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A Survey Study of Steering Wheel Vibration and Sound in Automobiles at Idle

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1 Introduction

In city traffic automobiles typically consume 30% of their fuel while at idle (Jurden, 1995). Decreasing the engine idle speed (600-840 rpm) is considered a means of reducing fuel consumption, however, lower-speed operation degrades the idle stability and increases engine idle oscillations. Even slight fluctuations of engine idle can cause unpleasant vibration and sound emissions leading to lower customer satisfaction (Hoard and Rehagen, 1997). Further, under idle conditions, the engine can be considered to represent the major source of vibration and sound which is transmitted to the driver within the vehicle cabin. Studies of the idle comfort of passenger cars (Stout et al., 2003) report that the overall perception of vehicle idle quality is mostly correlated to the level of satisfaction a customer has with the vehicle's engine. In this respect, modern diesel engine technologies provide a more stable engine combustion process due to the use of high pressure direct fuel injection.

When investigating what aspects of engine idle vibration and sound are important towards the driver's judgment of vehicle quality, consideration must be given to the role of the fuel type, the engine technology and the vehicle intermediate mechanical structures which are found between the emission source at the engine and the points of contact with the human body. Of the car/driver interfaces, the steering wheel (Pak *et al*., 1991) is the fundamental subsystem in the case of idle vibration due to the sensitivity of the skin tactile receptors of the hand (Bolanowski Jr and Gescheider, 1988) and due to the lack of intermediate structures such as shoes and clothing which can act to attenuate vibration stimuli.

The research presented in this paper describes a field survey of steering wheel vibration and interior car sound in automobiles at idle. The primary objective of the research was to quantify the intensity of the two stimuli in terms of the most commonly used human perception metrics. The steering wheel vibration stimuli were summarised in terms of the un-weighted root-mean-square (r.m.s.) acceleration, the ISO 5349-1 W_h-weighted r.m.s. and the W_s-weighted r.m.s. (Giacomin et al. 2004). The sound stimuli were summarised in terms of the un-weighted sound pressure level in decibels, the A-weighted sound pressure level in decibels and the Zwicker loudness in sones. The secondary objective was to verify if the steering wheel idle vibration and the sound at the ear were significantly different between diesel and gasoline powered automobiles.

2 Experimental Idle Tests

2.1 Automobile test population sample

The steering wheel vibration and interior car sound data were measured from a sample of 24 European automobiles which consisted of 12 diesel-powered automobiles and 12 gasoline-powered automobiles. All were equipped with 4-cylinder engines. The decision to focus the research on 4-cylinder engines was taken due to the popularity of this configuration. In order to introduce statistical variation into the data, the automobiles had substantially different engine characteristics. The diesel engines differed with respect to their fuel injection system which consisted of either an indirect injection (IDI) system, a direct injection (DI) system or a common rail turbocharged direct injection (CDTI) system. All gasoline powered automobiles had instead a multi-point injection system since this typology is the most popular among gasoline engines. Table 1 lists the specifications of the 24 automobiles used in this study.

[Insert here Table 1]

2.2 Test Measurements and Operating Conditions

The steering wheel vibration and sound data were measured using a SVANTEK portable field analyser model SVAN 947. The analyser had built-in functions which allow the reading of both the sound and vibration stimuli. Besides recording the time histories, the SVAN 947 was used to determine the unweighted r.m.s., the ISO 5349-1 W_h-weighted r.m.s. for hand-arm vibration exposure and the W_s-weighted r.m.s. developed for steering wheel rotational vibration exposure (Giacomin et al. 2004). The unit was also used to determine the un-weighted sound pressure level in decibels, the A-weighted sound pressure level in decibels and the Zwicker loudness in sones. The W_h frequency weighting of the SVAN 947 is based on ISO standard 5349-1, the acoustical A-weighting is based on IEC 60651, and the Zwicker loudness methods is based on ISO standard 532. In addition, the unit was programmed to implement a user-defined function to calculate the W_s frequency weighting for steering wheel rotational vibration following the frequency specifications and tolerances outlined by Giacomin et al. (2004). The meter conforms to the Type 1 specification for sound level meters (IEC 60651, 1979). Table 2 lists the steering wheel idle vibration and sound metrics which were measured for the 24 automobiles used in this study.

[Insert here Table 2]

A laptop PC was used to store the time histories of both stimuli for post-processing analysis. Both the analyser and laptop were run using a DC battery to eliminate electronic noise from vehicle systems. The sampling frequency of the SVAN 947 unit was 48 kHz. The recorded signals were post-processed in the laboratory by means of a LMS CADA-X 3.5BE software.

The vibration measurements consisted of acceleration data which were recorded at the steering wheel. The measurement point was taken on the surface of the steering wheel at the clockwise 60° position with respect to top centre. This location coincides about with the two o'clock hand grip position which drivers typically assume when holding an automotive steering wheel (Giacomin and Gnanasekaran, 2005). The direction of measurement for the steering wheel acceleration was taken tangential to the wheel. A single accelerometer was mounted rigidly to the steering wheel by means of a mounting clamp which guaranteed adequate coupling stiffness to frequencies in excess of 300 Hz. While the single accelerometer did not differentiate the rotational and the translational components of the steering acceleration, the approximation was made in the current study to associate the acceleration time history with the wheel rotational axis. Though non-negligible, the error implicit in this choice was considered acceptable for purposes of relative comparison.

The sound measurements consisted of sound pressure levels which were measured at the driver's ear at the centreline of the vehicle cabin. In order to obtain accurate and comparable sound measurements across different automobiles, the direction of measurement and the microphone position were taken in accordance with the guidelines of the British Standard BS 6086 (1981) which define the method of measurement of noise inside motor vehicles. The microphone position was taken with respect to the driver's seat which was occupied by the experimenter during the tests. The vertical co-ordinate of the microphone was at 0.7 ± 0.05 m above the intersection of the seat surface and the surface of the back of the seat. The horizontal co-ordinate was taken at 0.2 ± 0.02 m to the left of the vehicle from the middle plane of the seat. The microphone was mounted by means of a tripod which was secured to the unoccupied passenger seat. The microphone was oriented horizontally, pointing towards the windscreen.

In order to stabilise engine temperature and injection conditions, each automobile was left to idle for approximately 10 minutes before any recordings. After the 10 minute warm-up, the steering wheel vibration and sound were acquired for a duration of 1 minute for each idle condition. The test site was chosen to be in an open car park within the campus of Brunel University. An open space was chosen such that the sound inside the automobile cabin did not contain energy from reflections with surrounding buildings and structures. The distance of the automobiles from the nearest large buildings exceeded 20 m. In order to provide accurate sound measurements the level of background noise was measured in each test condition. With the engine off, the environmental background noise level measured outside the automobile was 60 dB on average, and 54 dB when measured inside the automobile cabin, including the inherent noise of the measuring equipment. With the engine idling the interior car sound was found to be 72 dB. Following British Standard BS 6086 (1981) which specifies a limit difference value of 10 dB between the sound pressure level of the interior car sound and that of the background noise, in this survey any automobile which achieved less than 10 dB was not included in the analysis. The vibration and sound signals were measured for each automobile in the following test conditions:

- automobile stationary with the engine idling;
- transmission in neutral gear;
- same experimenter sitting at the driver's seat during the test
- no human subject holding the steering wheel;
- approximately 20 ºC environmental temperature and 40% humidity.

3 Results

Figure 1 presents the steering wheel rotational idle vibration time histories and frequency spectra for two representative diesel-powered automobiles. Figures 1a and 1b present the data measured for car 2 which is a diesel-powered automobiles with an indirect injection system (IDI), while Figures 1c and 1d present the data for car 9 which is a diesel-powered automobile equipped with a common rail system (CDTI). As can be seen, the steering wheel idle vibration occurring in diesel-powered automobiles is characterised by low-frequency components with significant vibrational energy occurring between 20 and 40 Hz. The harmonic components occur at multiples or sub-multiples of the engine rotational frequency H_1 (10-14Hz). The second-order engine harmonic H_2 (20-28 Hz), which for a 4-cylider engine corresponds to the firing frequency of consecutive cylinders, was found to account for most of the energy of the steering wheel. Further, it can be seen that large amplitude modulation sidebands occur at frequencies above and below the second-order engine harmonic H_2, separated from the harmonic H_2 by the half-order engine harmonic $H_{1/2}$ (5-7 Hz). The data of Figure 1 suggest less amplitude modulation in the case of the common rail CDTI technology than in the case of the indirect injection IDI.

Figure 2 presents the steering wheel rotational idle vibration time histories and frequency spectra for two representative gasoline-powered automobiles. Figures 2a and 2b present the data measured for car 13 while Figures 2c and 2d present the data for car 17. As can be seen from Figure 2, the steering wheel idle vibration occurring in gasoline powered automobiles is also characterised by low-frequency components, with the second-order engine harmonic accounting for most of the spectral energy. For the gasoline-powered automobiles, higher order harmonics are also present above the second-order engine harmonic of about 27 Hz. The presence of modulation sidebands was found to be less prominent in the case of the gasoline powered automobiles.

[Insert Figure 1 here]
[Insert Figure 2 here]

Figure 3 presents the mean unweighted, the mean W_h-weighted and the mean W_s-weighted r.m.s acceleration amplitudes which were determined across the group of twelve automobiles from each of the two engine technologies reported in Table 2. The steering wheel idle vibration for the diesel-powered automobiles (0.44 r.m.s. m/s^2) was found to be higher than for the gasoline-powered automobiles (0.24 m/s^2), however, the differences were not found to be statistically significant at a 5% significance level when evaluated by means of a single factor ANOVA test (Hinton, 1999) for each of the three vibration intensity metrics.

[Insert Figure 3 here]

Figure 4 presents the idle sound pressure data for two representative diesel-powered automobiles. Figures 4a and 4b present the data for car 2 while Figures 4c and 4d present the data for car 9. As can be seen, the diesel idle sound is characterised by significant spectral energy at the second-order engine harmonic. Figure 5 presents the idle sound pressure data for two representative gasoline-powered automobiles. Figures 5a and 5b present the data for car 13 while Figures 5c and 5d present the data for car 17. Gasoline idle sound was also characterised by the second-order engine harmonic and by multiple and sub-multiple harmonic components. Significant sound energy for the diesel-powered automobiles occurred mostly in the frequency range from about 22 to 30 Hz, while for the gasoline-powered automobiles the frequency range extended from about 15 to 35 Hz. Further, from Figure 4b, it can be seen that the modulation sidebands of the second-order engine harmonic H_2 were greater in magnitude for the diesel-powered automobiles than for their gasoline-powered counterparts.

[Insert Figure 4 here]
[Insert Figure 5 here]

Figure 6 presents the mean un-weighted SPL in decibels, the mean A-weighted SPL in decibels and the mean Zwicker loudness in sones, which were determined across the group of twelve automobiles from each of the two engine technologies. The mean idle sound intensity for the group of the diesel-powered automobiles (85.66 dB) was found to be higher than for the gasoline-powered automobiles (74.85 dB). The difference was found to be statistically significant at a 1% significance level when evaluated by means of a single factor ANOVA test for each of the three sound intensity metrics.

[Insert Figure 6 here]

Figures 7 and 8 present plots of sound intensity metrics versus vibration intensity metrics for all 24 automobiles listed in Table 2. Figure 7 presents the diagram of the un-weighted sound pressure level in decibels as a function of un-weighted r.m.s. acceleration amplitudes, while Figure 8 presents the diagram of the Zwicker loudness in sones as a function of the W_s-weighted r.m.s acceleration amplitudes. In both Figures the mean values determined across the set of the diesel and the gasoline powered automobiles are also presented as a group centroid. While the number of automobiles tested is not sufficient for a rigorous statistical analysis for each subgroup of fuel injection system, the distribution of the data points does suggest the possibility that for diesel-powered automobiles the steering wheel vibration depends greatly on the type of fuel injection system. For example, the data of Figure 7 suggests that lower steering wheel acceleration amplitudes were measured for the diesel-powered automobiles which were equipped with direct injection (DI) than for the common rail (CDTI) or the indirect injection (IDI) systems. Further, the data of both Figures suggest the possibility that for the gasoline-powered automobiles the steering wheel vibration depends greatly, instead, on the vehicle model. For example the data of Table 2 and Figure 7 suggest that the highest steering wheel acceleration amplitudes were obtained in the case of the gasoline-powered automobiles for cars 22 and 23, which are both Alfa Romeo 156 models, and in the case of the diesel-powered automobiles for car 7 which is also an Alfa Romeo 156 model. The data from the current study thus supports the hypothesis that the design of the steering system and chassis is highly influential towards determining the vibration content at the steering wheel, as much so as the design of the engine injection system.

Figures 7 and 8 also suggest that, on average, the diesel-powered automobiles were characterised by higher steering wheel vibration intensity magnitudes than the gasoline-powered automobiles. However, the difference between the two engine technologies was not found to be significant by means of an ANOVA test at a 5% significance level. Figures 7 and 8 also suggest that, on average, the diesel-powered automobiles were characterised by significantly higher sound intensity values than the gasoline-powered automobiles as confirmed by an ANOVA test at a 1% significance level.

The results of the current study also suggest that the choice of statistical metric used to represent human perception has important implications towards the findings. For example, the data of Table 2 and Figure 8 suggest that when the steering wheel vibration is expressed in terms of the W_s-weighted r.m.s. acceleration, the difference in vibration intensity between the two engine technologies was greatly reduced. For example, the difference in vibration intensity between the gasoline-powered car 22 and the indirect injection (IDI) diesel-powered car 2 was greatly reduced when evaluated in terms of W_s-weighted acceleration.

Moreover, the data of Table 2 and Figure 8 suggest that when the idle sound is measured in terms of the Zwicker loudness metric, the difference in sound intensity between cars was greatly reduced. As for an example, the data of Figure 7 suggests that a difference of about 10 dB, which is greater than the well-known just-noticeable difference value of approximately 1 dB (Zwicker and Fastl, 1990), occurs among the gasoline-powered cars 13 to 18. However, when the sound is quantified using the more sophisticated Zwicker loudness method, as shown in Figure 8, a difference of less than the just-noticeable difference value of approximately 0.5 sone for loudness detection (Jeon et al., 2006) was obtained for the same cars.

[Insert Figure 7 here]
[Insert Figure 8 here]

4 Conclusions

Steering wheel idle vibration and sound were measured in field tests of 12 diesel-powered automobiles and 12 gasoline-powered automobiles. The steering wheel acceleration time histories were analysed in terms of the un-weighted r.m.s., the W_h-weighted r.m.s. and the Ws-weighted r.m.s. The sound pressure time histories were analysed in terms of the un-weighted sound pressure level in decibels, the A-weighted sound pressure level in decibels and the Zwicker loudness in sones. Both the steering wheel idle vibration and sound were found to be characterised by low-frequency harmonic components in the range from 6 to 40 Hz. The difference in steering wheel idle vibration intensity between the diesel-powered automobiles and the gasoline-powered automobiles was not found to be statistically significant at a 5% confidence level. The difference in idle sound intensity between the diesel-powered automobiles and the gasoline-powered automobiles was instead found to be statistically significant at a 1% confidence level. The results of the current study support the hypothesis that the design of the steering system and chassis is highly influential towards determining the vibration content at the steering wheel and the hypothesis that the sound at the human ear is highly dependent on the design of the engine combustion system.

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Table 1: Specifications of the 24 automobiles which were tested.

Car Number	Brand and Model	Capacity (cm^3)	Engine type	Turbocharged	No. of cylinders	Power (Hp)	Registration Date (year)	Age (km)
1	Ford Escort	1800	Diesel IDI	No	4	60	2002	108800
2	Citroen C15	1800	Diesel IDI	No	4	60	2000	60339
3	Citroen C1	1400	Diesel DI	No	4	55	2006	3640
4	Seat Leon	1900	Diesel DI	No	4	105	2006	7713
5	Ford Focus	1800	Diesel DI	No	4	90	2006	70
6	Vauxhal Agila	1300	Diesel CDTI	Yes	4	70	2004	44179
7	Alfa Romeo 156	1900	Diesel CDTI	Yes	4	115	2005	12474
8	Ford Mondeo	2200	Diesel CDTI	Yes	4	155	2006	15790
9	Toyota Avensis	2200	Diesel CDTI	Yes	4	150	2005	32656
10	Toyota Avensis	2200	Diesel CDTI	Yes	4	150	2005	7508
11	Jaguar X-Type	2200	Diesel CDTI	Yes	4	155	2005	14250
12	Peugeot 607	2200	Diesel CDTI	Yes	4	170	2002	12450
13	Nissan Micra	1200	Gasoline MultiPoint	No	4	89	2005	17344
14	Renault Clio	1400	Gasoline MultiPoint	No	4	98	2003	14375
15	Ford Fiesta	1400	Gasoline MultiPoint	No	4	80	2006	4700
16	Renault Megan C	1600	Gasoline MultiPoint	No	4	111	2006	19250
17	Vauxhall Meriva	1600	Gasoline MultiPoint	No	4	105	2006	23845
18	Seat Leon	1600	Gasoline MultiPoint	No	4	105	2001	55504
19	Ford Focus	1800	Gasoline MultiPoint	No	4	125	2006	1640
20	Vauxhall Astra	1800	Gasoline MultiPoint	No	4	125	2006	6163
21	Vauxhall Zafira	1800	Gasoline MultiPoint	No	4	140	2006	5805
22	Alfa Romeo156	1800	Gasoline MultiPoint	No	4	144	1998	149811
23	Alfa Romeo 156	2000	Gasoline MultiPoint	No	4	165	1999	67326
24	SAAB 900	2000	Gasoline MultiPoint	Yes	4	175	1995	199411

Table 2: Steering wheel idle vibration and interior car sound metrics of the 24 automobiles which were tested.

				Steering wheel idle vibration metrics			Interior car idle sound metrics		
Car Number	Brand and Model	Capacity (cm^3)	Engine type	Un-weighted rms [m/s^2]	rms (Wh) [m/s^2]	rms (Ws) [m/s^2]	SPL [dB]	SPL [dBA]	Zwicker Loudness [sones]
1	Ford Escort	1800	Diesel IDI	0.36	0.16	0.12	90.7	55.3	10.0
2	Citroen C15	1800	Diesel IDI	0.91	0.52	0.19	85.7	55.1	11.3
3	Citroen C1	1400	Diesel DI	0.16	0.10	0.05	77.8	52.2	7.8
4	Seat Leon	1900	Diesel DI	0.11	0.05	0.02	73.4	47.5	6.0
5	Ford Focus	1800	Diesel DI	0.21	0.12	0.05	88.9	59	12.8
6	Vauxhal Agila	1300	Diesel CDTI	0.37	0.24	0.10	83.4	49.4	6.6
7	Alfa Romeo 156	1900	Diesel CDTI	0.97	0.55	0.20	91.7	54.2	9.1
8	Ford Mondeo	2200	Diesel CDTI	0.17	0.05	0.03	85.2	50.2	6.7
9	Toyota Avensis	2200	Diesel CDTI	0.85	0.52	0.21	85.4	45.5	4.3
10	Toyota Avensis	2200	Diesel CDTI	0.37	0.22	0.09	91.2	48.6	5.2
11	Jaguar X-Type	2200	Diesel CDTI	0.45	0.26	0.11	81.7	47.5	5.5
12	Peugeot 607	2200	Diesel CDTI	0.36	0.22	0.09	92.7	56	9.6
13	Nissan Micra	1200	Gasoline MultiPoint	0.08	0.04	0.03	70.6	41.4	3.6
14	Renault Clio	1400	Gasoline MultiPoint	0.07	0.03	0.02	73.4	40.3	3.3
15	Ford Fiesta	1400	Gasoline MultiPoint	0.13	0.08	0.03	68.5	44.5	4.4
16	Renault Megan C	1600	Gasoline MultiPoint	0.09	0.04	0.03	79.4	41.9	3.6
17	Vauxhall Meriva	1600	Gasoline MultiPoint	0.07	0.05	0.02	69.0	39.8	3.1
18	Seat Leon	1600	Gasoline MultiPoint	0.10	0.06	0.03	71.1	43.5	3.7
19	Ford Focus	1800	Gasoline MultiPoint	0.11	0.06	0.02	80.5	39.1	2.8
20	Vauxhall Astra	1800	Gasoline MultiPoint	0.36	0.22	0.09	72.0	44.6	4.0
21	Vauxhall Zafira	1800	Gasoline MultiPoint	0.18	0.10	0.04	75.9	43.2	3.5
22	Alfa Romeo156	1800	Gasoline MultiPoint	0.79	0.42	0.18	81.8	46.8	5.0
23	Alfa Romeo 156	2000	Gasoline MultiPoint	0.69	0.36	0.14	75.8	42.8	3.8
24	SAAB 900	2000	Gasoline MultiPoint	0.27	0.16	0.06	80.1	48	5.4

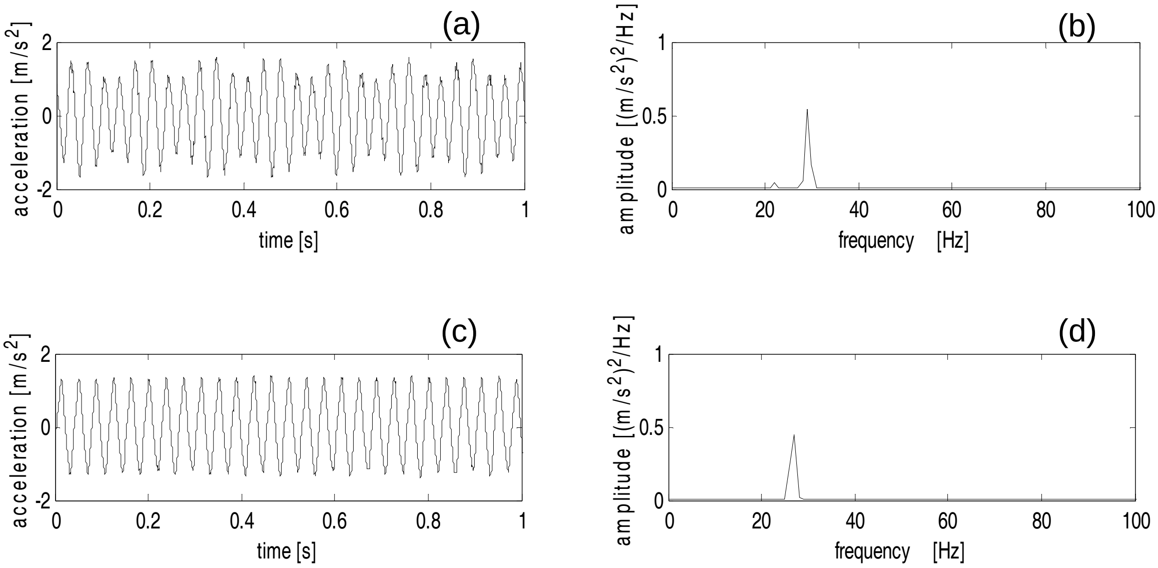

Figure 1. Steering wheel idle acceleration time histories and power spectral densities for two representative diesel-powered automobiles:
(a) and (b) car 2 - Citroen C15 1.8 L Diesel IDI.
(c) and (d) car 9 - Toyota Avensis 2.2 L Diesel CDTI.

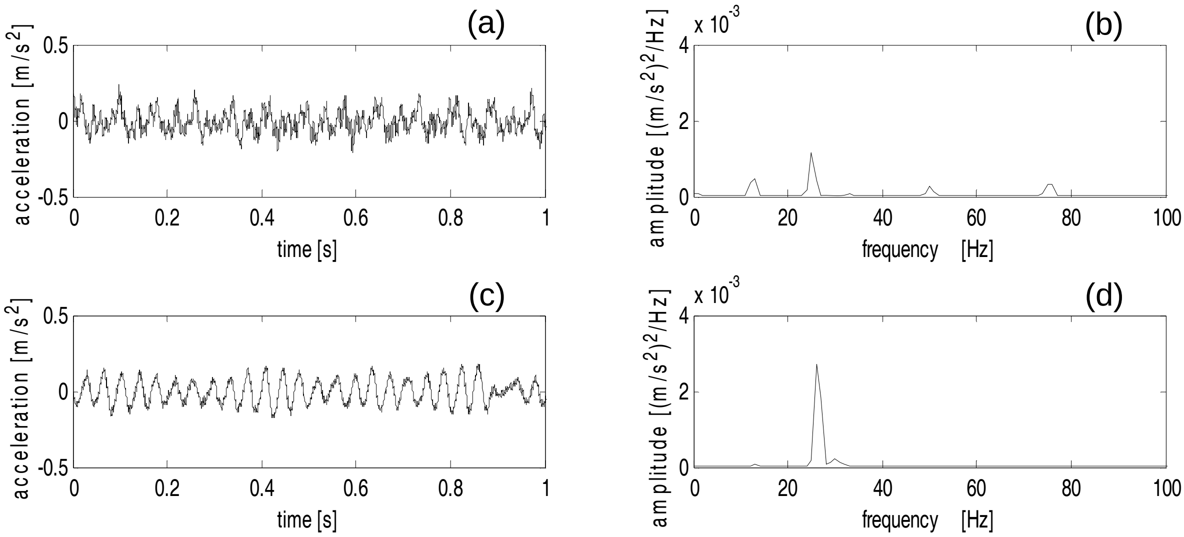

Figure 2. Steering wheel idle acceleration time histories and power spectral densities for two representative gasoline-powered automobiles:
(a) and (b) car 13 - Nissan Micra 1.6 L Gasoline Multi point injection.
(c) and (d) car 17 - Vauxall Meriva 1.6 L Gasoline Multi point injection.

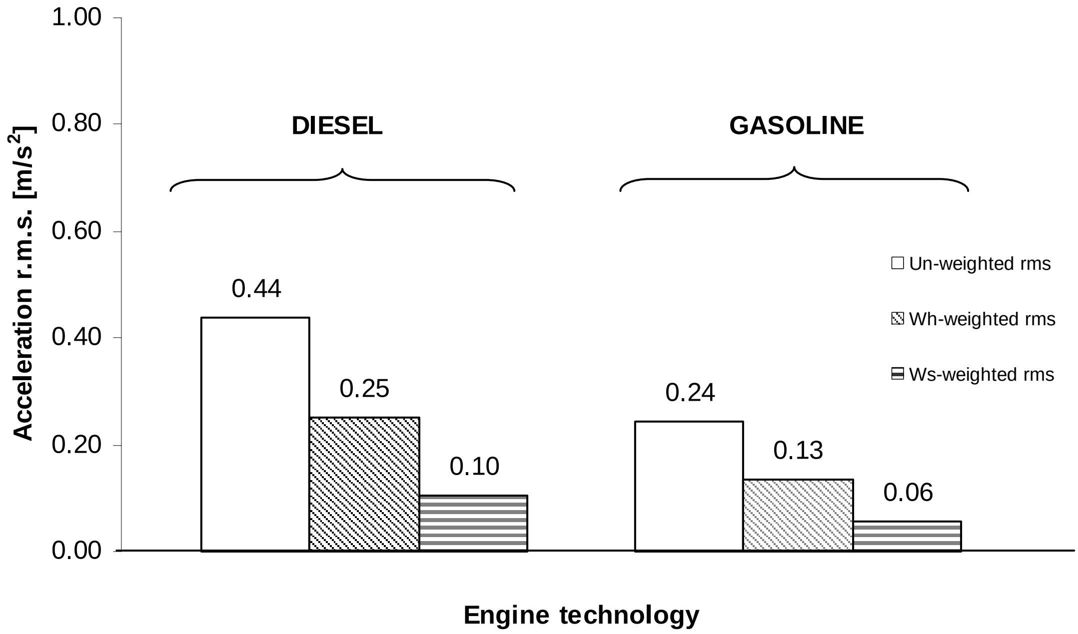

Figure 3: Mean idle steering wheel acceleration r.m.s. values determined for the group of twelve diesel-powered and the group of twelve gasoline-powered automobiles.

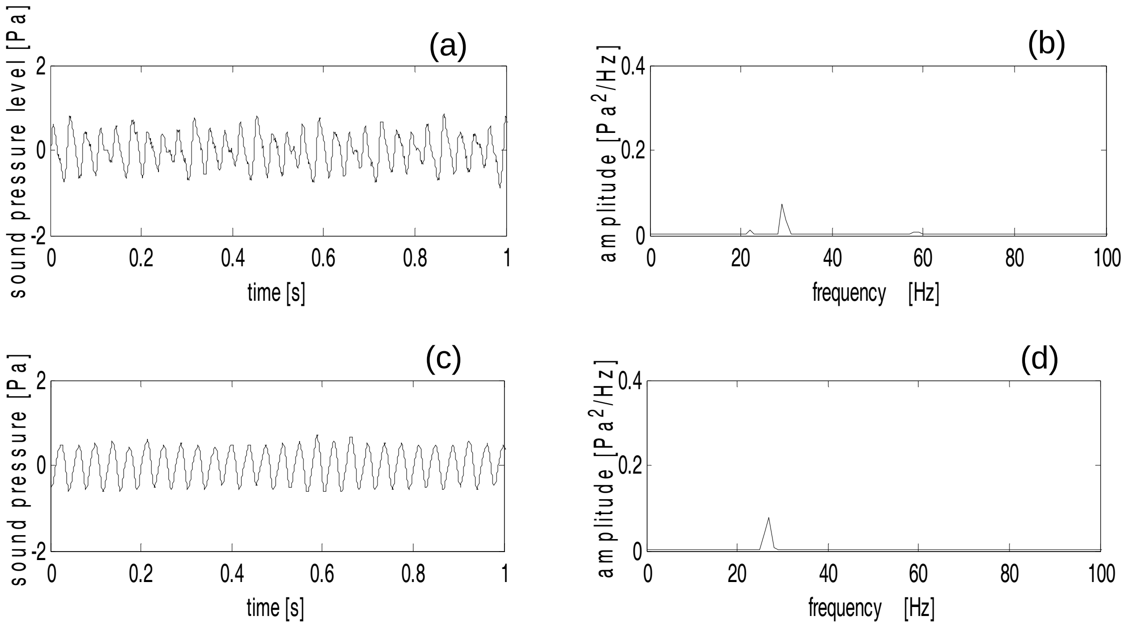

Figure 4. Interior idle sound pressure time histories and power spectral densities for two representative diesel-powered automobiles
(a) and (b) car 2 - Citroen C15 1.8 L Diesel IDI.
(c) and (d) car 9 - Toyota Avensis 2.2 L Diesel CDTI.

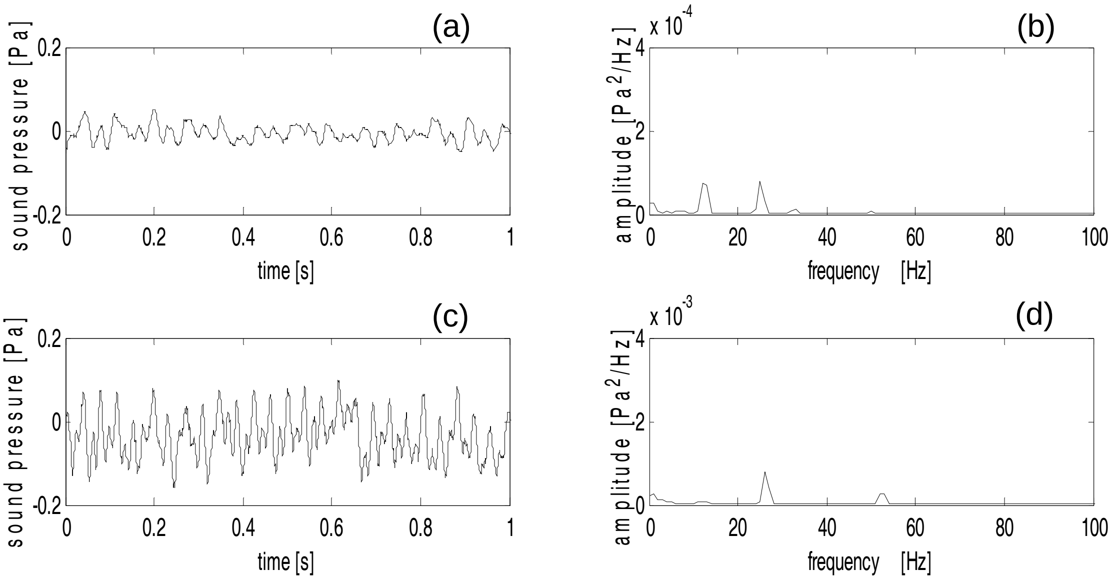

Figure 5. Interior idle sound pressure time histories and power spectral densities for two representative gasoline-powered automobiles:
(a) and (b) car 13 - Nissan Micra 1.6 L Gasoline Multi point injection.
(c) and (d) car 17 - Vauxall Meriva 1.6 L Gasoline Multi point injection.

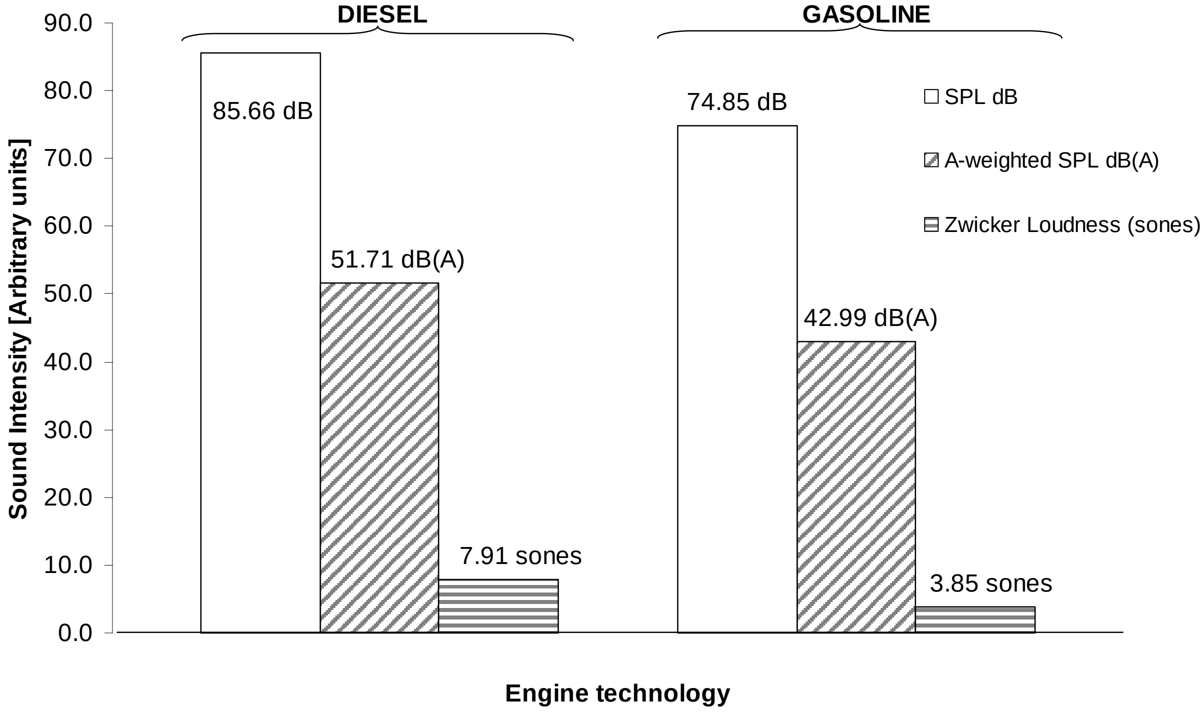

Figure 6. Mean idle sound intensity metrics determined for the group of twelve diesel-powered and the group of twelve gasoline-powered automobiles.

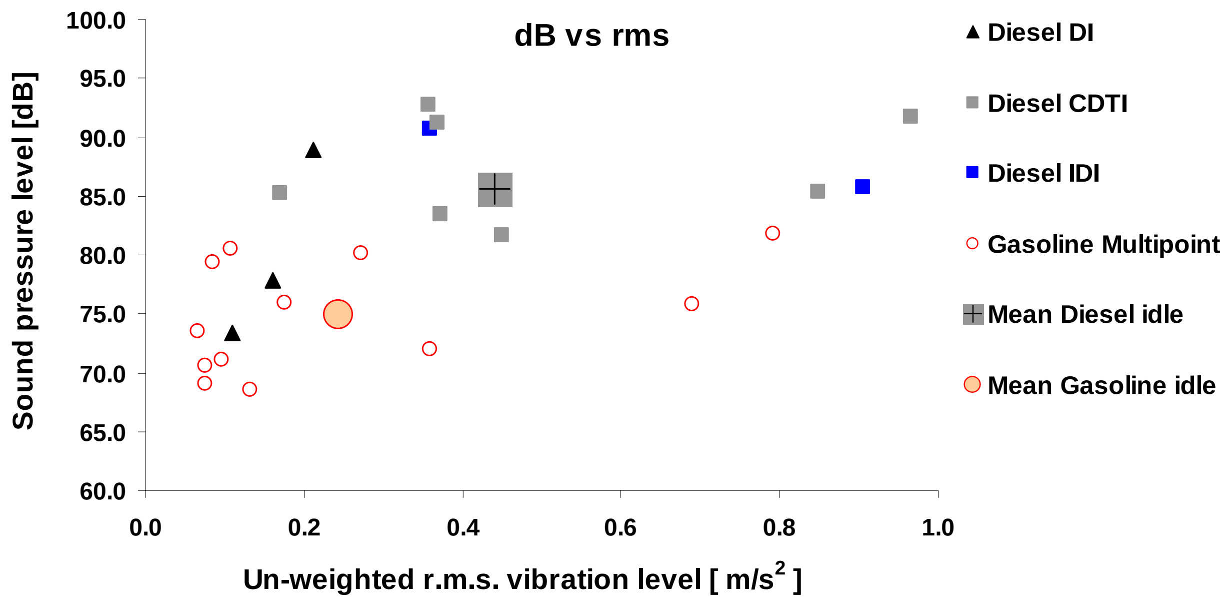

Figure 7 Plot of un-weighted sound pressure level in decibels as a function of un-weighted steering wheel r.m.s acceleration for the 24 automobiles.

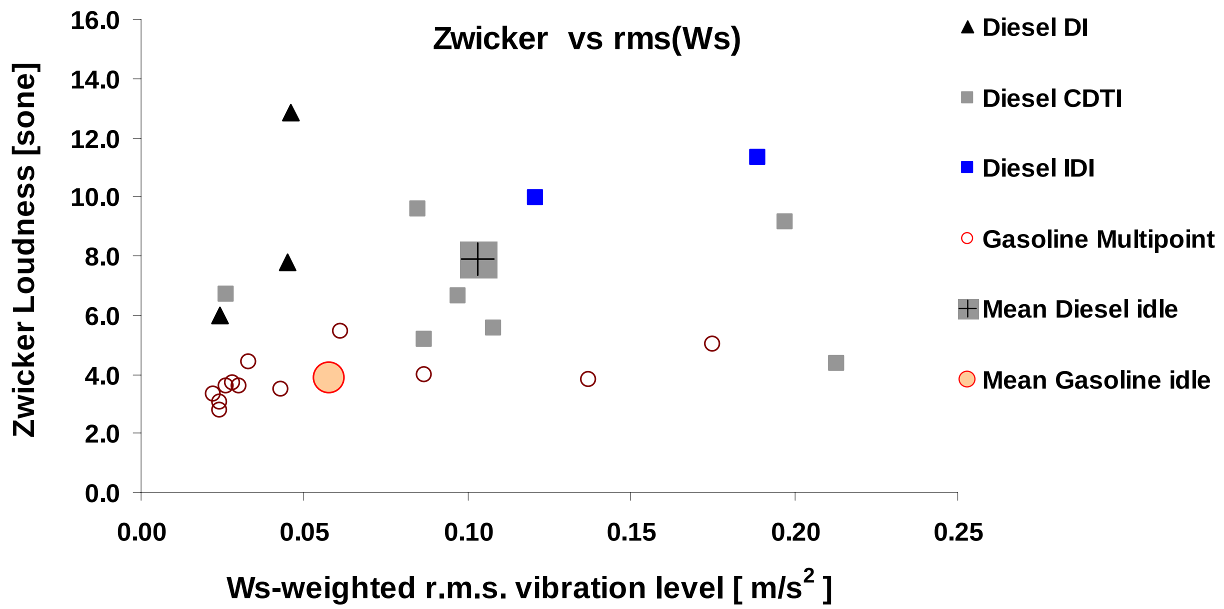

Figure 8 Plot of Zwicker loudness in sones as a function of the W_s-weighted steering wheel r.m.s. acceleration for the 24 automobiles.