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Vibro-acoustical comfort in cars at idle : human perception of simulated sounds and vibrations from three and four cylinder diesel engines

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Abstract

This paper deals with comfort in diesel cars running at idle. A bench was used to reproduce the vertical vibrations of the seat, the vibrations of the steering wheel and the noise measured at the driver's ears. Two paired comparison tests were carried out using stimuli recorded in seven cars equipped with 3 or 4 cylinder engines. In the first one, subjects were exposed to seat vertical vibrations only, and had to indicate the most comfortable stimulus within each pair. Results could be described by the unweighted root-mean-square values of the signal. The use of ISO 2631 weightings reduced the accuracy of the description. In the second experiment, subjects were exposed to all stimuli (vibrations and sounds). Their task consisted in evaluating the similarity between the two simulated situations, indicating which one was the most comfortable, and explaining the reasons for their choice, freely describing the similar and different features of the stimuli. Those free verbalizations were recorded and carefully analysed, providing information about the way the sound and vibrations were perceived and contributed to the evaluation of the overall comfort. Also, similarity evaluations were analysed through a multi-dimensional scaling technique to establish the perceptive space. Both analysis suggest the following results :

- the description of the vibrations was less complex than the description of the sounds (for which many features were mentioned by subjects) ;
- the verbalisations were helpful as regards to the understanding of the perceptive space;
- the preference was mainly related to the vibration of the seat and the pleasantness of noise.

1 Introduction

Car passengers are exposed to complex stimuli, and their evaluation of the product is strongly dependent on all the encountered stimuli. Some interactions between sensorial modalities may exist. For example, interactions between visual and sound stimuli have been reported in many cases (an example for soundscapes is presented in [14]). With regards to sound and vibration, which are often due to the same sources in cars, many studies have been conducted (overviews can be read in [1] or [9]). From the great variety of stimuli used in the previously published studies, it seems that sound can have an effect on vibration perception, and vice-versa. An important question is the one regarding the contribution of sound and vibration to the overall evaluation of the multi-sensorial situation. Both sound and vibration significantly contribute to the evaluation, unless one stimulus

is strongly dominant, being the only contributor to the overall evaluation. In a study dedicated to cars at idle [9], it was shown that such multi-sensorial models could be dependent on test subjects. steering wheel vibrations in particular, had to be taken into account by only half of the jury, while seat vibrations and noise were important for all subjects.

The goal of this study was to investigate the perception of noise and vibrations in cars at idle, for cars equipped with three or four cylinder engines. Indeed, some manufacturers have recently developed three cylinder engines,- in order to reduce fuel consumption. This solution can be very convenient for small cars having engine capacities about 1200 cm³. But the efforts exerted by such engines on the chassis are very different from those exerted by conventional engines. Dominant frequencies are lower (see figure 1), and the torque component in the direction orthogonal to the plane of the cylinders is important. For the supplier of engine mounts, the challenge consists in designing components which can still ensure a high level of comfort for passengers of such cars.

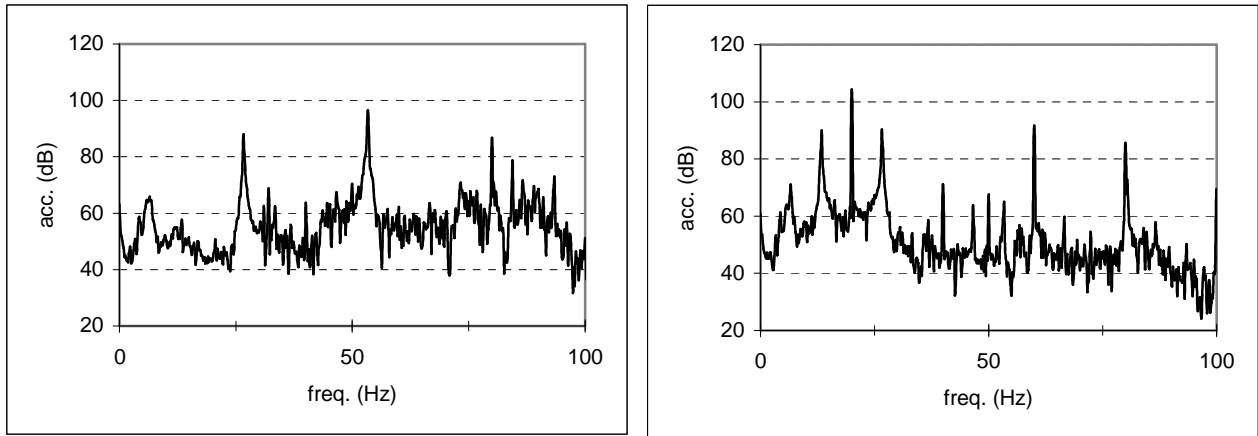


Figure 1 : typical spectra of a vertical acceleration of a seat. Left : 4-cylinder engine; right : 3-cylinder engine.

In the study reported in that paper, the human perception of sound and vibration produced by three and four cylinder engines was compared in two steps : a first experiment was focused on seat vertical vibrations only, while a second experiment also used steering-wheel vibration and noise measured at the driver's ears, thus recreating a multi-modal situation.

2 Sound and vibration stimuli

The simulation bench, previously developed by the Laboratoire Vibrations-Acoustique and Hutchinson Paulstra, was used. That bench is described in details in [9]. It allows the reproduction of the vertical direction seat vibration and the fore-and-aft steering wheel vibration, as well as noise recorded with a dummy-head. Therefore, a subject can be placed in a situation representing a car running at idle in a realistic way.

The bench is equipped with a real car seat. The bench reproduces the vertical vibration at the seat's guides with a high accuracy (the difference between the level measured in the car and on the bench being lower than 2 dB for the frequency components of the signal being below 80 Hz). But, as the

seat does not always correspond to the real one, the bench cannot exactly reproduce all the original cars, since the effect of the different seats is not taken into account

In the reported study, recordings were realised in seven Diesel engine cars, four of them being equipped with 3-cylinder engines and the three other ones with 4-cylinder engines. The cubic capacities of engines (all of them being of the common-rail type) varied from 700 cm³ to 1900 cm³. Cars were running at hot idle. An accelerometer was vertically fixed to the front of the interior driver's seat track, and a second one was fixed at the centre of the steering-wheel, aligned along the direction of the steering column (as a previous study [9] had shown that it was the dominant vibration axis at idle). Also, a dummy head (Cortex – 01dB Metravib) was placed on the driver's seat. All signals were simultaneously recorded at the sampling frequency of 48 kHz.

The rms values of seat vibration varied from 92 to 98 dB (ref. 10⁻⁶ m.s⁻²); steering-wheel vibration varied from 96 to 108.5 dB and noise levels were between 55 and 68 dB(A).

A set of 15 second samples was prepared from the recordings. They consisted of four synchronous channels : seat vibrations, steering-wheel vibrations, and noise at the two ears of the dummy-head. After being filtered to compensate the mechanical transfer function of the bench or of the headphones, these samples could be used for the subjective experiments.

3 First experiment

3.1 Procedure

The first experiment was focused on seat vibrations only. The seven stimuli were presented in pairs according to a Ross series [11], after a preliminary random arrangement, ensuring that each subject was submitted to a different series. Two pairs were added at the beginning of the experiment for training, giving a total number of 23 pairs.

The subject was asked to imagine himself or herself as seated in a real car running at idle. The subject's task consisted in selecting the preferred stimulus (tie answers were allowed). Each pair could be repeated if requested by the subject. 30 subjects participated to the experiment (20 males and 10 females). 25 of them were students, who had never participated to any subjective experiment before, and 5 were members of the laboratory.

3.2 Results

The averaged preference probabilities were analysed according to a Bradley-Terry-Luce model to obtain the merit score of each stimulus. These merit scores are presented in table 1 ; in this table and in the following of the paper, stimuli recorded in cars with a four-cylinder engine are labelled 4c1 to 4c3, whereas those recorded in cars with a three-cylinder engine are labelled 3c1 to 3c4). According to this model, the merit scores U_i are related to preference probabilities P_{ij} by the relation

$P_{ij} = \frac{U_i}{U_i + U_j}$. The correlation coefficient between the preference probabilities estimated from that

model and the real ones was high ($R = 0.98$), indicating that the BTL model could be used in that case (it was checked that this model was more appropriate than other ones, eg. a Thurstonian model).

Car	Comfort merit score
4c1	1.31
4c2	9.35
4c3	1.00
3c1	0.36
3c2	3.23
3c3	0.71
3c4	0.10

Table 1: Comfort merit scores of the car stimuli . 4c1 to 4c3 : 4-cylinder engine cars ; 3c1 to 3c4 : three-cylinder engine cars.

It can be seen in table 1 that seat vibrations are generally more comfortable in four cylinder engine cars than in three cylinder engine ones.

The preference probabilities could be related to seat vibration levels. As a BTL model was used, a vibration index was derived from the acceleration values in the following way : if γ_i and γ_j are the root-mean-square values of the unweighted vertical vibrations (expressed in $m.s^{-2}$), the index is defined as

$$I_{ij} = \frac{\gamma_j}{\gamma_i + \gamma_j} \quad (1)$$

The relation between this index and the averaged preference probabilities can be seen in figure 2. The correlation coefficient between the two sets of values was $R = 0.87$. On the other hand, using weighted accelerations (according to ISO 2631) as input values for the index, lowered that correlation ($R = 0.66$, see figure 3). This means that the normalised weightings may not be the most convenient ones for car applications, as it had already been demonstrated in other studies [2].

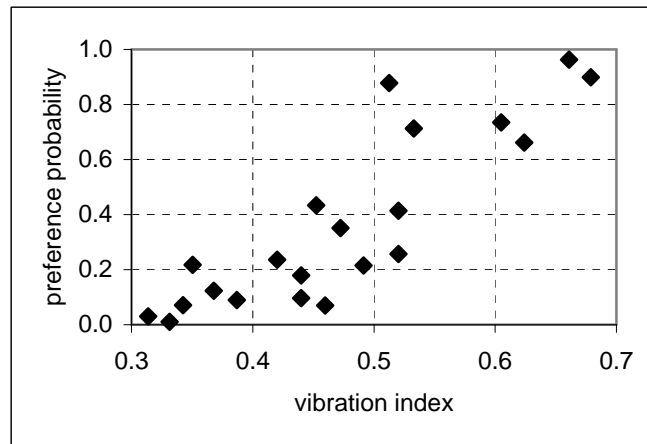


Figure 2 : relation between preference probabilities (seat vertical vibrations) and the index computed from the unweighted vertical vibrations measured at the seat's tracks.

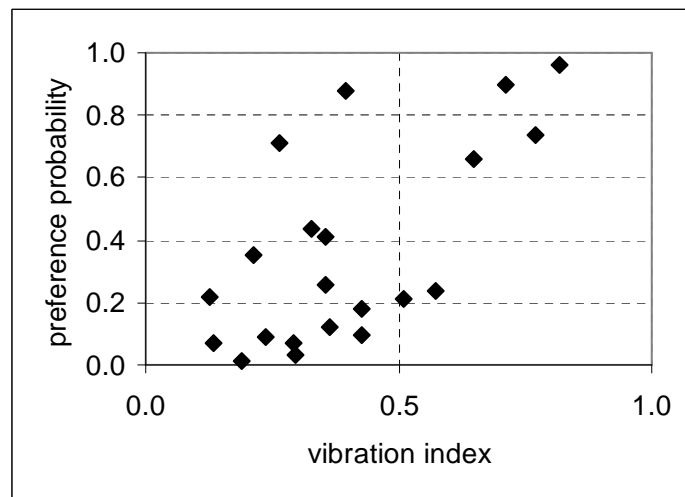


Figure 3 : relation between preference probabilities (seat vertical vibrations) and the index computed from the unweighted vertical vibrations measured at the seat's tracks.

4 Second experiment

4.1 Procedure

Different methods can be used to understand the contribution of noise and vibration to comfort. One typical procedure consists in asking subjects to give their preference on one of the two stimuli presented in pairs or to evaluate the level of their similarity using a numerical scale. A perceptual space can be derived from the results, but its dimensions have to be identified by a further analysis. Such a procedure is widely used in sound quality applications, but in a multi-modal situation (noise plus vibration), this identification is more difficult to be done, since subjects take a complex set of parameters into consideration when giving their judgments. Another procedure (often named as *semantic differentials*) consists of using a set of pre-defined bipolar or unipolar scales of features (for example soft-loud, regular-irregular, and so on) representing a certain semantic continuum. In

this case, subjects must indicate the degree of presence of each feature in stimuli (an example for musical sounds can be read in [13]). One of the limitations of such a procedure is that the pre-defined scales may contain verbal features that do not correspond to the ones that subjects take into consideration in reality.

It was hence decided to use a procedure based on free verbalizations produced by subjects during their comparison task. This method had been already used in studies dealing with musical timbres [12], diesel engine sounds [4, 7] or car door closing sounds [10]. It is based on the principle that verbal expressions produced by a subject during a comparison task can be used to identify some aspects of subjective representations of the stimuli ; the verbal comparison is a key point in that procedure [5]. The verbal data analysis result in the identification of a set of stimulus features taken into consideration by listeners during the experiment. The importance of each feature for subjects is also evaluated through this analysis.

In this experiment, subjects were asked to compare the comfort in each pair of stimuli. They had to put their hands on the steering-wheel and they were not focused on noise or vibrations, so that each of these aspects could be spontaneously evoked during verbal evaluations of comfort. All possible pairs of different cars (21 pairs), plus two learning ones were presented to subjects in a randomised order. For each pair (which could be presented as often as necessary for each subject), subjects had to :

- evaluate the similarity between cars (by selecting a number between 0 and 10);
- indicate the most comfortable car;
- freely explain their answers. Their verbalizations were recorded as a Mp3 file.

The same 30 subjects participated to this experiment.

4.2 Perceptual space

The individual similarity evaluations were analysed using the Indscal algorithm [3] ; it appeared that a 3-dimensional space was convenient to represent the perceptual space. That can be seen on figure 4, which depicts the values of Kruskal's stress for each number of dimensions (this stress represents the error between the real individual dissimilarities and those computed from the sound coordinates in the perceptual space). This 3-dimensional space is shown in figure 5. The first axis clearly makes a distinction between three cylinder engines (labelled 3c1 to 3c4) and four cylinder ones (labelled 4c1 to 4c3). However, it should be emphasized that subjects were not informed about the number of cylinders of each car (they did not even know that this number could vary between stimuli), so it does not explain the reason why those two kinds of engines were so clearly separated. It could be guessed that the second axis was related to the vibrations of the steering wheel : cars 4c1, 4c2 and 3c4 had very low levels of such vibrations (in car 3c4, the engine is located at the back of the car, and the steering-wheel has no connections with it). But the third axis could not be understood.

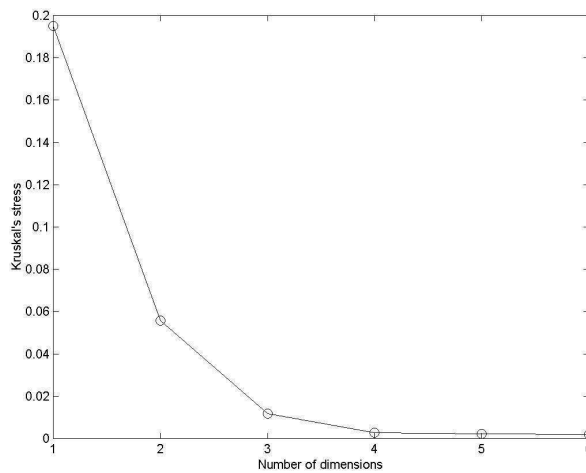


Figure 4 : stress values for each number of axes of the perceptual space

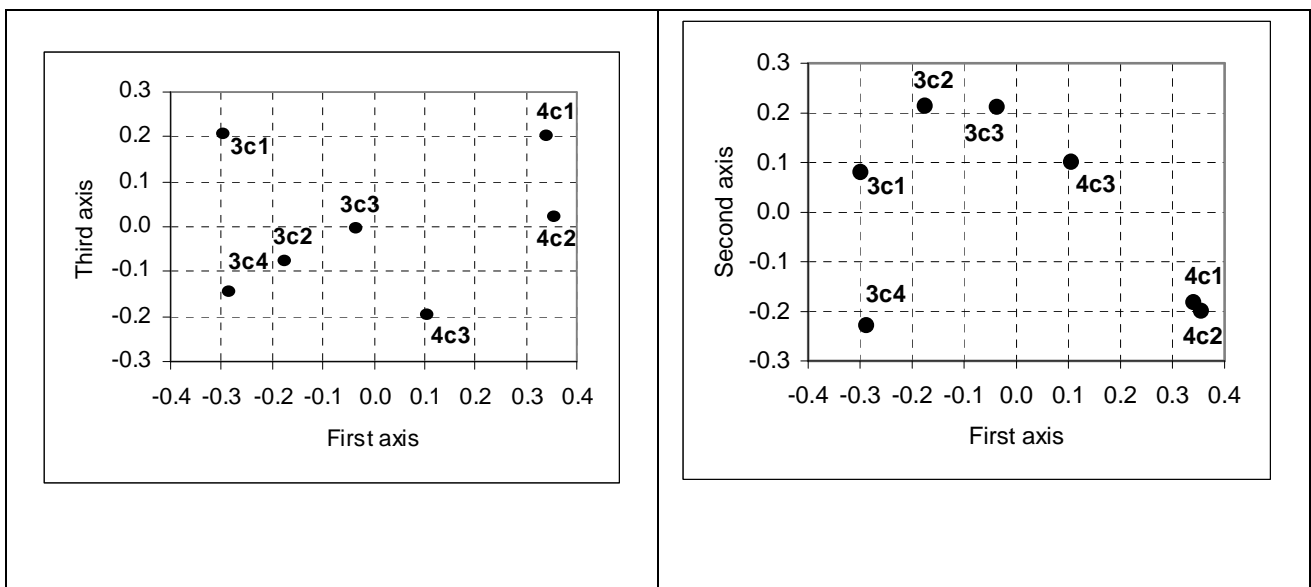


Figure 5: perceptual axis of similarity evaluations

4.3 Analysis of verbalizations

Verbalizations produced by subjects were transcribed and analysed according to the scheme detailed in [12]. The first step consisted in separating the meaningful verbal units (e.g. “the first car is the noisiest” or “in the second car, seat vibrations are irregular”). These verbal units were entered into a database along with other information (e.g. the subject’s number, the stimuli of the pair during which the verbal unit had been produced, the complex event to which it referred, etc.) ; that gave a table of more than 5600 lines. The next steps of the analysis refined the description of verbal units ; finally, they were labelled as referring to noise only, vibrations only or to the general

situation (e.g. “the first car is more comfortable”). For a verbal unit referring to vibrations, another field indicated whether it was related to seat or steering-wheel vibrations (or to vibrations in the general meaning).

The number of verbal units produced by a subject varied from 133 to 414, the average value being 246. Thereafter, when comparing the relative use of the different descriptive categories, the number of utilizations of a given category for a given subject was normalized with respect to the total number of verbal units produced by that subject.

The last step of the analysis consisted in grouping together verbal units that were thought to refer to the same characteristics of the events ; for example, “the noise is louder” and “the sound level is greater” were grouped into the same “loud” category. 15 categories thus appeared, among which 6 were very rarely used ; thereafter, only the 9 main categories will be taken into account. These categories are listed below, as well as some examples of verbalizations related to each of them :

- high level ("*the noise is loud*", "*there are many vibrations in the steering wheel*",....)
- shaking ("*I feel shaken as if I was seated on the engine*", "*I can hear the vibrations in the noise*",...)
- damped ("*noise is coming from further*", "*I feel more isolated from the noise*",...)
- annoying ("*the noise is less annoying*", "*the second one (stimulus) is tiring*",...)
- sharp ("*the vibration has a higher frequency*", "*the sharp noise in the background is less audible*",...)
- pleasant ("*globally speaking, this one is more pleasant*", "*the seat vibrations are comfortable*",...)
- windy ("*it sounds as if I was driving with the open windows*", "*the noise is more like a fan*",...)
- regular ("*very smooth for seat vibrations*", "*noise is more regular*",....)
- front located ("*noise is louder in the left ear*", "*for both stimuli, the left/right balance is correct*",...)

First of all, it should be noted that the number of verbal units, explicitly related to noise or vibration, was similar: 115.3 for noise and 112.2 for vibrations. On the other hand, verbal units only describing the situation in general (e.g. “both cars are rather comfortable”) were less often produced (18.5), which indicated that subjects distinguished stimuli in a natural way.

An important difference between sound and vibration descriptions is that very few categories were used for vibrations (figure 6). The category “high level” was by far the most commonly used (75% of the total number of verbal units related to vibrations) ; other categories were “shaking”, “annoying”, “pleasant” and “regular”. For noise descriptions, rates of use were less different : the most important one (“loud” once again) represented only 25% of the total number. Subjects had an analysis capability greater for sounds than for vibrations.

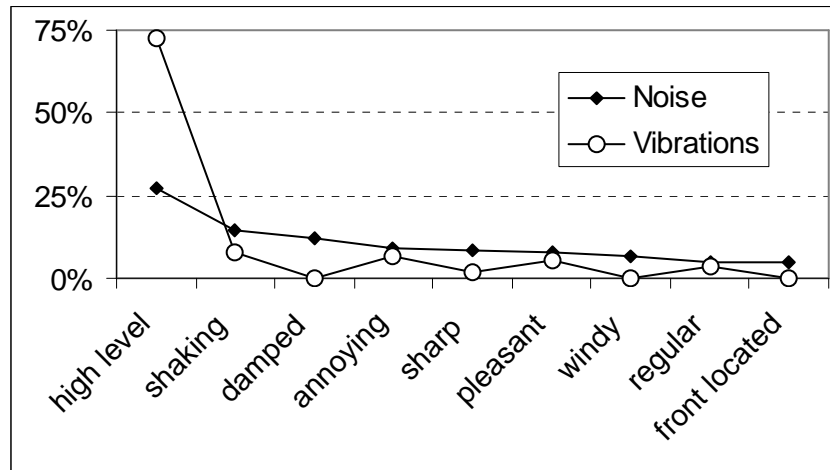


Figure 6 : rates of use of the different verbal categories

The final results provided by the analysis were the “verbal portraits” of cars. For each car and each of the feature categories, the numbers of occurrences in the database were counted, either in the positive or in the negative way (e.g. “the sound is loud” or “the sound is of low level”) [12].

The amplitude of features (F_i , i denoting one of the seven sets of stimuli) was defined as follows : if ($F_{i_{pos}}$) is a mean frequency of use of “positive” verbal units (e.g., “louder”) and ($F_{i_{neg}}$) is a frequency of “negative” units (e.g., “less loud”, or “low”), then

$$F_i = |k_{pi}| * (F_{i_{pos}} - F_{i_{neg}}) \quad (2)$$

where k_{pi} characterizes the weighting of the difference in the whole group of the verbal units :

$$k_{pi} = (F_{i_{pos}} - F_{i_{neg}}) / (F_{i_{pos}} + F_{i_{neg}}) \quad (3)$$

The index k_{pi} makes possible to estimate the asymmetry of a certain feature represented in the description : the higher the positive (or negative) directedness of evaluations is, the closer the value F_i to the mean value of occurrence of the verbal units of the given group will be. That computation could be done without separating the different stimuli, or for each of them. Figure 7 shows examples of these evaluations (for the “high level” characteristics) ; it can be seen that, for example, car 3c1 had high vibration levels, while its noise level was rather low (as it appears from the negative rating). Car 3c4 was penalised by its noise and seat vibration levels, while the steering wheel was very quiet. Also, generally speaking, vibration levels were higher in 3-cylinder cars than in 4-cylinder ones.

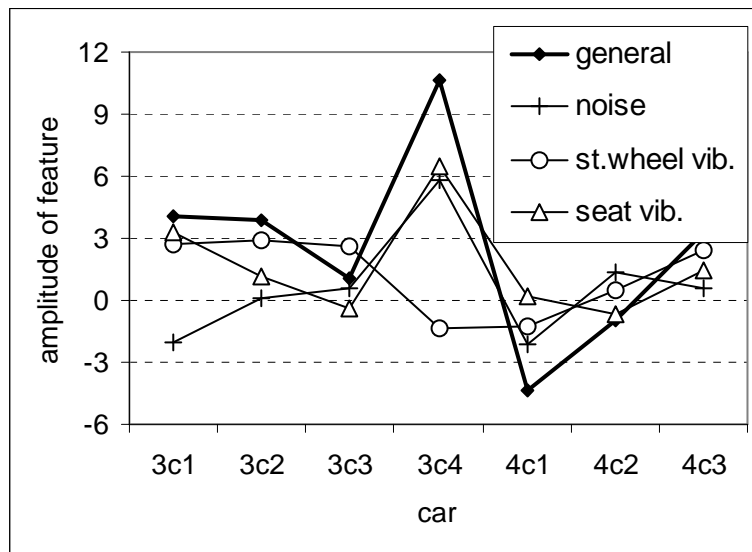


Figure 7 : examples of stimulus verbal portraits

It can be noted that some correlations between features extracted from verbalizations and physical parameters could be found :

- high level of sounds and its annoyance were correctly described by loudness, when computed according to ISO 532-B standard ($R = 0.84$ for "high level" and 0.92 for "annoyant"). The correlation with A-weighted level was slightly smaller (resp. $R = 0.61$ and 0.82) ;
- annoyance of seat vibrations was more correlated with unweighted root-mean-square acceleration values ($R = 0.94$) than with weighted values ($R = 0.76$), confirming the results of the first experiment.

The most important point was that these verbal portraits could be used to understand the perceptual space obtained from the Indscal analysis of similarity ratings. The correlation coefficients between stimulus coordinates on each axis of that perceptual space and the values of the verbal portraits (as some examples are presented in figure 7) were computed. It appeared that :

- the shaking characteristics (in general) and the "high level" one (with respect to vibrations only) were highly correlated with the first axis ($R=-0.95$) ; as that axis made a clear difference between three and four cylinder engines, these features can be considered as distinctive of the number of cylinders ;
- the subjective level of steering wheel vibrations explained the second axis ($R=0.93$) ;
- noise pleasantness was the underlying factor of the third axis ($R=0.93$).

Therefore, an important result is that the analysis of free verbalisations allowed the understanding of the perceptual space. As mentioned before, it had been noted from the perceptual space that its first axis was related to the number of cylinders of the engine ; but the perceptual reason of that relation could only be understood from the verbalization analysis. That was also true for the third axis : as it was related to a complex attribute (sound pleasantness), any direct interpretation of that axis could not have been obtained.

4.4 Preference evaluation

First of all, the number of circular errors was computed for each subject according to the method exposed in [8]. Such an error occurs when, in a triad of stimuli A, B and C, a subject answers that, for example, he prefers A to B, B to C but C to A. It appeared that the number of circular errors was significantly greater than it was in the case of the first experiment (in which only seat vibrations were used), as it can be seen in figure 8 ; the difference between the two mean values (1.7 and 4.6) is significant ($p < 0.05$). That probably means that, in a multi-modal situation, features which are taken into account while comparing them to sets of stimuli, may vary according to stimuli.

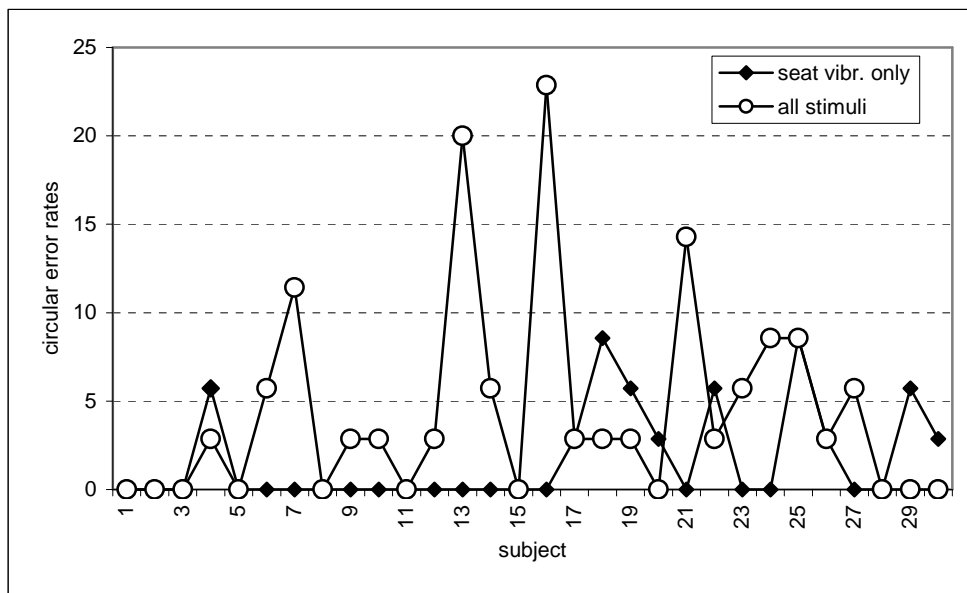


Figure 8 : circular error rates of each subject in both experiments

The preference probabilities in pairs were analysed according to a Bradley-Terry-Luce model, to obtain the merit score of each stimulus ; once again, that model could be used, as the correlation coefficient between the measured preference probabilities and those computed using the values given by the model was high ($R=0.95$). In Table 2 are shown the merit scores of the sets of stimuli, as well as those obtained in the first experiment.

Car	Comfort merit score (seat vibr. only)	Comfort merit score (all stimuli)
4c1	1.31	5.05
4c2	9.35	1.33
4c2	1.00	1.22
3c1	0.36	1.05
3c2	3.23	0.55
3c3	0.71	1.30
3c4	0.10	0.16

Table 2 : BTL scores of stimuli

In Table 2, it can be seen that the most appreciated stimuli were recorded in a four-cylinder car and the least ones in a three-cylinder car (please remind that, as the seat used on the bench was the same for all stimuli, any conclusion about the cars themselves cannot be drawn). More generally, three-cylinder engines provided stimuli for which the comfort due to noise and vibrations was reduced, as compared to classical engines.

To identify some useful metrics for this situation, a linear regression analysis was conducted in order to approximate the preference probabilities with combinations of three metrics, inspired from the understanding of the perceptual space : as the first axis was related to "shaking", one parameter was estimated from the envelope fluctuation of the acceleration signals. Namely, the parameter was defined as $L_{90}-L_{10}$, L_{90} , being the 90th percentile of the histogram of the envelop of seat vibrations and L_{10} the 10th one. But because the first axis could also be explained by the "high-level of vibrations", a second parameter was simply the rms values of seat acceleration. A third metric was the rms-value of steering-wheel acceleration (which could explain the second axis of the perceptual space) and a fourth one the loudness computed according to ISO 532-B standard (third axis). For each metric, an index was computed according to eq. (1) ; the values of this index for all pairs were taken as input data for the regression analysis.

The best model involved loudness and the unweighted root-mean-square acceleration of the vertical vibration of seats only :

$$P_{ij} = A \frac{\gamma_j}{\gamma_i + \gamma_j} + B \frac{N_j}{N_i + N_j} + C \quad (4)$$

It was highly significant ($F(2,18)=36.7$, $R_{adj}^2=0.78$), as it can be seen on figure 9, which represents the predicted preference probabilities versus the measured ones. In that model, the standardized values of the coefficients were similar for the two metrics, indicating a more or less equal contribution of each feature to the overall comfort.

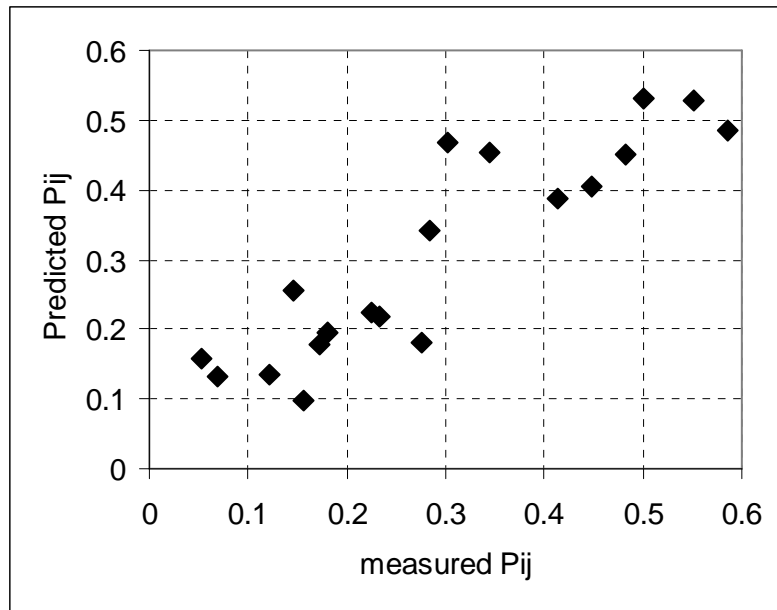


Figure 9 : relation between measured and predicted preference probabilities

5 Conclusions

The main conclusions of this study were the following ones :

- for the comparison of comfort due to vertical seat vibrations, it can be recommended not to use the frequency weightings defined in ISO 2631. A more correct model could be obtained from the unweighted root mean square values of the acceleration measured at the seat track;
- it seems that seat vibrations and noise were more important contributors to the overall comfort than steering-wheel vibrations. This overall comfort could be predicted from rms-values of seat acceleration and noise loudness computed according to ISO 532-B standard.

More generally, this study shown that an analysis of free verbalizations can provide very useful information about the subject's perception in a complex (i.e. multi-modal) situation. The quantification of features for the various stimuli (verbal portraits) could be related to data obtained from psycho-physical studies (the perceptual space computed from similarity ratings) ; moreover, these verbal portraits can be used to explain this perceptual space.

The difference between three and four cylinder engines was clear for subjects, as it could be seen in the perceptual space (the first axis of which being structured by this feature). The free verbalization analysis made clear that the two important features structuring this axis were the level of vibrations and their irregularity (often described as "shaking character"). Though this irregularity could be approximated from the modulation analysis of the envelope of seat acceleration signals, the best model of comfort was built from the rms-values of these accelerations, as mentioned above. The small number of stimuli prevented from identifying which of these two features was the most important one from the perceptual point of view.

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