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Influence of noise and vibration to comfort in diesel engine cars running at idle

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Abstract : a bench has been designed and built : it allows that a subject can be placed on a car seat excited in the vertical direction; the subject also has his hand on a vibrating steering wheel and can hear noises through headphones. Thus a realistic simulation of the environment of the driver of an engine car running at idle is possible.

After measurements on six cars, three paired comparison tests have been conducted :

- in the first one, the test person is only exposed to noise;
- in the second one, he/she is also exposed to vibrations measured in the cars, but he/she is always asked to evaluate only sounds;
- in the third one, he/she is then asked to evaluate the overall annoyance of the situations while being exposed to all stimuli.

The comparison between the results of the first two tests proves that vibrations have an influence on sound perception in a small but significant way.

In the third test, the jury can be separated in two groups of people using different criteria : for the first one, the overall annoyance is only related to the vibratory stimuli, whereas in the second one, noise stimuli are also important for the evaluation.

Résumé : un banc d'essai a été réalisé pour permettre de placer un sujet dans des conditions représentant celles rencontrées dans un habitacle de voiture fonctionnant au ralenti. Le sujet est assis sur un siège vibrant verticalement, les mains posées sur le volant qui vibre selon la colonne de direction. Simultanément, le sujet entend par un casque le bruit enregistré par un mannequin acoustique.

Après des mesures dans six voitures diesel (common rail), trois tests de comparaisons par paires ont été réalisés :

- dans le premier, le sujet n'est exposé qu'aux sons;
- dans le deuxième, il est également exposé aux vibrations, mais sa tâche est toujours de ne comparer que les sons;
- dans le troisième enfin, il doit comparer le confort global de chaque véhicule.

La comparaison des résultats obtenus pour les deux premiers tests a montré que la présence de vibrations peut, de façon légère mais significative, influencer le jugement porté sur les sons. Par ailleurs, dans le troisième test, deux stratégies différentes ont été mises en évidence : certains auditeurs ne tiennent compte que des stimuli vibratoires alors que d'autres utilisent l'ensemble des stimuli pour comparer le confort des véhicules.

PACS n° : 79

1. Introduction

Noise and vibration perception had been widely studied, leading to normalized indicators as for loudness (ISO 532B) or for exposure to vibrations, either for the whole-body (ISO 2631-1) or for upper-members (ISO 5349-1)

Nonetheless, the perception of these two modalities when simultaneously present has not been thoroughly examined yet, whereas this situation is a current one. Actually, in road or air transportation vehicles, buildings close to roadways or railways, noise is obviously accompanied by vibrations, all this information potentially contributing to the annoyance experienced by an individual.

In such a complex environment, two questions can be asked :

- can the presence of a modality modify the perception of the other one ? It would imply a necessary enrichment of reproduction systems to reproduce the whole situation ;
- what is the contribution of each of these modalities to the global comfort of passengers or annoyance experienced by residents ?

The already published results concerning the influence of vibrations on noise perception are contradictory. This interaction was not significant in studies from Howarth and Griffin [1], Aubrée and Roland [2] or Weber *et al.* [3], but it was in studies from Richter *et al.* [4], Paulsen and Kastka [5] or Västfjäll *et al.* [6]. The reciprocal interaction (of noise upon vibration sensation) was mentioned by Howarth and Griffin [1], but appeared to be not significant in the study made by Paulsen and Katska [5].

In the previous studies, the contribution of both sensorial modalities to the assessment of the global annoyance could be described by a linear model without any interaction by Howarth and Griffin [1, 7] or Paulsen and Katska [5], while more complex non linear models were used by Aubrée and Roland [2] or Dempsey *et al.* [8].

The difficulty in the comparison of these results lies in the great disparity between the different experimental conditions :

- The signals could be artificial ones (pure sounds or narrow band noise) [6, 8], or recorded from real sources (tramway or train passage [1, 2, 8] or an industrial press [8]);
- The levels of these sound or vibration signals were very different from one study to the other one, which makes the comparison difficult (noise levels are not even mentioned in [2] and [6]). Moreover, the vibration levels are expressed in the papers using different metrics (acceleration, ISO-weighted acceleration or velocity);
- Subjects were lying down or standing [2, 4], seated either on a stiff seat [1, 5, 7], or on a real one [3, 6, 8].

As a consequence, it is difficult to deduce any general perceptive phenomenon that could exist in a car running at idle from the existing literature.

This study had thus two objectives :

- To develop a simulation bench of a vehicle running at idle allowing to place an individual in a vibratory and acoustic environment similar to what can be experienced in a real car;
- To use this bench to determine the importance of the interaction between vibrations and noise in a vehicle, on the one hand, and the contribution of these two types of stimuli to the evaluation of global annoyance on the other hand.

2. Bench

2.1. Specification

2.1.1. Acoustics

From an acoustic point of view, the specification aimed to reproduce the noise a subject would perceive while seating in the car cabin. The solution of dummy head recordings and headphone reproduction has been selected, because of its very simple use. Idle noise measurements in different cars had shown that the level of very low frequencies (below 80 Hz) was not important enough to justify the use of an additional subwoofer, which reproduces perception of very low frequencies through the body [9].

2.1.2. Vibration

Measurements had been carried out on two diesel engine cars (4 cylinders, common rail) so as to identify most important excitations. These cars were equipped with 12 accelerometers (model PCB Icp® 333B32, with a weight of 4 g), calibrated using a Bruel & Kjaer 4291) :

- one on the engine as a reference;
- six on the slides of the driver's seat (4 vertical ones at the extremity of each slide, one in the longitudinal direction and one in the transversal direction) ;
- five on the steering wheel, as is shown on figure 1. Two of these accelerometers (numbered 2 and 4 on figure 1) were placed in the steering column direction and three in the steering wheel plan (two, numbered 1 and 3, in the "vertical" direction of the steering wheel and one in the transversal direction, fixed at the center of the wheel). In that way, the rotation and translations of the wheel could be identified.

All the accelerometers were conditioned by a PCB 481A device, and the signals were digitally converted by a 16 input front-end, driven by Ideas software.

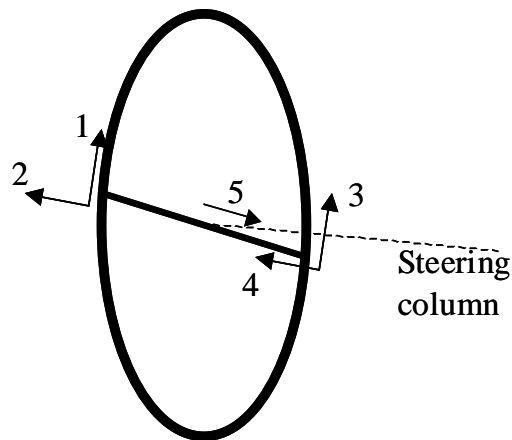


Figure 1 : Position and orientation of the accelerometers placed on the steering wheel.

Measurements had been made while the car was running at hot idle.

Analysis had been achieved taking into account the normalized frequency weightings, from ISO2631-1 (whole body) for the seat measurements and NF EN ISO 5349-1 (upper members) for the steering wheel.

This analysis showed that :

- for the seat, the vertical direction dominated the accelerations in the seat plan ;
- for the steering wheel, the most important displacement was the translation one in the steering column direction. There was no steering wheel rotation movement.

It had thus been decided to reproduce these two steering excitations. Vibrations being at the feet of the individuals were considered to be similar to the ones measured under the seat for simplicity reasons. Lastly, gear lever vibrations were also of an important level, but it hadn't been tried to reproduce them, because the situation was the one of a driver having his hands on the steering wheel.

2.2 Realization

The bench is made of two independent parts (figure 2), one for the seat and the other one for the steering wheel.

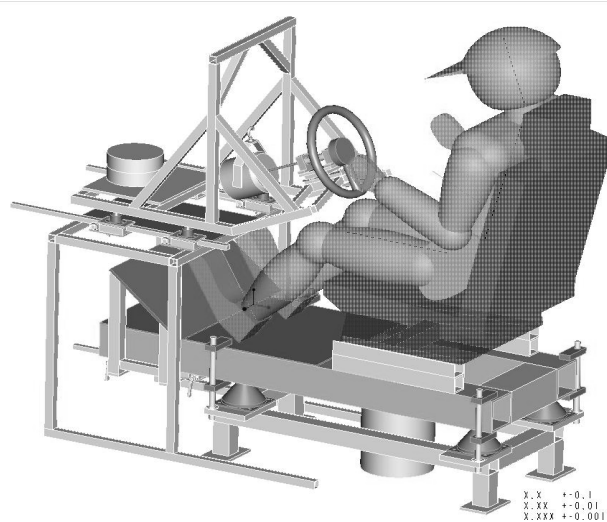
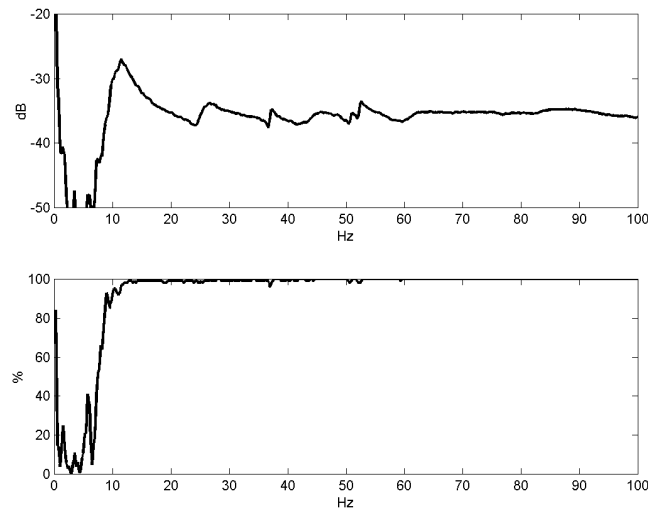


Figure 2 : Test bench

The seat is fixed on a metallic platform being put on four springs. The suspension eigen-frequency of this platform (with a person seated on it) is about 12 Hz, which is convenient for idle application; indeed, in such a case, the first frequency to be reproduced is about 12.5 Hz (it corresponds to the firing frequency of a particular cylinder, in the case of a 4-cylinders 4-stroke engine running at about 750 rpm). This platform is moved by an electrodynamic shaker which has not to support its mass because of the springs : its power can thus be reasonable (here 200 N_{rms}, this value being over-dimensioned for this application).

The transfer function of the device (between the electric signal at the input of the shaker amplifier and an accelerometer fixed on a seat's slide) is shown on figure 3, as well as the coherence between these two signals.



*Figure 3 : Transfer function of the seat part of the bench. Top : modulus (dB ref. $1 \text{ ms}^{-2}/\text{V}$);
bottom : coherence.*

The coherence is very high at frequencies above 10 Hz, which indicates the linearity of the system, and the transfer function does not exhibit too important differences between its maximum and minimum level (about 15 dB). That allows to invert that transfer function in order to filter the signals measured on vehicles, so that the mechanical influence of the system can be corrected.

The steering wheel is fixed to a column sliding on socket balls and linked to a second shaker of lesser power. Here again, the transfer function of the device, only depending a little on the individual having his hands on the steering wheel, has been corrected from measured signals.

Signals to be reproduced (two acoustic channels and two vibratory ones) stored and numerically filtered on a PC computer, are converted to analog signals by audio multi-channel card (Gina 24 by Echo) at the frequency of 51200 Hz (that frequency has to be the

same for all output channels of the audio card, though far too important for the vibratory signals). This card guarantees a good time synchronization of all channels.

3. Experiments

3.1. Measurements

Four other common rail diesel engine cars had been used for the recording of signals to be reproduced on the bench, in addition to the two vehicles used for the specification of the bench. All these cars were of the middle range and equipped with in-line 4 cylinders engines, their cubic capacity varying between 1.7 l and 2.1 l.

The measurement device included for each of them :

- An accelerometer placed vertically at the front end of the right side of the driver's seat;
- An accelerometer of the same model placed on the steering wheel, in the direction of the column;
- An acoustic dummy head (Bruel and Kjaer 4133) put on the driver's seat.

The accelerometers, as well as the other measuring devices, were the same as those used for the specification of the bench (part 2.1.2).

All engines were running at hot idle.

A 7s sequence of each recording was then selected ; the vibratory signals were filtered in order to compensate for the bench mechanical transfer functions, which made these sequences ready for reproduction.

The ranges of the stimuli were :

- 51 to 60 dB(A) for noises;
- 0.1 to 0.8 m.s⁻² for the seat acceleration (after the use of the ISO 2631-1 weighting);
- 0.7 to 3 m.s⁻² for the steering wheel acceleration (after the use of the ISO 5349-1 weighting).

In figure 4 is presented an example of vibration spectrum (measured at the seat slide of car D). The harmonic nature of the stimuli is visible on that figure : the first important peak in the spectrum is for a frequency of 27.5 Hz, which corresponds to the firing frequency of the engine (second order harmonic of the rotational speed of 825 rpm).

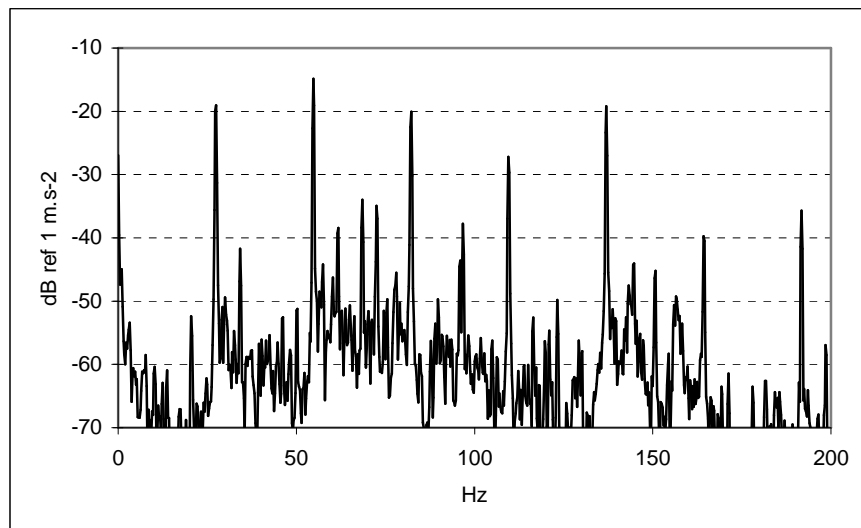


Figure 4 : Spectrum of the vertical vibration measured at the seat slide in one of the cars

3.2. Perceptual tests

It had been decided to carry out three tests in order to reach the objectives of the study (assessment of the vibration interaction on sound evaluation and of the contribution of each modality for global annoyance) :

- In the first one (called **test 1** later on), a subject sitting on the bench was only submitted to the acoustic stimuli ; his task was to compare noise comfort of the stimuli;
- In the second one (**test 2**), he was submitted to all the stimuli (acoustic and vibratory ones), but his task still was to only assess sounds. The comparison between the results obtained in this test and the previous one had to give indications on the influence of vibrations on the evaluation of sounds ;
- Lastly, in the third test (**test 3**), a subject, submitted to all stimuli had to assess the global comfort of his situation.

An individual successively took part to these three tests, in an order which was balanced between the different test persons so as to suppress any range bias.

These three tests followed a similar procedure of pair comparison, using the Ross-series technique [10] after a previous permutation of the signal order to be presented. A pair was made of two signals of 7s each, separated by an interval of 0.5s. The subject could repeat the pair as often as he wanted to. A test included 15 pairs, plus two repeated ones and two pairs of equal signals used to evaluate the consistency of the subject.

The subject had to give his answer on a 5 level scale ("I prefer A a lot", "I prefer A", "A and B are equivalent", etc.....), this answer being recorded by the computer as a number included between 0 and +1. Moreover, the total time being necessary to the individual was also recorded.

Explanations were given to the test person on situations that were to be presented to him and the task he had to achieve before each test. There especially was an emphasis in test 2 on the fact that he had to make a comparison between nothing but the sounds. The following instruction was given to him : *imagine you are sitting in a car running at idle. You will be*

presented sound and vibration environments recorded in two different cars. Please indicate the sound which is more comfortable for you.

34 people participated to the whole experiment. The jury was essentially made of men (26 men, 8 women) having an average age of 25. Their audibility threshold was not measured, but none of them reported any hearing impairment.

4. Results

In each test, average preferences had been converted into merit scores of each stimulus with the following expression :

$$\mu_i = \frac{1}{5} \sum_{j \neq i} P_{ij} \quad (1)$$

where P_{ij} is the averaged preference between stimuli i and j .

As each stimulus was presented in five pairs, μ_i is included between 0 and 1 (value 1 indicating that the stimulus had been estimated to be much less comfortable than all the other ones).

Moreover, circular errors of each individual had been evaluated from the method presented in [11]. A circular error exists in a triad of stimuli i, j and k if $P_{ij} > 0$, $P_{jk} > 0$ and $P_{ik} < 0$. Though the number of circular errors can be used to reject some people from the panel (a too high number of circular errors indicating a not reliable subject), it was only used in that study as an indicator of the difficulty of each experiment.

4.1. Test 1

Figure 5 shows scores, computed from equation (1) for the six vehicles.

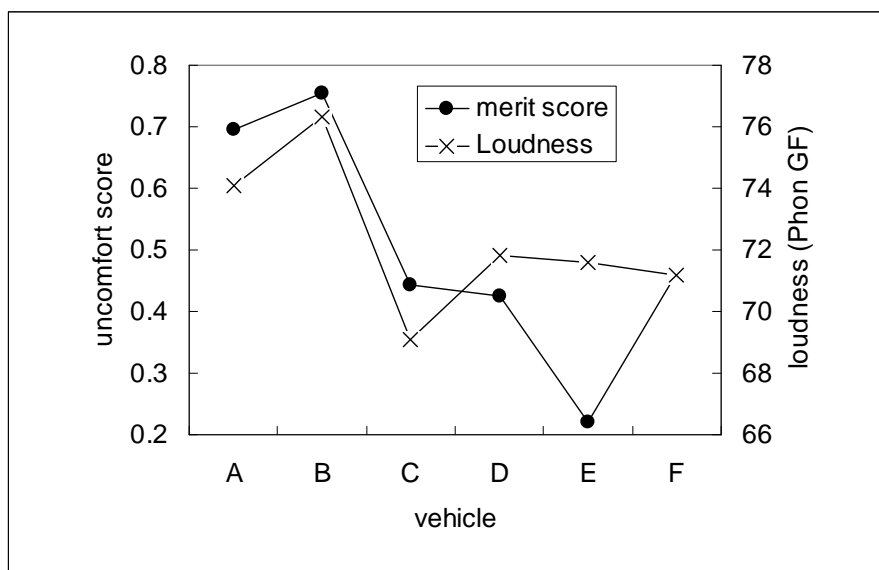


Figure 5 : Merit scores (black circles) and loudness values (crosses) of the six noises.

Values varied between 0.2 and 0.75, showing a good discrimination of noises. In addition, loudness was computed using the normalized model (ISO 532B) as implemented in the Mts Sound Quality© software. The chosen value was the average of some values of each channel of the acoustic dummy head, as proposed by Chouard [12] ; that value was finally converted into Phons. Figure 5 shows that loudness is very related to uncomfot; but figure 5, as well as the value of the correlation coefficient between merit scores and loudness ($R = 0.75$) clearly indicates that loudness doesn't explain all the variations. The sound of vehicle E was particularly much more appreciated than those of vehicles C, D and F : the preference probabilities P_{EC} , P_{ED} and P_{EF} were significantly different from 0.5, at a confidence level higher than 0.99. But loudness values of these four sounds are equivalent. Clearly the timbre of this noise is very important : it sounds less deep than the other ones. But it was not possible to identify any relevant metric of this feature : the pitch of the sound is similar (around 27 Hz, because the rpm of diesel engines at idle have more or less the same values), and neither the

sharpness nor the Spectral Center of Gravity were different for that noise than for the other ones. Therefore, it was not possible to build an accurate indicator of sound evaluation in that case.

4.2. Test 2

Figure 6 presents the merit scores in tests 1 and 2, and confidence intervals corresponding to 95% of each average value.

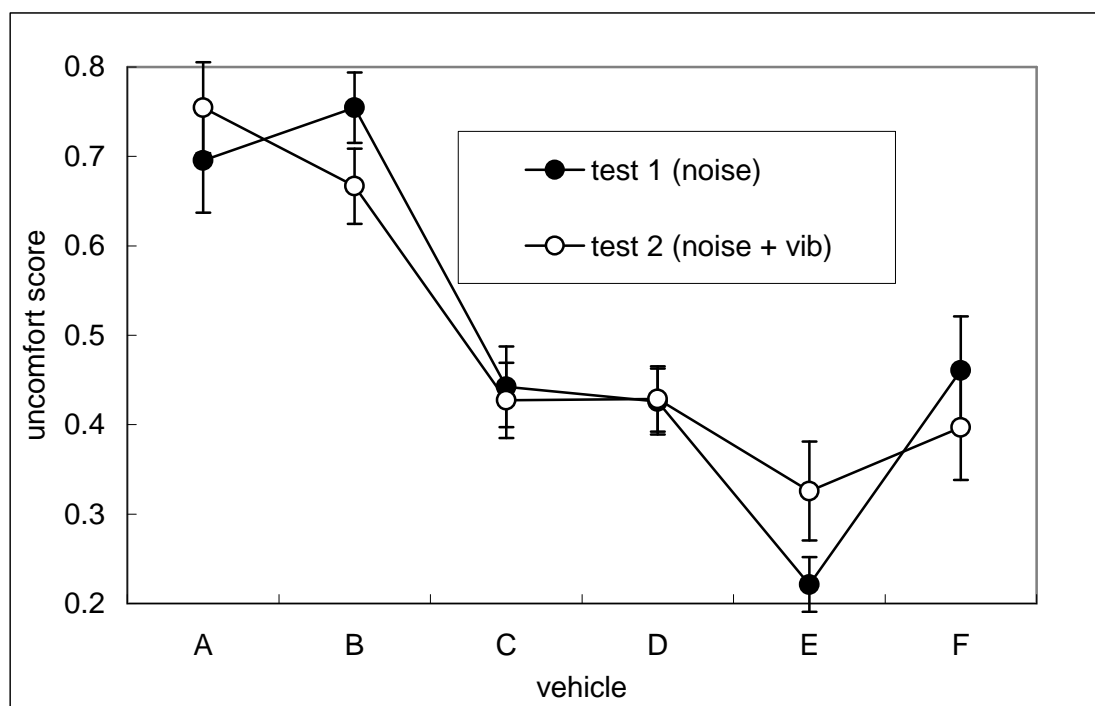


Figure 6 : Merit scores for noise in test 1 (black circles) and 2 (open circles).

The results obtained in both tests were very similar. Nonetheless, differences existed for vehicles B, E and F. A comparison between averages showed that these differences were significant at a probability $p=0.99$ (Student t values were respectively 4.1, 3.9 and 2.9 for a significance level of 2.74). The presence of vibrations could thus slightly modify sound perception. It had to be noticed that such an influence appeared to be logical : vibration levels

were low for vehicle B, leading to a noise perception improvement. On the contrary, vehicle E presented important vibration levels, decreasing the noise appreciation.

4.3. Test 3

The first observation concerned the average circular errors rate : it was significantly more important for this third test (12.6 %) than for the previous ones (respectively 3.7% and 4.6%). That revealed a greater difficulty for the individuals to achieve the task they were asked.

The uncomfot scores are shown in figure 7 : the ranking of cars is clearly different from what was obtained in the first two experiments : for example, car C is the least comfortable, while it was medium ranked in tests 1 and 2.

In addition, a greater inter-individual variability existed. This variability had been put forward by a clusters identification of scores attributed by each listener, using the K-means technique [13]. This analysis allowed to separate the panel into two equally numbered sub-groups (17 people) the scores of whom being very different (figure 7).

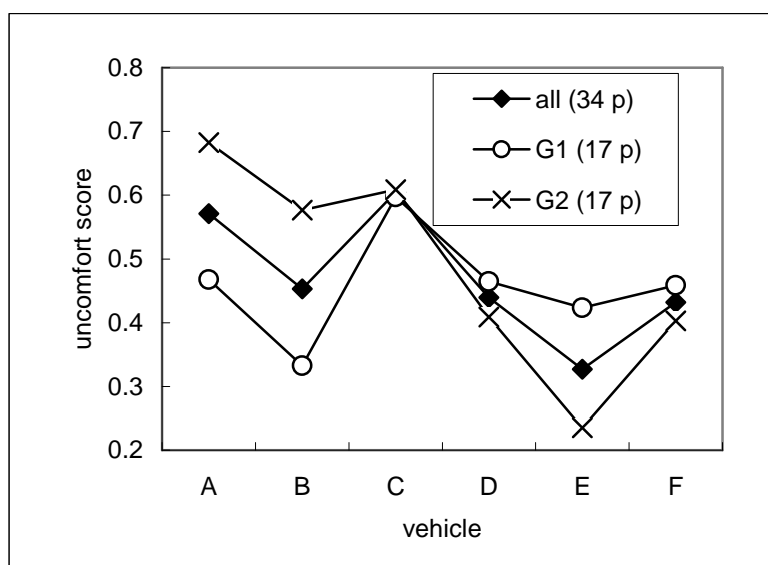


Figure 7 : Scores computed for both individual sub-groups from test 3.

Generally, the score range was more important for group 2 (from 0.25 to 0.7) than for group 1 (from 0.35 to 0.6) ; this difference appeared also with circular error rates , which are 18% for group 1 and 7.3% for group 2. The task thus seemed to be much more difficult for the first group of subjects.

An indicator representing the obtained scores in each group had been looked for. Such an indicator had to take acoustic and vibratory stimuli into account. As previously mentioned, it was not possible to identify an accurate indicator of test 1 results from usual sound metrics. It had thus been decided to use the subjective merit scores from test 1 in the model of test 3, while vibratory stimuli were taken into account through their weighted root-mean squares acceleration values.

In that way , in each group, a score model had been searched in the following form :

$$Score_{test3} = A + B. \gamma_{seat} + C. \gamma_{wheel} + D. Score_{test1} \quad (2)$$

Where :

- $Score_{test3}$ are merit scores as shown in figure 7;
- $Score_{test1}$ are merit scores of the first test (figure 4);
- γ_{seat} and γ_{wheel} are rms values of weighted accelerations measured on the bench;
- parameters A , B , C and D being computed through a multiple regression analysis.

This approach resulted in two satisfactory models for predicting vehicle merit scores. An interesting fact is that for the first group, a very satisfactory model could be obtained without taking into account the merit scores of test 1, equation (2) being reduced to :

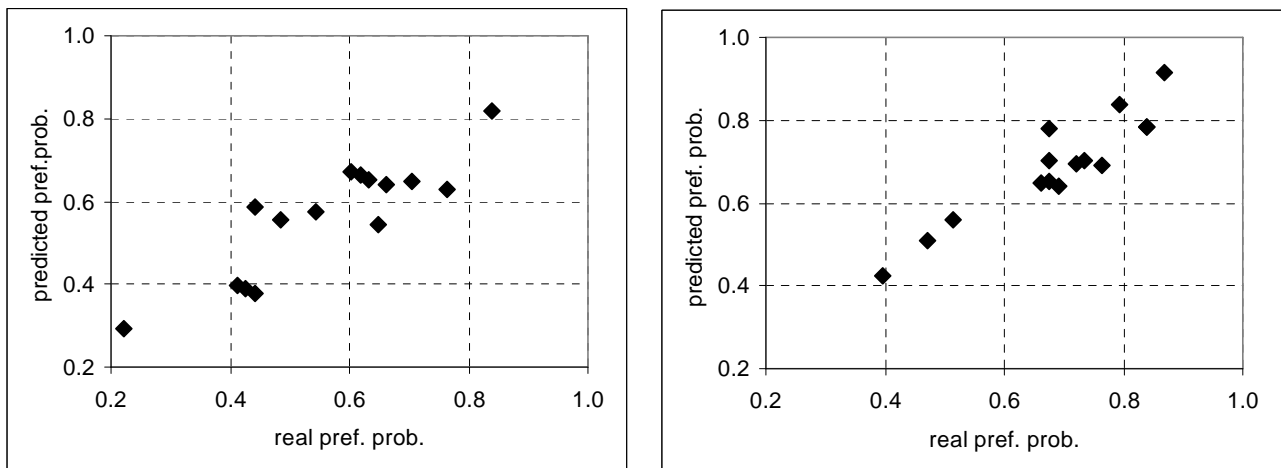
$$Score_{test3} = A + B. \gamma_{seat} + C. \gamma_{wheel} \quad (3)$$

Correlation coefficients between scores measured and reproduced by each model were $R=0.95$ for group 1 (using eq. (3)) and $R=0.99$ for group 2 (using eq. (2)).

These models were checked in the following way : from the predicted merit scores (μ_i), average preferences in each pair of stimuli were computed back by the relation

$$X_{ij} = \mu_j - \mu_i \quad (4)$$

The comparison between these computed preferences and preference probabilities showed a linear relation between these values for each group (figure 8). Correlation coefficients were $R=0.81$ for group 1 and $R=0.91$ for group 2, showing the reliability of the models.



*Figure 8 : Average preferences vs. preferences computed from the merit scores models.
Left : Group 1; right : Group 2.*

5. Discussion

The first test confirmed the importance of loudness in the assessment of car noise [14, 15], and, in a second order, the one of the low frequency content of sounds [15].

The second test shows a slight influence of vibrations on noise perception. That conclusion agrees with those from Paulsen and Katska or Västfjäll *et al.* [5, 6], meanwhile such an

interaction had not been identified by Howarth and Griffin or Aubrée and Roland [1, 2]. It can be presumed that this discrepancy is due to differences in the levels of the signals used in these different studies. Howarth and Griffin [1] used noises in the range of 54 to 79 dB(A), and vibrations ranging between 0.02 and 0.125 m/s² (measured at the bottom of a rigid seat). In the present study, noise levels were lower (51 – 60 dB(A)), and vibration levels were higher (0.1 – 0.8 m/s² on the seat slide, which represents more important levels for the passenger, even taking into account the attenuation of the seat). Such levels were comparable to those used by Paulsen and Katska [5] (noise levels between 32 and 60 dB(A), vibration levels between 0.05 and 0.32 mm/s, using a rigid seat, while the levels of our study, when expressed in velocity, were comprised between 0.5 and 1.5 mm/s). It can thus be understood that more important vibration levels influenced noise perception of lower levels. A similar comparison with other studies cannot be made, because noise levels are not mentioned in [2] and [6].

The third test emphasizes a great inter-individual variability : some subjects only use vibration information to compare the comfort of presented situations, whereas other ones also take account of noise. In [2], it is mentioned that, at high level of vibrations, noise influence is weaker. It may be possible that in our case, the stimuli are close to such a situation, because the velocities measured on the seats slides are in the order of magnitude of the stimuli used by Aubrée and Roland [2].

For subjects taking into account the whole set of stimuli (noise and vibrations), preference model (eq. (1)) is linear and thus comparable to the models proposed by Howarth and Griffin [1, 7], in the sense that it is not necessary to introduce an interaction between the stimuli, as Dempsey *et al.* [8] found useful in their study.

It can also be noted that, in such a linear model, the coefficients of seat and wheel vibrations (B and C in equations (2) and (3)) are of the same orders of magnitude, whatever the subjects group. It seems that seat and steering wheel vibrations are of equal importance to subjects, which is in contradiction with the results from Amman *et al.* [16], who found that seat contribution is four times more important than the wheel one. Once more, this discrepancy may be due to range differences of the signals; but that range is not exposed in Amman *et al.*, which prevents to understand such a discrepancy.

6. Conclusion

Interactions between sound and vibration is certainly a complex phenomenon, depending upon the relative levels of the signals. The conclusions of the existing literature should be considered with care, because they depend on the range (if not on the spectra) of the stimuli used in the experiment. It would be helpful to study that interaction in an exhaustive way, in order to improve knowledge about it and to evaluate its importance in the different practical conditions in which it can be present.

Nevertheless, this study shows that vibrations are very important in the evaluation of comfort by car drivers, which can make necessary the use of mechanical benches to reach a realistic enough restitution.

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