Human Perception of Diesel Engine Idle Vibration

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While the human perception of diesel engine noise has been the subject of numerous studies, the perception of the vibrational disturbance reaching the driver has not previously been investigated. This contribution presents the results of a recent research study performed at Sheffield University which analysed the nature of diesel engine idle, and modelled the associated human growth function. The results have shown that the largest component of diesel idle irregularity arriving at the steering wheel is amplitude modulation of the firing frequency and that the human subjective response grows with a power exponent greater than 1.0 for modulation values greater than 0.2.

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Introduction

Internal combustion diesel engines produce vibration emissions due to combustion forces, inertial forces and structural resonances of the crank shaft and engine block. Periodic variations in the crank shaft angular velocity arise due to the stochastic nature of the combustion process from cycle-to-cycle, and due to an unequal distribution of fuel from cylinder-to-cylinder. In addition, fuel economy can lead to low idle speeds which further increases the irregularity.

Vibration power spectra measured for diesel engines while at idle typically contain low frequency harmonics of the firing frequency from 1 to 400 Hz, crank shaft bending frequencies from 400 to 800 Hz and combustion chamber resonances in the range from 800 to 4000 Hz. Engine idle vibration belongs to a class of waveforms characterized by a mixture of deterministic and non-stationary random components. When cycle-to-cycle variations are large the driver perceives a rough, or unsteady, vibration stimuli which us often associated with poor vehicle performance or poor fuel quality.

When investigating what aspects of the engine idle vibration are important towards the driver’s opinion of the quality of the vehicle and fuel, consideration must be given to the role of the intermediate mechanical structures which are found between the emission source at the engine and the points of contact with the human body. As shown in Figure 1 the points of contact through which the driver perceives engine vibration include the pedals, the gearshift, the seat and the steering wheel. Of these, the most important is the steering wheel (Giacomin and Abrahams, 2000) due to great sensitivity of the skin tactile receptors of the hand and due to the lack of intermediate structures such as shoes and clothing which can act to attenuate vibration stimuli.

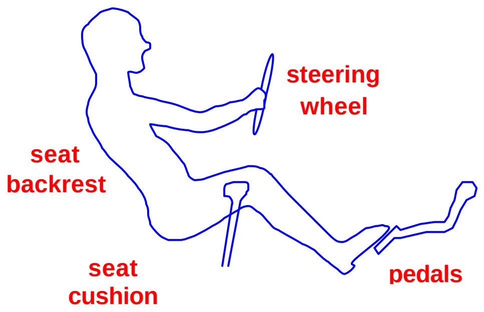

Fig. 1 – Vibrational disturbances at the driver.

Focussing attention on the steering wheel suggests the importance of the steering system components which often have important vibrational modes (either the wheel itself or the column assembly) in the frequency range from 20 and 60 Hz.

Effect of vehicle and of fuel

In order to establish the possible variations that can be introduced by the engine technology, the vehicle design and the fuel type, a set of vibration recordings were performed using two automobiles of widely differing injection technology and using twelve different diesel fuels having cetane numbers ranging from 27.1 to 77.0. The first vehicle was a Renault 19 1.9 L with a turbocharged engine, mechanical injection and a prechamber. The second was a Ford Focus 1.8 L which was also turbocharged but which had a common rail injection system. Table 1 presents the physical characteristics of the 12 fuels.

Fuel	Density [kg/m^3]*	Viscosity [mm^2/s]**	Cetane Number
Fuel 1	773.1	——	77.0
Fuel 2	824.1	2.27	52.9
Fuel 3	826.9	3.19	63.3
Fuel 4	811.4	2.94	69.3
Fuel 5	837.3	2.93	52.4
Fuel 6	837.3	3.40	50.7
Fuel 7	830.1	2.72	54.5
Fuel 8	817.7	1.95	54.9
Fuel 9	837.6	3.33	56.5
Fuel 10	847.4	2.22	44.7
Fuel 11	836.1	1.93	41.4
Fuel 12	915.3	——	27.1

* Density at 15 ºC
** Kinematic viscosity at 40 ºC

Table 1 – Fuels tested.

Each test consisted of approximately 5 minutes of running at idle to stabilise the thermodynamic conditions followed by 2 minutes of vibration recording by means of triaxial accelerometers placed at the engine block and steering wheel. The sampling rate for all data was 2048 Hz.

The root-mean-square (r.m.s.) acceleration amplitudes in the directions of the greatest response (fore-and-aft at the engine block and tangential at the steering wheel) are presented in Figures 2 and 3 in units of m/s^2. Levels were found to be lower, at both the engine block and the steering wheel, in the case of the automobile equipped with common rail injection. Further, the ability of the controller to compensate fuel differences is evident.

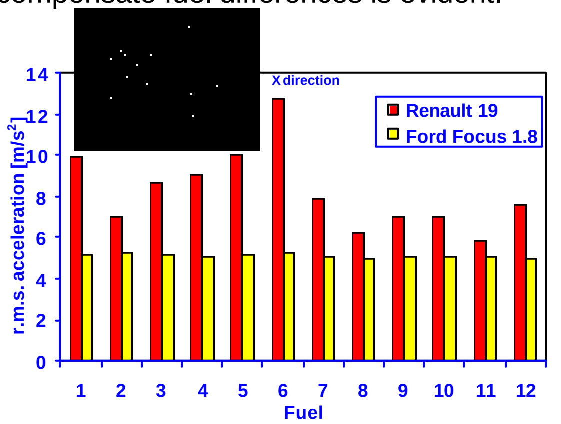

Fig. 2 – Vibration levels at the engine block.

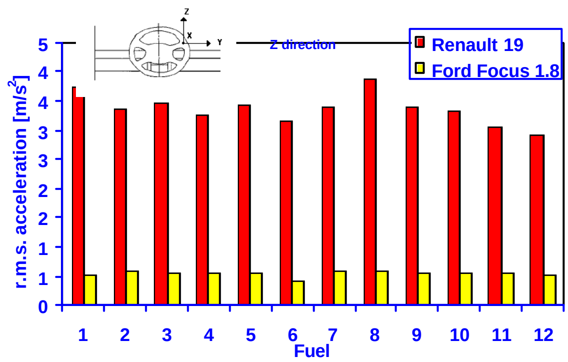

Fig. 3 – Vibration levels at the steering wheel.

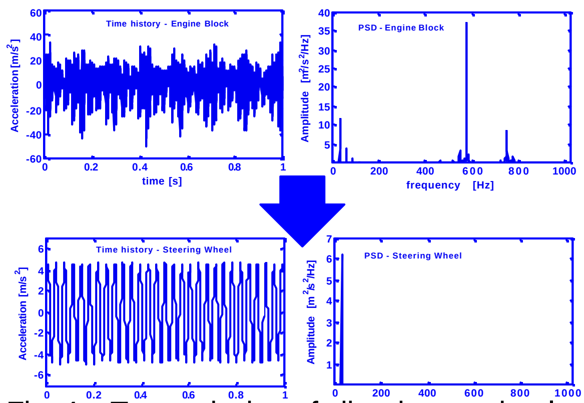

Fig. 4 – Transmission of vibration to wheel.

Figure 4 illustrates instead the nature of the transmission of the vibration occurring from the block to the steering wheel, which in all measured cases reduced the frequency bandwidth of the stimuli to only the low order harmonics of the engine rotation. While remaining an important acoustic problem, the vibration occurring at engine combustion frequencies was found to be reduced to insignificant levels at the steering wheel in all cases tested.

Nature of diesel engine idle vibration

Analysis of the acceleration time histories was performed for all data acquired at the engine block and at the steering wheel. Time domain, frequency domain and combined time-frequency domain analysis were performed (Ajovalasit and Giacomin, 2003). The nature of idle vibration stimuli is illustrated by Figure 5 which presents both the time histories and the frequency spectra of a fuel which had a high cetane number (fuel 10) and one with a low cetane number (fuel 2). Considering only the low frequency components of the signal, amplitude modulation is evident in the form of sidebands about the second harmonic (H2) of the engine rotational frequency.

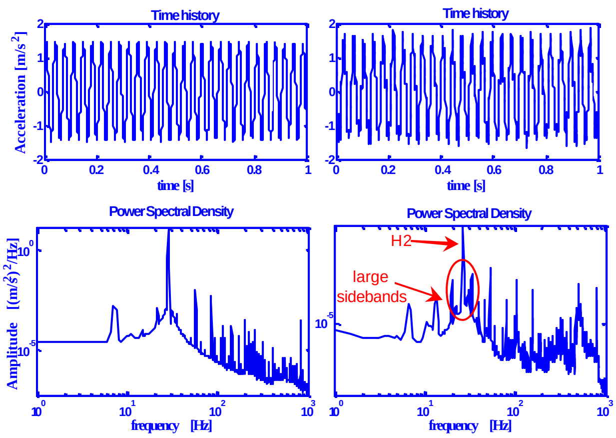

Fig. 5 – Regular and irregular idle vibrations.

At frequencies below 40 Hz all measured idle vibration signals were found to be adequately described as amplitude modulated signals of the form

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

where A_0 is the amplitude of the carrier, m is the modulation depth, f_m is the modulation frequency, f_c is the carrier frequency, t is time, and j and q are phase angles.

Psychophysical tests of human response

Having analysed the nature of the idle stimuli which reach the driver, psychophysical tests of human response (Ajovalasit and Giacomin, 2004) were performed using a laboratory simulator. The steering rotational vibration test rig (shown in Figure 6) can reproduce stimuli to frequencies in excess of 300 Hz with average signal reproduction errors of less than 5 percent (Giacomin et. al. 2004).

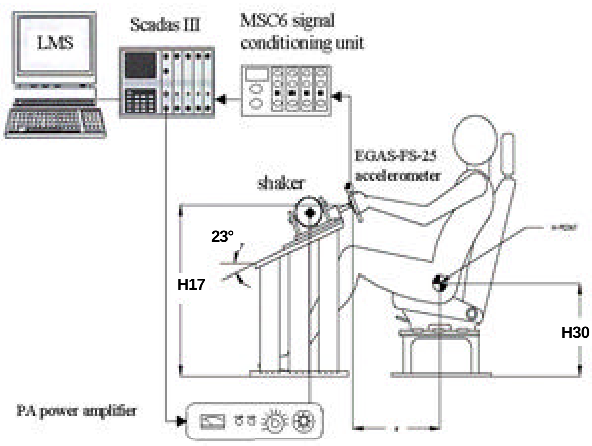

Fig. 6 – Steering vibration simulator.

Using the analytical expression for amplitude modulation, a set of 7 tangential acceleration time histories were defined having modulation depths m in the range from 0.0 to 1.0. The stimuli were developed to represent a four cylinder diesel engine at idle at 780 rpm, therefore the carrier frequency f_c was taken to be the firing frequency second harmonic of 26 Hz, and the modulation frequency f_m was taken to be the one-half engine order of 6.5 Hz. The stimuli were therefore characterised by amplitude modulation sidebands at 19.5 Hz and 32.5 Hz. All stimuli were scaled to the same r.m.s. acceleration amplitude so as to isolate modulation depth as the only test parameter. The acceleration value chosen was the mean value obtained by averaging all of the test data obtained from the Ford Focus automobile and the 12 fuels. The r.m.s. values ranged from 0.31 to 0.43 m/s^2 across the fuels, with a mean value of 0.41 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 40 Hz. In all the experiments the phase of both the carrier and the modulating waves were chosen equal to zero (j = 0, q = 0) for simplicity. A two second section of each of the 7 test stimuli is presented in Figure 7.

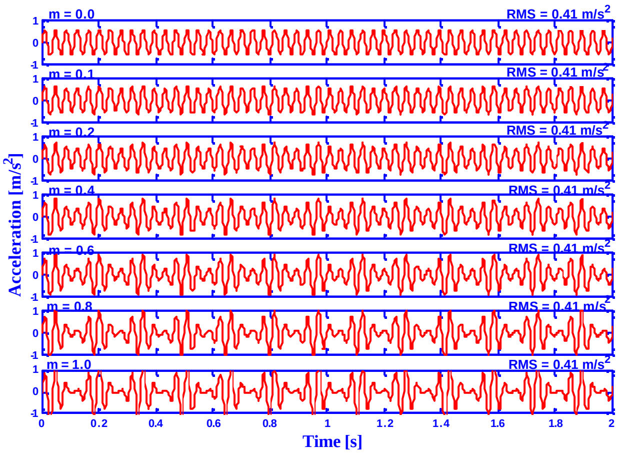

Fig. 7 – Amplitude modulated test stimuli.

In order to judge the reliability of the measured human subjective responses, two semantic descriptors and two different psychophysical test protocols were used. From preliminary testing with a variety of semantic descriptors a decision was taken to use one prothetic descriptor, the word “unpleasantness”, for judging the size of the stimuli and one metathetic descriptor, the word “roughness”, for judging the quality.

Two psychophysical test protocols were chosen based on their contrasting strengths and weaknesses. The first procedure was a paired-comparison protocol (Gescheider, 1997) of the type commonly used in automotive ergonomics. Paired comparisons can provide accurate sensory distances from one stimuli to the next, but suffer the limitation of providing data which possess only interval scale properties. In order to obtain ratio scale outputs, a second psychophysical protocol was also attempted. Ratio scale data was obtained using the Borg CR-10 category-ratio scale (Borg, 1998).

Each of the four human response tests (two semantic descriptors and two protocols) was performed using 25 participants whose general characteristics are presented in Table 2.

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

Table 2 – Statistics of the test participants.

All tests provided qualitatively similar results. Except for translations of the y-axis intercept of the average subjective responses, all four tests suggested two distinct regions of human response. A model of human perception of idle vibration has been proposed by the authors which is subdivided into two modulation regions as shown in Figure 8.

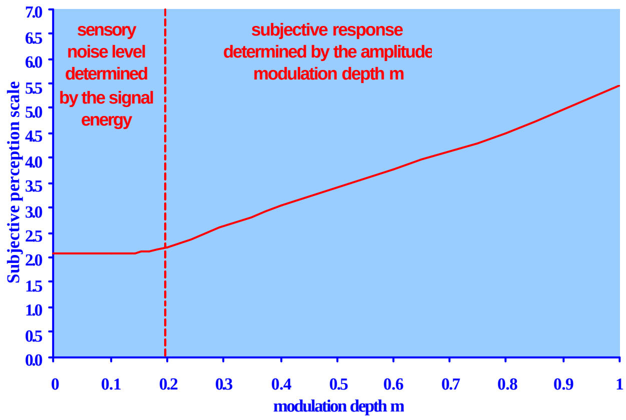

Fig. 8 – Proposed model of human response.

For modulation values below m = 0.2 human perception is insufficiently accurate to distinguish stimuli based only on modulation depth. Human perception in this region is characterised by sensory noise which appears to be proportional to the overall r.m.s. value of the stimuli. For values above approximately 0.2 the human response grows according to a Steven’s Power Law defined by the expression

$$S = a\, I^{n}$$

where *S* is the human subjective response, a is a constant of proportionality defined by the measurement units adopted, *I* is the r.m.s. intensity of the vibration stimuli in units of m/s^2 and *n* is the power exponent defining the growth of the human response. For modulation depths greater than the threshold of human perception (m=0.2), the power exponent was found in this research to take on a value of 1.3, suggesting a nonlinear, positively accelerating, human response. Figure 9 presents the Stevens' Power Law determined for modulation depth values greater than 0.2, plotted as a function of the relative modulation determined by subtracting the threshold value of 0.2 from all values.

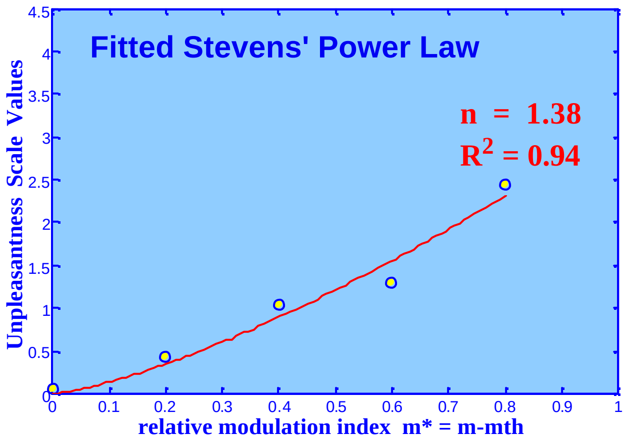

Fig. 9 – Power law above threshold.

Summary

The research described here has established that little vibrational energy from combustion frequencies reaches the vehicle driver by means of the steering wheel, and that the stimuli occurring in typical road vehicles under a range of fuel conditions can be modelled as amplitude modulated harmonic signals. Diesel cetane number was found to provide only a crude measure of idle performance, and was insufficient for predictive purposes. Knowledge of fuel additive content is required to evaluate the possible effect of fuel mixture on idle performance.

Psychophysical testing using two semantic descriptors and two test protocols suggested that humans cannot discriminate amplitude modulated steering wheel vibration stimuli with modulation values less than approximately 0.2. The authors have suggested a general model of human perceptual response to idle vibration which treats separately modulation depths which are below, or above, the 0.2 threshold. The human perceptual growth function above 0.2 was found to be nonlinear and positively accelerating, with an exponent value of approximately 1.38.

Further vehicle and psychophysical research is required to evaluate if the proposed approach can be extended to gasoline engined vehicles. Further research is also required to provide accurate predictions of the human sensory noise occurring at modulation depths that are less than 0.2.

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