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Multi-excitation discomfort in a car: contribution from sound and vibrations

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ABSTRACT

Sound and vibration can be considered as the two main sources of discomfort when driving. The objective of this study is to quantify the relative influence of each of these sources on the overall discomfort. Based on the knowledge of the relative influence of vibration sources in interaction with the driver, such as seat, floor or steering wheel. Powertrain vibration situations have been generated in a way that each vibration interface induces an equivalent level of discomfort. In a driving simulator, showing a straight road, 25 sound and vibration situations were presented to 15 participants. Vibration presented were 30 Hz signal with levels ranged from 110 to 120 dB at the floor and steering wheel interfaces and 100 to 110 dB for the seat (0 dB ref : 10-6 m/s²) added with a rolling noise between 60 and 76 dB A. For each situation, the participant were asked to rate their overall feeling of discomfort, using a Borg scale between 0 and 50. This experiment evaluates the relative discomfort induced by noise and vibration and allowed to determine their relative weighting in an overall discomfort index. Results and limitations will be presented at the congress.

1. INTRODUCTION

During a driving experience, vibration and noise are among the most important sources of discomfort. While noise is primarily perceived by the ears, vibrations can be perceived at several interfaces such as seat, feet or hands. Several studies have focused on the perception of vibration and noise modalities independently, resulting in the creation of psychoacoustic indicators such as loudness [1] or vibration comfort indexes: respectively for Whole-body vibrations [2] and Hand-transmitted vibrations [3]. When the presentation of noise and vibration is simultaneous, some studies aimed to assess the relative influence of each on the global discomfort. This topic has been widely covered in the field of housing for Railway noise and vibration [4] [5] [6] which showed that the simultaneous evaluation of noise and Whole-body vibrations is necessary to estimate overall discomfort.

In the automotive field, [7] [8] and [9] were interested in equivalent issues, introducing several vibratory sources, including steering wheel vibrations. [10] and [11] attempted to assess the influence of steering wheel vibrations and noise, without the presence of other vibratory sources, and showed that an increase in noise tended to increase the perception of steering wheel vibrations.

All these studies agree that noise and vibration contribute significantly to overall discomfort and can be calculated from the effect of each stimulation taken independently. However, there is no awareness of the

interaction between sound and vibration perception. According to [4] [8] [12] the interaction is non-significant and the sum of the contributions is sufficient to describe the overall discomfort. On the other hand, [4] [13] and [15] describe a phenomenon of noise "masking" on vibration and vice versa, whereby the evaluation of one modality could be affected by the level of excitation of the other one.

These differences led to the construction of different models depending on noise and vibration:

$$[4] \quad \Psi = a \cdot \Psi_{vib} + b \cdot \Psi_{noi} + c \quad (1)$$

$$[12] \quad \Psi = a \cdot \varphi_{dB\ vib} + b \cdot \varphi_{dB\ noi} + c \quad (2)$$

$$[4] \quad \Psi = a \cdot \Psi_{vib} + b \cdot \Psi_{noi} + c \Psi_{vib} \cdot \Psi_{noi} \quad (3)$$

$$[9], [15] \quad \Psi = \sqrt{\Psi_{vib}^2 + \Psi_{noi}^2} \quad (4)$$

Where Ψ represents the overall discomfort, Ψ_{vib} the sensation induced by excitation $\varphi_{dB\ vib}$, and Ψ_{noi} the sensation induced by excitation $\varphi_{dB\ noi}$. In [4] [9] and [15] Ψ_{vib} and Ψ_{noi} are expressed according to Stevens' power laws defined in each study. Depending on the studies, the coefficients a, b and c vary and there is no consensus between the studies. These coefficients may vary according to the stimuli studied or the experimental procedure, but they also vary according to the physical quantity used to describe the noise and the vibration. Most of the time $\varphi_{dB\ noi}$ is estimated by SPL or weighted pressure (dB(A)) and $\varphi_{dB\ vib}$ is estimated by VDV or r.m.s. acceleration, weighted according to [2] or [3]. A choice in the use of one of these quantities could explain variations in the coefficients between studies. However, all of these models gave a strong correlation with experimental data. As can be seen in the proposed models, only the interaction and quadratic models, (3) and (4), allow the "masking" to be considered. In a similar issue, [16] suggests the introduction of a model called "The energy difference model" to explain the influence of two noise sources on the global annoyance. This model describes the phenomenon of "masking" and is expressed as follows:

$$\Psi = a \cdot \varphi_1 + b \cdot \varphi_2 + c |\varphi_1 - \varphi_2| \quad (5)$$

Where Ψ_1 and Ψ_2 represent the contribution of source 1 and 2. φ_1 and φ_2 are expressed in dB.

Based on these various findings, the present experiment aims to respond to several issues:

- To evaluate the relative influence of noise and vertical vibrations transmitted through the seat, the floor and the steering wheel, in a complete car simulator.

- To discuss the interaction between the vibratory and sound modalities on the global discomfort.
- To evaluate the relevance of the models proposed by the literature, in an automotive context and to introduce “*The energy difference model*” to describe the global discomfort induced by noise and vibration.

2. EXPERIMENT

2.1 Apparatus

The experiment is performed in a full NVH simulator, presented in Figure 1. The simulator is a complete vehicle, in front of a screen showing a scrolling road. Vibrations are reproduced using three shakers, placed on the steering column, under the driver's seat and under a platform modelling the carpet. Vibrations are induced in Z_{floor} , Z_{seat} and Z_{wheel} directions, presented in Figure 2. Vibration levels are measured on the steering wheel and floor using triaxial ICP accelerometers and on the seat using a triaxial wafer, also presented in Figure 2.



Figure 1. Full NVH simulator

Sound reproduction is achieved using open headphones and a subwoofer placed behind the driver's seat. A binaural restitution is performed and a calibration is carried out before the experiment using a dummy head.



Figure 2. Measurement point and direction of excitation

2.2 Subjects

15 subjects, 6 women and 9 men, aged between 24 and 56 years old, with an average height of 175 cm, took part in the experiment. The participants declared to have no vibration-related illnesses and no hearing problems.

Subjects received oral instructions in relation to the context of the study and the test procedure before the experiment begins. They had the possibility to adjust their seats to feel comfortable, but were forced to place their heels on the crosses and their hands between the yellow bands, as shown in Figure 2. In order to limit the differences in grip force applied on the steering wheel, a training session is carried out before the experiment by a sequence of 10 grips on a handle calibrated at 10N. During the experiment, the subjects has the ability of using the calibrated handle to control their gripping force.

2.3 Stimuli

The vibratory stimuli of the study were chosen to reproduce five vibratory situations representative of a low speed automotive vibratory excitation. The acceleration levels presented in the Z_{floor} , Z_{seat} and Z_{wheel} directions are listed in Table 1. For each of these situations, the excitation levels in the other directions were at least 8 dB_{vib} lower at the steering wheel interface and at least 10 dB_{vib} lower at the floor and seat interfaces.

Situation	Floor (dB_{vib})	Seat (dB_{vib})	Wheel (dB_{vib})	Frequency (Hz)
V1	110	100	110	30
V2	112.5	102.5	112.5	30
V3	115	105	115	30
V4	117.5	107.5	117.5	30
V5	120	110	120	30

Table 1. Levels and frequency of stimuli generation (dB_{vib} : reference $a_0 = 10^{-6} m/s^2$)

The noise used for the experiment is a synthesis of stationary noise, recreating a binaural situation at the driving position. It represents a driving situation on an open road at a constant speed (50 km/h), where the noise is mainly produced by the road and the aerodynamic noise. As can be seen in Figure 3, the spectrum presented to each ear is close together and does not have any marked harmonic components. From this sound, 5 sound situations have been created to obtain a presentation varying from 60 dB(A) to 76 dB(A) in steps of 4 dB(A) at the participant's ear (noted from S1 to S5). A calibration task is carried out before the experiment using a dummy head. Acoustic level are not control for each subject during the experiment and it is considered that the noise level does not vary significantly between subjects.

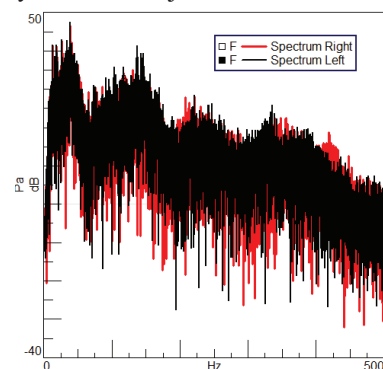


Figure 3. Spectrum of the noise measured by the dummy head

All combinations of vibration and sound situations were tested, leading to 25 situations.

2.4 Procedure

The aim of the experiment is to evaluate the overall discomfort generated by noise and vibration. Thus, for each vibratory and noise situation, the subjects evaluate their sensation of discomfort on a scale between 0 and 50, presented in figure 4, adapted from [17] in the evaluation of loudness. The evaluations are stored by an experimenter outside the vehicle (in audio connection with the participant).

Perceived Discomfort	Rating
Extremely Uncomfortable	50
Very Uncomfortable	45
	40
Uncomfortable	35
	30
Mildly Uncomfortable	25
	20
Slightly Uncomfortable	15
	10
Very Slightly Uncomfortable	5
Not Uncomfortable At All	0

Figure 4. Ranking scale with wording

To increase the immersion in the simulator and the realism of the situations, the choice is made to switch continuously from one noise and vibration situation to another, i.e. without interruption of noise and vibration stimulation. This procedure is closer to a real driving situation, where the noise and vibration stimulations are permanent. To achieve the continuous transition from one situation to another, an adaptive protocol has been set up. As an example, let us take the n situation, where the steering wheel vibration levels are presented in Figure 5. At the beginning of the evaluation phase, the message "please evaluate the new situation" appears on the screen to inform the participant.

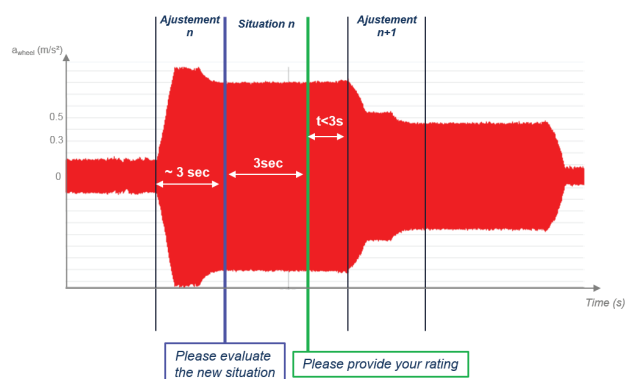


Figure 5. Steering wheel vibrational excitation depending on time

After 3 seconds, the message "please provide your rating" pops up on the screen. Once the rating has been given, the experimenter starts an automatic procedure of adaptation

of levels. As the sound level is not controlled during the experiment, its level simply changes between the gains defined before the experiment. On the other hand, the vibratory levels are adapted and controlled for each participant, due to the important influence of the body on the response of the vibratory system. Thus, between each situation and each vibratory interface, a corrective gain adapts the excitation level to reach a precision of ± 0.5 dB with respect to the target value. Once the excitation has stabilised more than 0.5 s within this interval, the message "please evaluate the new situation" is displayed and the evaluation of the $n+1$ situation begins. On average, the adaptation phases is about 1 to 2 seconds.

A training session presenting five situations is carried out prior to the experience leading to the evaluation of 30 situations and an experience time of about 15 minutes.

3. RESULTS

3.1 Inter-individual analysis

An analysis of Pearson's correlation on participant evaluations ($\Psi_{i,j}$) shows that no participant is significantly out of line with the rest of the population. A hierarchical classification of the correlations between participants, estimated from the scores given for each situation, is carried out using a Ward's method, presented in Figure 6. As can be seen, it appears that two statistically different groups can be discriminated. This hierarchy is not correlated with the anthropometric data of the participants nor with their gender. Although the averages scores of the two groups are not significantly different ($p \sim 0.07$) it can be noted that Group 1 is more severe than Group 2 in the use of the scale. These differences could possibly explain the differences between the two groups.

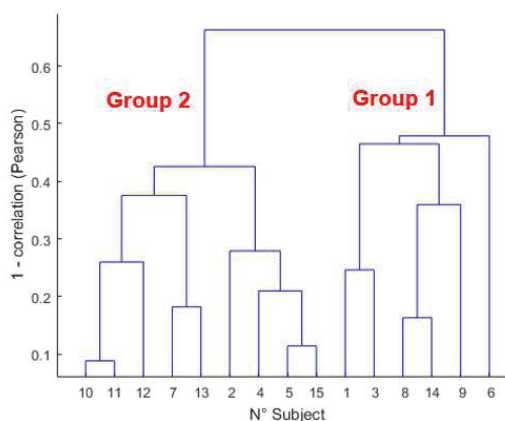


Figure 6. Hierarchical classification (Ward method)

However, due to the limited number of individuals in each group (6 participants in Group 1), further analysis are conducted by considering the entire panel as a single group.

3.2 Statistical analysis

Figure 7 shows the average ratings applied for each combination of vibration and noise. First, it can be seen

that vibration and noise appear to have an effect on the overall discomfort rating. It also seems that, as the vibration or noise level increases, the effect of the second modality tends to decrease.

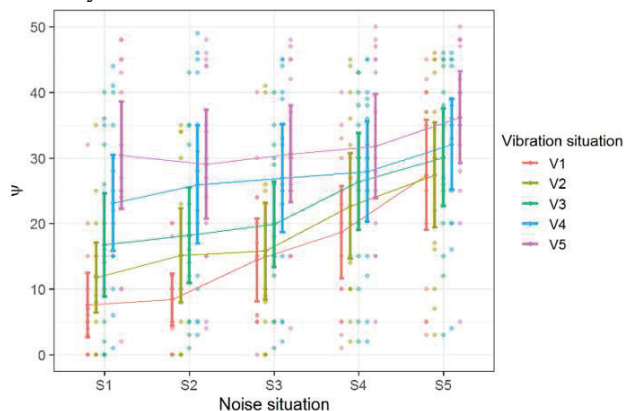


Figure 7. Averages ratings for all the situations

To confirm these assumptions, a repeated measures ANOVA on $(\Psi_{i,j})$ and two factors {Noise S1-S5 and Vibration V1-V5} was carried out, using R® software. Only the main effects and first-order interactions are included in the model. This ANOVA reveals significant effects of the Noise factor ($p < 0.0001$) and Vibration factor ($p < 0.0001$). There is also a significant effect between Noise and Vibration ($p \sim 0.0005$).

As can be seen in Figure 8 and 9, the overall discomfort increases with increasing noise or vibration levels, independently. It can be noticed that the evolution of (Ψ) as a function of the vibratory situation seems to be linear ($R^2 \sim 0.994$), as presented in figure 8. However, the link between vibratory excitation and (Ψ) is not direct because the vibratory situation is a combination of multiple excitations (floor, steering wheel and seat). On the other hand, the evolution of the excitation level at each interface is identical and about $2.5 \text{ dB}_{\text{vib}}$. Thus, a variation of $2.5 \text{ dB}_{\text{vib}}$ on each vibratory interface induces on average a variation of the discomfort about $\Delta(\Psi) \sim 4 \text{ pts}$ on the ranking scale.

Similarly, it can be seen from Figure 9 that the evolution of (Ψ) as a function of the noise situation (directly related to the level in dB(A)) seems to follow a linear relationship ($R^2 \sim 0.94$). Here, a noise level variation of 4 dB(A) (level variation between two noise situations) induces on average a variation of discomfort about $\Delta(\Psi) \sim 3 \text{ pts}$ on the ranking scale. The overall discomfort can also be described as a polynomial of order 2, which is a better approximation ($R^2 \sim 0.995$). However, given the small number of points, it is difficult to choose one or the other representation. It can nevertheless be noted that the model in the form of a 2nd order polynomial is more sensitive to variations in measurements and that linear modelling is preferable.

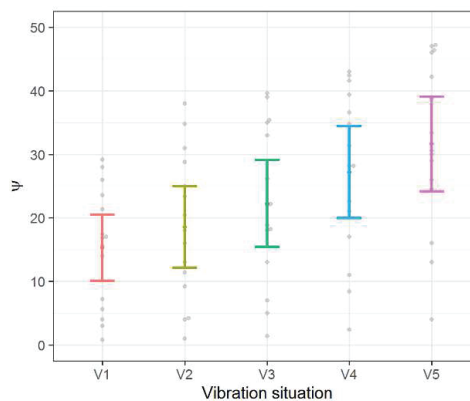


Figure 8. Averages rating as a function of the vibratory situation

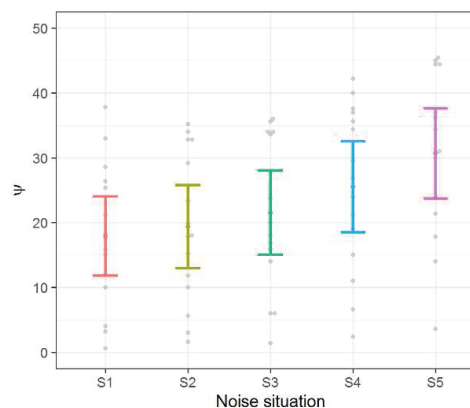


Figure 9. Averages rating as a function of the noise situation

As shown in the literature, both noise and vibration influence the overall feeling of discomfort. In this experiment, it can also be noticed that at high excitation level, a "masking" phenomenon seems to appear. Indeed, when the vibratory level increases the variations in sound level no longer have any influence on the sensation of discomfort. The same observation can be made when the sound level increases, as can be seen in Figure 10. It therefore seems necessary to consider this effect when building predictive models.

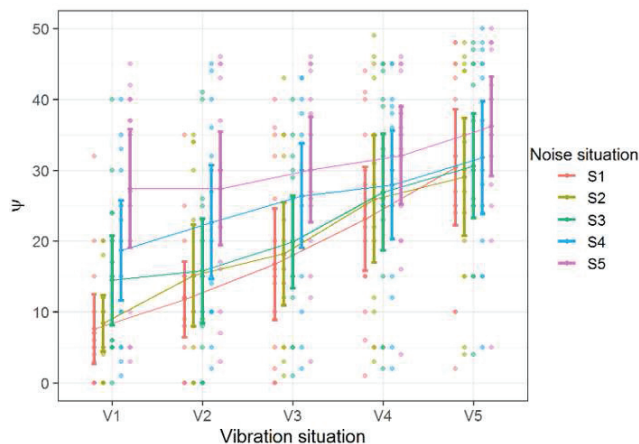


Figure 10. Averages rating depending on the vibration and noise situations

3.3 Predictive models

To evaluate the relative contributions of noise and vibration to the sensation of discomfort, the vibration and sound levels have been standardized. Since the evolution of the vibration level is identical for each interface (evolution over a range of 10 dB in steps of 2.5 dB) it is possible to consider only one of the interfaces to describe vibrational evolution. Two variables A_s and A_v have been constructed to express the relative variations of noise and vibration situations, such as:

$$A_s = \frac{N_{dB(A)} - \min(N_{dB(A)})}{\max(N_{dB(A)}) - \min(N_{dB(A)})} = \frac{N_{dB(A)} - 60}{16}$$

$$A_v = \frac{N_{dBvib\ wheel} - \min(N_{dBvib\ wheel})}{\max(N_{dBvib\ wheel}) - \min(N_{dBvib\ wheel})} = \frac{N_{dBvib\ wheel} - 110}{10}$$

Note: Although A_v is defined from the steering wheel vibration levels, a variation in A_v corresponds to a variation on all vibration interfaces simultaneously.

Based on A_v and A_s parameters, the models presented in the introduction have been adapted and implemented to estimate the overall feeling of discomfort ($\Psi_{i,j}$) for each situation. The results and parameters of the models are presented in Table 2 and a Prediction/Measurement comparison is presented in Figure 11. As can be seen, all these models give a strong prediction of the overall discomfort. However, it seems that *Mdl 1* is the less efficient model. This can be explained because it does not make it possible to describe the “masking” phenomenon from one modality to the other.

On the other hand, the other three models give equivalent results, both on the value of the correlation coefficient and on the variability of the parameters. It can nevertheless be noted that the variability of the parameters of *Mdl 3* is significantly lower than that of *Mdl 2* and *Mdl 4*. However, *Mdl 3* does not make it possible to discriminate the relative influence of noise or vibration, whereas *Mdl 1*, *2* and *4* tend to show that the influence of vibration (b) is greater than that of noise (a).

<i>Mdl 1</i>	<i>Mdl 2</i>
$\Psi = a \cdot A_s + b \cdot A_v + c$ $a = 12.7, \sigma_a = 1.4$ $b = 16.7, \sigma_b = 1.4$ $c = 8.3, \sigma_c = 1.1$ $R^2 = 0.9$	$\Psi = a \cdot A_s + b \cdot A_v + c \cdot A_v \cdot A_s + d$ $a = 20, \sigma_a = 1.6$ $b = 24.1, \sigma_b = 1.6$ $c = -14.6, \sigma_c = 2.6$ $d = 4.6, \sigma_d = 1$ $R^2 = 0.96$
<i>Mdl 3</i>	<i>Mdl 4</i>
$\Psi = a \sqrt{A_s^2 + A_v^2} + b$ $a = 21.9, \sigma_a = 1$ $b = 5.6, \sigma_b = 0.8$ $R^2 = 0.96$	$\Psi = a \cdot A_s + b \cdot A_v + c A_v - A_s + d$ $a = 12.7, \sigma_a = 1.4$ $b = 16.7, \sigma_b = 1.4$ $c = 6.6, \sigma_c = 0.9$ $d = 5.6, \sigma_d = 0.7$ $R^2 = 0.97$

Table 2. Predictive models

Mdl 2 and *Mdl 4* provide equivalent results, however *Mdl 4* is easily interpretable from a physical point of view and allows us to maintain a 1st order model. It expresses the idea that perception is directly correlated to a difference in stimulation between noise and vibration. Thus, if the vibratory level is important in front of the sound level, its influence becomes predominant due to the term $|A_v - A_s|$ and vice versa. Therefore, the rest of the analysis will focus on this model and the evaluation of its parameters.

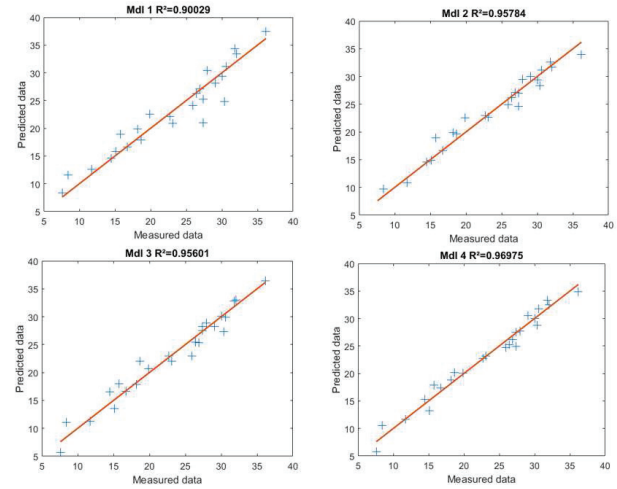


Figure 11. Comparison between measured data and predicted data from each model of Table.2

To evaluate the robustness of the parameters a , b , c and d and the sensitivity to variations in situations of *Mdl 4*, a bootstrap analysis [18] was carried out, 2000 random draws of 25 vibratory and sound situations. Figure 12, presents the occurrence of the values found for parameters a , b and c for each random draw. The empirical median of each parameter on the whole analysis is $a_{emp} = 12.7$, $b_{emp} = 16.8$ and $c_{emp} = 6.5$. It can be noted that these values are very close to the mean values found in Table 2. It is also noticeable that the contribution of parameter c is not negligible and explain part of the overall feeling of discomfort. Finally, the analysis shows that the inequality $a < b$ is true for 1999 draws on 2000. It can therefore be concluded that the relative contribution of vibrations is greater than the noise contribution in this experiment. This result has also been proposed by [12]. However, although the data have been standardised, the influence of sound and vibration is dependent on the range of variation of the selected levels. The result proposed here, shows that given a range of sound variation between 60 and 76 dB(A) and a vibration excitation range of 110 to 120 dB_{vib} for the feet and steering wheel and 100 to 110 dB_{vib} for the seat, vibration contributes more than noise to the feeling of discomfort. In this case, the range of vibration and sound variation is representative of a driving situation. This experiment leads to the conclusion that vibration has a substantially greater effect than noise and that it is necessary to take into account an interaction parameter in an automotive context.

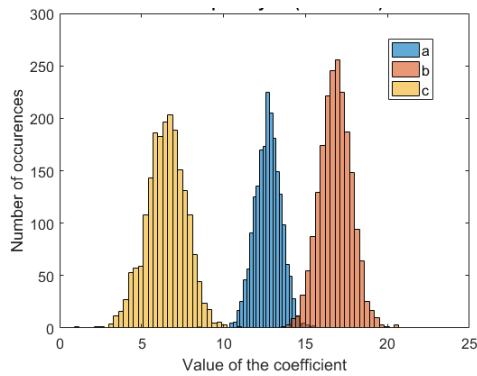


Figure 12. Occurrences of bootstrap analysis for each parameter

3.4 Equivalent comfort curves

Based on *Mdl 4* and the discomfort terms proposed on the scale Figure 4, equivalent discomfort curves were constructed and presented in Figure 13. As can be seen, these curves result in two straight lines whose intersection corresponds to an equivalent between noise and vibration excitation (according to A_v and A_s). Again, the abscissa shows the steering wheel vibration level, but it should be considered that it corresponds to an equivalent excitation on the floor and a lower excitation of 10 dB_{vib} on the seat. The whole vibratory modality finally generates the discomfort rate. These curves make it possible to evaluate each situation on the scale but also to associate a term to describe the feeling of discomfort produced.

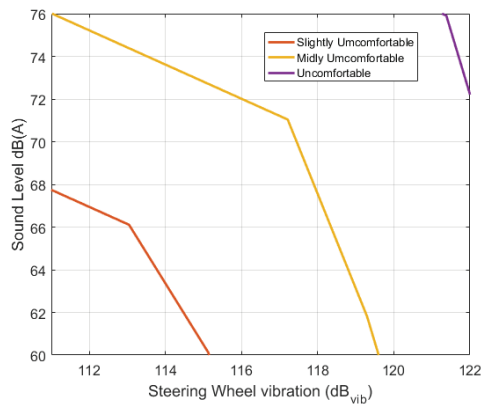


Figure 13. Equivalent discomfort curves, depending on noise and vibration of each interfaces

4. CONCLUSION

The experiment presented in this article showed that noise and vibration had a significant influence on overall vehicle discomfort with a larger contribution of vibration in contrast with the noise excitation. A masking effect of one modality on the other has also been highlighted. Thus, when the vibratory or sound level becomes important, the level of excitement of the other modality no longer significantly influences the overall feeling of discomfort. To improve comfort in the vehicle, it is therefore necessary to consider both noise and vibration. The study has also focused on the evaluation of the models proposed in the literature and shown that it was important to include an

interaction term, particularly to describe the masking phenomenon highlighted. A model of "energy differences" has been finally selected, as it offers the best prediction and makes it possible to maintain a model of order 1. This model is also easy to interpret in terms of perception and describes the sensitivity of sensation to the difference in excitation level between the two disturbances. Based on this model, equivalent discomfort curves have been constructed. To increase the feeling of comfort in the driving position, it is therefore necessary to study noise and vibration simultaneously. The use of discomfort zones could help to make a strategic choice on the modality to be treated first to significantly reduce the feeling of discomfort. To complete this experiment, it would be interesting to study the relative influence of each vibratory modality to understand their relative importance in the discomfort generated by the vibrations.

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