8	0,41	0,847	1.16	(0.357)	2.588	(0.795)	3.79	(1.638)	4.22	(1.412)
m = 1.0	0,41	0,925	2.302	(0.182)	3.555	(0.587)	3.93	(1.628)	4.55	(1.582)

Since the zero point of the Thurstonian interval scale and the unit of measurement of the Borg ratio scales are not unique, a common scale was required to facilitate comparisons. Studies of the temporal sensitivity of the tactile system performed by Weisemberger **(14)** indicated that the depth of modulation m_{th} necessary to just allow discrimination between a modulated and an unmodulated sinusoidal carrier waveform of 25 Hz was 0.2 for modulation frequencies ranging from 5 to 10 Hz.

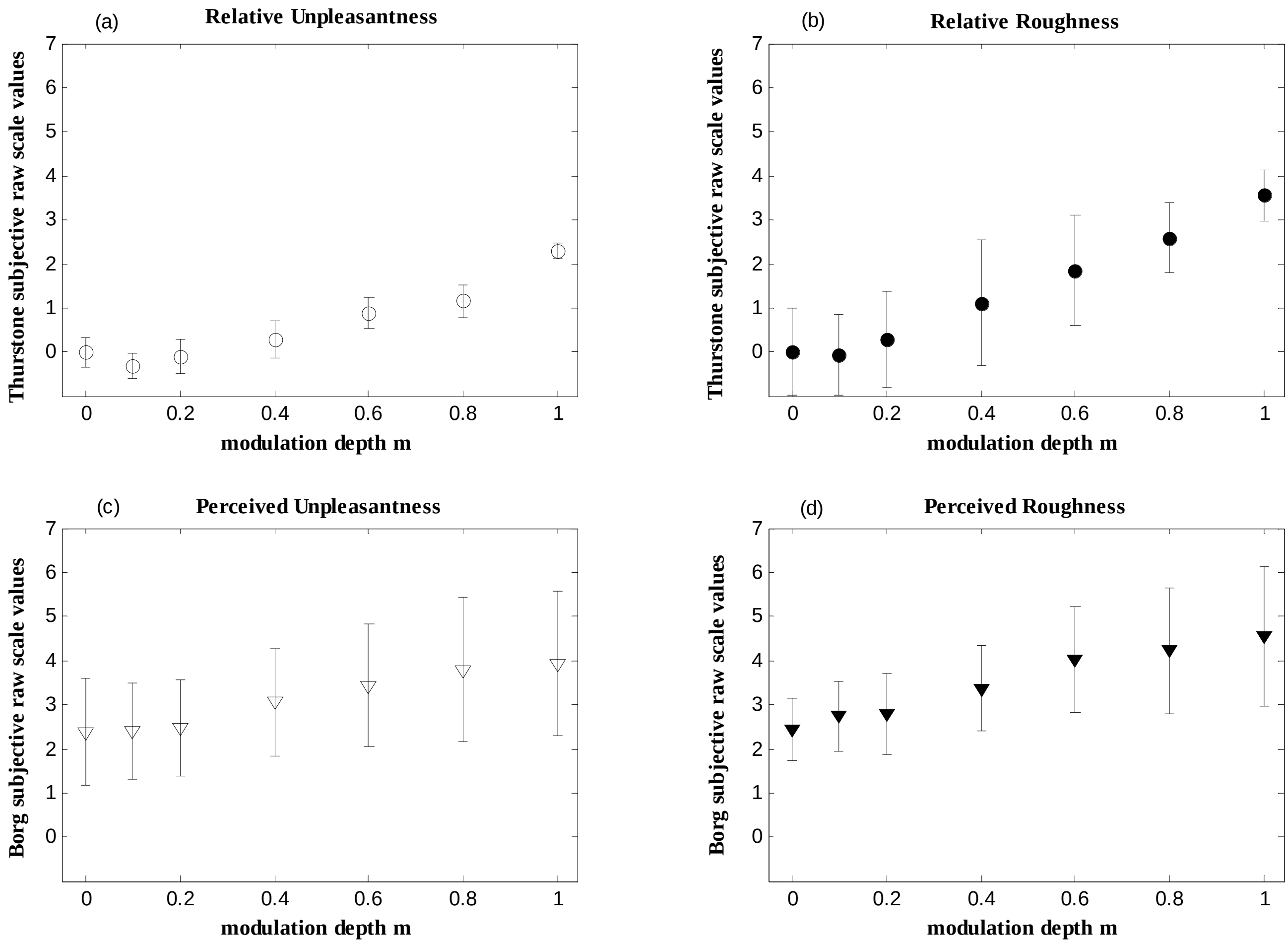

Fig. 6 - Subjective raw scale values as a function of modulation depth m: (a) relative unpleasantness, Thurstone scale ; (b) relative roughness, Thurstone scale; (c) perceived unpleasantness, Borg CR-10 scale; (d) perceived roughness, Borg CR-10 scale. Data are shown as mean ± 1 standard deviation.

Based on this observation, and the current results for the experimental condition of f_c = 26 Hz and f_m = 6.5 Hz (as shown in Fig. 6), it can be assumed that a modulation depth value of approximately 0.2 represents a point of separation between two different human response characteristics. Below the point m = 0.2 subjects do not perceive differences in amplitude modulation and the sensation magnitude can be interpreted as sensory noise relative to the energy of the unmodulated waveform. Above the point m = 0.2 the sensation magnitude growths monotonically as a function of the modulation depth m. A schematic representation of the proposed model of human perception of amplitude modulated vibration delivered to the hand is shown in Fig. 7.

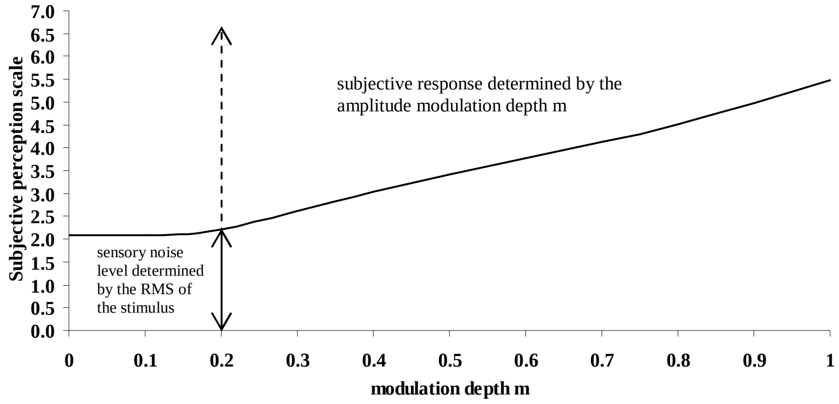

Fig. 7 - Model of human hand-arm perception of vibrotactile amplitude modulated stimuli.

Psychophysical relations of the type occurring for modulation depths greater than 0.2 are compactly expressed by means of the well-known Stevens' Power Law which in its most general form is expressed as:

$$R = R_o + k(X - X_{th})^n \qquad (5)$$

where R is the subjective perceived magnitude, X is the stimulus magnitude (expressed here as modulation depth m), k is a constant determined from the measurement units, and n is the exponent of the power law and the two constants R_o and X_{th} indicate the starting point of the growth function on the response axis (y-axis) and on the stimulus axis (x-axis) respectively. In the current analysis the constant R_o represents the sensory response to the harmonic stimuli when no actual modulation is present and X_{th} is the value of the modulation depth at threshold m_{th}. The use of expression (5) implies that the sensation magnitude R is a power function of effective stimulation above the threshold of amplitude modulation m_{th}. The value X_{th} to which the physical stimuli on the x-axis were rescaled was chosen equal to $m_{th} = 0.2$, whereas the constant value R_o was taken to be equal to the average value of the responses to the stimulus corresponding to modulation depth of m = 0.0, m= 0.1 and m= 0.2 for both psychophysical scales.

After translating the raw data on both axes the growth functions of human perceived unpleasantness and roughness of the vibration could be determined as a function of the difference in modulation depth with respect to threshold $m^* = m - m_{th}$ as shown in Fig. 8. Figure 8a presents the experimentally obtained unpleasantness scale values and the fitted Stevens' power law obtained using Thurstone's method (n = 1.38) and obtained using the Borg CR-10 scale (n = 0.61). Figure 8b presents the roughness scale values and the Stevens' power law obtained using Thurstone's method (n = 0.92) and obtained using the Borg CR-10 scale (n = 0.63). In order to test the internal consistency of Thurstone scale values, a Chi-Squared test **(28)** was used. No systematic deviations between the Thurstone's scale values were found at significance level $p < 0.01$. In order to identify any statistically significant differences among the Borg scale values, a one-factor ANOVA test was performed using the modulation depth parameter m as the independent variable. Statistically significant differences between the Borg scale values were found at 1% confidence level ($p < 0.01$). For each of the four experiments the coefficient of determination (R^2) was also determined (Table 4) when correlating the subjective responses to the relative modulation index m*.

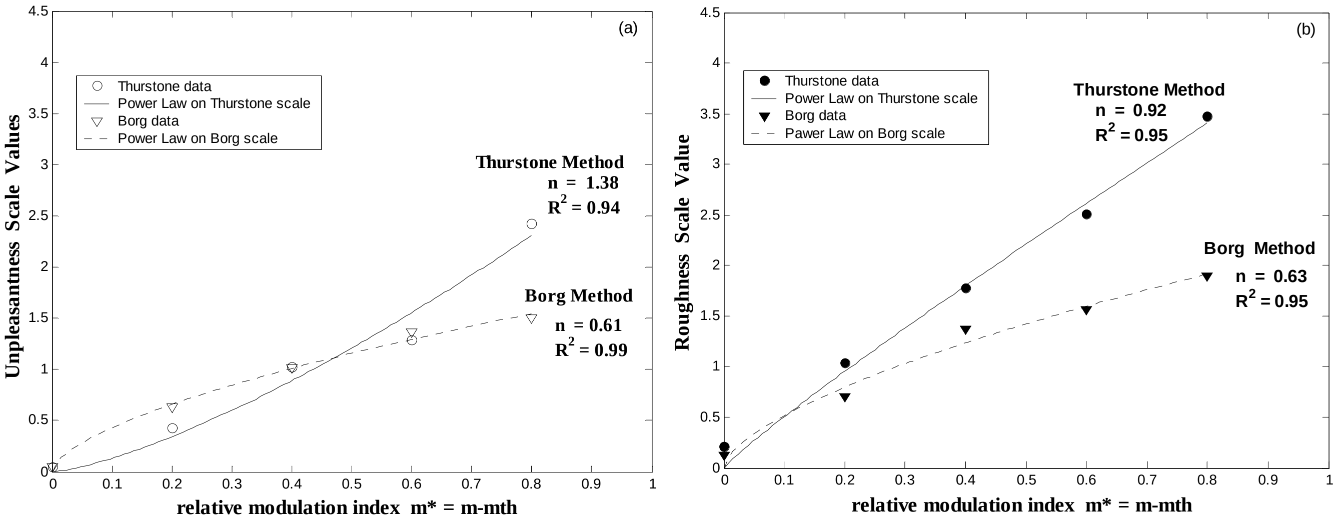

Fig. 8 - Growth functions of human perceived disturbance of amplitude modulated steering wheel idle vibration obtained by means of Thurstone paired comparison method and by using the Borg CR-10 scale: (a) perceived unpleasantness; (b) perceived roughness.

Table 4- Stevens' power exponents n and coefficients of determination R^2 determined from the data from experiments I, II, III, IV

Experiment	Scaling Method	Sensory attribute	Stevens' Power Exponent, n	Coefficent of determination, R^{2} **
I	Thurstone (indirect method)	Perceived Unpleasantness	1.38	0.94
II		Perceived Roughness	0.92	0.95
III	Borg CR-10 scale (direct method)	Perceived Unpleasantness	0.61	0.99
IV		Perceived Roughness	0.63	0.95

** $p < 0.01$

4. DISCUSSION

The sensory attributes of vibration unpleasantness and vibration roughness belong to the group of perceptual dimensions based on the quality, rather than on the intensity, of the stimulus. Such dimensions are generally thought to depend on more than a single sense modality **(32)**. Studies performed for this class of sensory continua have shown that subjective roughness of emery cloths stoked with the fingers grew with a Stevens' exponent of 1.5 with respect to the diameter of the grit particles **(16)**, subjective hardness produced when rubber samples are squeezed between thumb and finger grew with a Stevens' exponent of 0.8 with respect to physical hardness, and that perceived auditory roughness can be described by a power function with exponents ranging from 0.8 to 1.8 with an average value of 1.4 **(33)**.

In the present work the perceived unpleasantness and roughness of amplitude modulated steering wheel acceleration stimuli were found to depend on the psychophysical protocol used. As can be seen from Fig. 8 the growth exponent n describing the human subjective response obtained by means of Thurstone's method of paired comparison was greater than unity for the perceived unpleasantness dimension and nearly equal to unity for the perceived roughness, whereas the exponents from the Borg CR-10 experiments remained nearly constant with a average value of 0.62 for the two dimensions. In this and other research studies performed by the authors the use of the Borg CR-10 scale has lead to smaller Stevens' exponents than paired comparison methods. While difficult to demonstrate analytically, the lower exponent seems to be a reflection of an artifact in the Borg scale which occurs when only a portion of the dynamic range of the scale is used. In the research described here the mean subjective response of the test group was never greater than 5.0, thus accounting for less than half the dynamic range of the Borg CR-10 scale.

Given the differences in the experimental data and fitted Stevens' power laws obtained by means of the two psychophysical protocols, consideration of related metrics is useful to lend support to one or the other of the data sets. An obvious metric for comparison is the vibration dose value (VDV) which is commonly used for quantifying the perceived intensity of the human response to vibration. Figure 9 presents the VDV values of the test stimuli as a function of $m^* = m - m_{th}$. The VDV values (y-axis) have been translated for comparison purposes by removing the sensory noise associated with the unmodulated sinusoidal signal ($m = 0.0$). From figure 9 it can be seen that the perceived intensity predicted by means of the VDV value increases with relative modulation index m* with a Stevens' power exponent of n = 1.32. Since the VDV value has found widespread acceptance in the human vibration and human testing communities it is reasonable to assume that the power exponents obtained by means of Thurstone's paired comparison method provide a closer measure of human response to amplitude modulated steering wheel vibration than the results obtained using the Borg CR-10 scale.

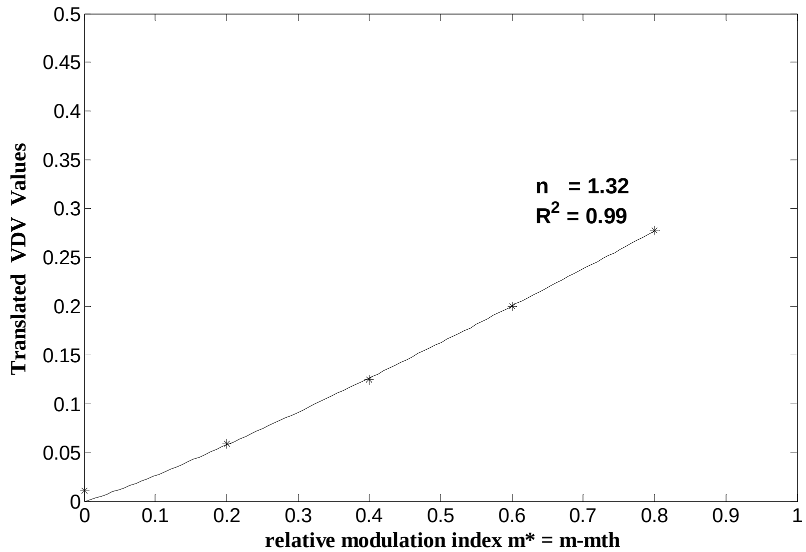

Fig. 9 – Translated Vibration dose value (VDV) as function of relative modulation index m* = m-$m_{th.}$

5. CONCLUSIONS

The purpose of this study was to quantify the human subjective response to steering wheel vibration caused by diesel engine idle. Based on the results of previous investigations by the authors diesel engine idle vibration stimuli occurring at the steering wheel of automobiles was modeled as an amplitude modulated harmonic signal having a carrier frequency of 26 Hz, a modulation frequency of 6.5 Hz and a RMS energy level of 0.41 m/s^2. Evaluations of seven levels of modulation depth parameter m (0.0, 0.1, 0.2, 0.4, 0.6, 0.8, 1.0) were performed in order to define the growth function of the human perceived disturbance. Two semantic descriptors of the human response and two psychophysical test protocols were used. The semantic attributes of unpleasantness and roughness were chosen as descriptors of the human response to idle vibration exposure, and the human subjective evaluations were performed by means of Thurstone's method of paired comparison (Case III) and by means of the category-ratio Borg CR-10 scale. The results suggest that there is a critical value of modulation depth m = 0.2 below which human subjects cannot perceive differences in amplitude modulation and above which the stimulus-response relationship increases monotonically with a power function. Thurstone's paired comparison indirect scaling method appears to be more effective in assessing amplitude modulated steering wheel vibration than direct evaluation using the Borg CR-10 scale. Stevens' power exponents suggest that the perceived unpleasantness is nonlinearly dependent on modulation depth m with an exponent greater than 1 and that the perceived roughness is dependent with an exponent close to unity.

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