19th INTERNATIONAL CONGRESS ON ACOUSTICS
MADRID, 2-7 SEPTEMBER 2007

PSYCHOACOUSTIC ANALYSIS OF RATTLING NOISE INSIDE VEHICLE CABINS

PACS: 43.50.Lj

Rossi, Federico[1]; Nicolini, Andrea[2]
[1]University of Perugia, Department of Industrial Engineering; via G.Duranti 67, 06125 Perugia, Italy; frossi@unipg.it
[2]University of Perugia, Department of Industrial Engineering; via G.Duranti 67, 06125 Perugia, Italy; nicolini.unipg@ciriaf.it

ABSTRACT
Annoyance due to rattling noises for vehicle passengers is investigated here. The investigation was carried out in the following steps: a measurement campaign, physical analysis of the measurement results and a jury test. The jury test was led by selecting a jury composed of 60 people with healthy hearing. The jury was tested by different noise signals stemming from different sources. Two psychoacoustic parameters were evaluated by the jury test: annoyance and pleasantness. Psychoacoustic indexes depending on loudness and sharpness metrics were found by a regressive analysis.

INTRODUCTION
Acoustic comfort for car passengers is made up by many factors: vibrations, shocks, accelerations and decelerations, engine noise, cabin acoustic insulation, rolling noise. Rattling noises are often responsible of acoustic discomfort. They may be generated by many causes: mechanical adjustment of seats, setting of instrument panel drive grips (for windscreen wipers or direction signals), safety belts hook/unhook, doors opening/closing, centralized closing, etc. However, it may be very difficult to assess the discomfort due to these noises. For instance, a positive connotation of a noise may be associated to the rattling noise the closing of a door makes because it may be associated with a sensation of solidity or compactness of the passenger car. This paper deals with the proposal of evaluation indexes of annoyance and pleasantness due to rattling noises in vehicle cabins. Indexes represent the average sensation of a jury which was subjected to a jury test. The investigation was carried out by these following main steps:

a) a measurement campaign was conducted to record rattling noise signals near the passenger's hearing position.
b) Rattling noises due to noise sources inside the vehicle cabin were studied by an objective analysis. Psychoacoustic metrics were evaluated for each noise signal.
c) A jury test was carried out with binaural headphones. A jury was requested to detect annoyance and pleasantness due to each noise signal [1]. Two methods were used:
    - Semantic Differential method [2];
    - Pair Comparison method [3].
d) Psychoacoustic indexes were found by regressive analysis. Indexes correlate "No annoyance" and "Pleasantness" to the psychoacoustic metrics.

The proposed indexes allow to point out the most unpleasant and annoying noises for car passengers; motor vehicle factory designers may use the proposed relations in order to design a comfortable motor vehicle.

THE MEASUREMENT CAMPAIGN
A measurement campaign was led by using a test bench. Measurement equipment is made up of a Digital Signal Recorder (DAT) and a test head for binaural recordings. Measurements were performed at CRF (Centro Ricerche Fiat - Turin – Italy) thanks to an agreement between FIAT Auto S.p.a. and University of Perugia. Recordings were checked in order to detect rattling noise signals due to mechanical and structural vehicle components. The selected noises were caused

by routine activities usually occurring in the passenger cars or by drivers. Thus, 27 rattling noise signals were found. Each signal is an average 2 seconds long. The causes which generated the selected signals are shown in Table 1.

Table 1.- causes which generated the individuated noise signals

Kind of Signals	*Reference numbers*	*Generating causes*
Rattling noise	From n.1 to n.6	Rattling noise due to a plastic panel which surrounds the gear lift
	From n.7 to n.11	Rattling noise due to the plastic container which replaces the car radio
	From n.12 to n.15	Safety belts which hit against the vehicle lateral panels
	From n.16 to n.22	Safety belts hooking/unhooking
	From n.23 to n.27	Seat backrest

Measurement results showed that rattling noises are characterized by a discontinuous spectrum with medium frequency main components (300-1600 Hz).

METHODOLOGY FOR PSYCHOACOUSTIC EVALUATION

The found noise signals were analysed in order to obtain mathematical relations among selected psychoacoustic metrics by regressive analysis. The adopted methodology is based on two main phases:

– objective analyses by a numerical code;
– jury tests using binaural headphones (subjective analyses).

The correlation between the objective and the subjective analyses allowed to obtain relations between psychoacoustic metrics; the obtained relations allowed to predict “No annoyance” and “Pleasantness” due to rattling noises only by objective analyses. Figure 1 shows the adopted methodology and how the obtained results may be used in order to predict “No annoyance” and “Pleasantness” due to rattling noises.

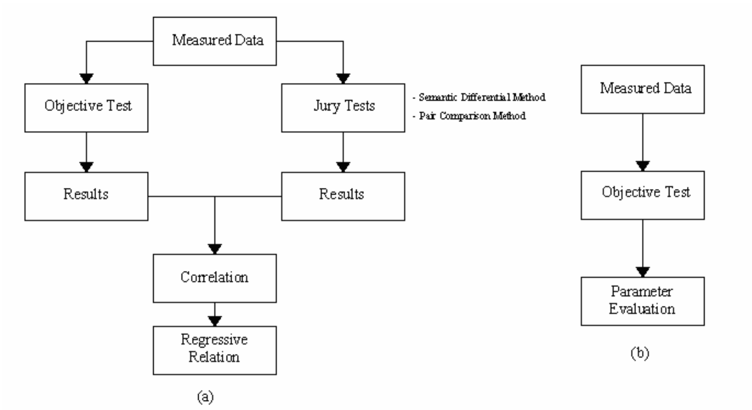

Figure 1.- (a) the adopted methodology; (b) method for psychoacoustic parameters evaluation

The following metrics were evaluated by the objective analysis using a numerical code:

- stationary loudness (N_{SM}) [4];
- roughness (R) [4];
- fluctuation strength (F) [4];
- statistical loudness: loudness mean (N_M), maximum and minimum values (N_{max} and N_{min}), standard deviation (N_σ), percentile values (N_{10}, N_{50} and N_{90}) [4];
- statistical instantaneous loudness: loudness mean (N_{iM}), maximum and minimum values (N_{imax} and N_{imin}), standard deviation ($N_{i\sigma}$), percentile values (N_{i10}, N_{i50} and N_{i90}) [4];
- statistical sharpness (Zwicker method): mean (S_{ZwM}), maximum and minimum values (S_{Zwmax} and S_{Zwmin}), standard deviation ($S_{Zw\sigma}$), percentile values (S_{ZwN10}, S_{ZwN50} and S_{ZwN90}) [4];
- statistical sharpness (Aures method): mean (S_{AuM}), maximum and minimum values (S_{Aumax} and S_{Aumin}), standard deviation ($S_{Au\sigma}$), percentile values (S_{AuN10}, S_{AuN50} and S_{AuN90}) [5].

The jury test was conducted as follows:

1. A jury of 60 people in the 18-30 year-old range was chosen. The jury hearing ability was previously verified by an audiometric analysis.
2. A Semantic Differential method was applied to the jury for the preliminary analysis [2]; this method was preferred for the preliminary analysis as opposed to Pair Comparison method because observers may lose concentration on the test if subjected to too many comparisons. Results obtained by Semantic Differential method were used to sort the investigated signals in terms of annoyance or pleasantness. A multisession method was used: The jury was subjected to three different random sessions constituted by the investigated signals. In this way, the jury is not influenced by the order of presentation of the signals. Furthermore:

   – Each jury member was exposed to five sample noises before beginning the test in order to make him sensitive to the kind of noises he was going to assess.

   – Each jury member evaluation time was a free choice; furthermore, each jury member may listen again to the proposed noise in order to keep his concentration high.

   The following parameters were chosen to be found by the jury tests:

   – annoying/not annoying to characterize the noise inside the vehicle cabin;

   – unpleasant/pleasant to characterize the vehicle solidity and stability; a noise signal may give the passenger a sense of sturdiness. This fact is represented by a pleasant sensation.

   Jury test parameter values are in [1, 7] range for Semantic Differential method. Maximum value corresponds to a highly good signal while minimum value corresponds to a highly bad signal. Thus, parameter scale values are associated to different descriptors (see Table 2).

Table 2.- Jury test scale for Differential Semantic analysis

Scale Values	*Annoying/not annoying scale*	*unpleasant/pleasant scale*
1	Highly annoying	Highly unpleasant
2	Fairly annoying	Fairly unpleasant
3	Slightly annoying	Slightly unpleasant
4	Neutral	Neutral
5	Slightly not annoying	Slightly pleasant
6	Fairly not annoying	Fairly pleasant
7	Highly not annoying	Highly pleasant

3. A Pair Comparison method was applied to signals characterized by similar characteristics in terms of annoyance and pleasantness [3]. The eight worst noises obtained by the Semantic Differential method were chosen for each subjective parameter and each kind of noise. It was shown an inhomogeneous trend for the same rattling noise in the annoyance and pleasantness scales.

   The jury was asked the following questions:

   - Which noise is less annoying?
   - Which noise is more pleasant?

   Jury test parameter values are in the [0, 1] range, where 0 corresponds to a signal which was never chosen by the jury and 1 to a signal which was always chosen by the jury. Thus, small values are associated to negative characteristics, in a way close to the Semantic Differential scales. No problems are related to the order of presentation in this case. The only caution was to avoid to always present the same signal as first or second in the proposed pair. Each jury member was free to choose the delay time between the first and the second signal in a proposed pair and the delay time between two different pairs.

A regressive analysis was performed in order to find relations between the selected subjective parameters (“No annoyance” and “Pleasantness”) and the objective psychoacoustics metrics. The relations were obtained by Pair Comparison jury test results. The proposed relations were tested by applying them to the signals which were evaluated by the Semantic Differential method.

OBJECTIVE ANALYSIS

Objective analysis allowed to evaluate the psychoacoustics metrics values. Results are shown in Table 3 (only the metrics which may be used to evaluate the proposed psychoacoustic index are reported for brevity).

Table 3.- Psychoacoustic metrics values

Metrics	*Rattling Noise (Ref. Number)*								
	1	2	3	4	5	6	7	8	9
N_M (sone)	2.93	2.77	3.02	3.15	2.89	2.86	3.01	3.04	3.04
N_{10} (sone)	3.48	3.02	4.03	4.28	3.61	3.18	3.42	3.89	3.79
N_{iM} (sone)	2.92	2.77	3.02	3.14	2.89	2.86	3.01	3.03	3.04
S_{Aumax} (acum)	1.78	1.79	1.79	1.82	1.81	1.73	2.75	2.66	2.58
Metrics	*Rattling Noise (Ref. Number)*								
	10	11	12	13	14	15	16	17	18
N_M (sone)	2.84	2.98	3.06	3.01	2.89	3.05	5.02	5.11	6.43
N_{10} (sone)	3.04	3.51	3.60	3.43	3.34	3.55	12.48	12.01	17.90
N_{iM} (sone)	2.84	2.97	3.05	3.01	2.89	3.05	4.98	5.08	6.39
S_{Aumax} (acum)	2.06	2.34	1.72	1.72	1.75	1.75	2.30	2.52	2.57
Metrics	*Rattling Noise (Ref. Number)*								
	19	20	21	22	23	24	25	26	27
N_M (sone)	4.15	5.73	5.28	4.97	2.56	2.26	2.13	2.30	2.38
N_{10} (sone)	8.99	14.39	12.57	11.32	4.33	2.87	2.77	3.20	3.55
N_{iM} (sone)	4.13	5.69	5.24	4.94	2.54	2.25	2.12	2.29	2.37
S_{Aumax} (acum)	1.91	2.54	2.39	2.43	0.93	0.81	0.85	0.82	0.79

SUBJECTIVE ANALYSIS

Semantic Differential jury test

Semantic Differential method was applied for a jury test. Average results obtained in the three sessions are reported in Table 4 both for “No annoyance” and “Pleasantness” parameters. The eight signals characterized by the smallest values for each parameter were chosen for Pair Comparison jury test. This method was applied for the following reasons:

- to limit the number of tests. Too many tests may make loss the jury concentration;
- the signals for Pair Comparison analysis are selected close to each other in terms of the evaluation given by the Semantic Differential Method. Thus, they are probably similar in terms of disturbance given to the car passenger. In this way, relations obtained by regressive analysis are very accurate.

Table 4.- Semantic Differential jury test results

Rattling Noise Reference Number	*No annoyance*	*Pleasantness*	*Rattling Noise Reference Number*	*No annoyance*	*Pleasantness*
1	4.96	4.96	15	5.14	4.23
2	5.24	4.82	16	4.27	5.14
3	4.74	5.05	17	4.05	4.61
4	4.67	4.67	18	3.53	5.38
5	5.00	4.92	19	4.42	5.22
6	5.44	4.75	20	3.82	4.55
7	4.55	3.53	21	3.85	4.44
8	4.51	4.15	22	3.98	4.25
9	4.38	4.04	23	5.71	5.74
10	4.48	4.30	24	5.71	5.58
11	4.33	4.28	25	5.71	5.71
12	5.03	4.58	26	5.49	5.32
13	5.49	4.31	27	5.33	5.65
14	5.55	4.88			

Pair Comparison jury Test

Results obtained by the Pair comparison method referring to the investigated signals are shown in Table 5. It is shown that the most annoying rattling signals are mainly due to safety belts hooking/unhooking, while the most unpleasant rattling signals are due to the empty plastic car radio container jittering.

Table 5.- Pair Comparison results

No Annoyance		*Pleasantness*	
Reference Number	*Jury Test results*	*Reference Number*	*Jury Test results*
9	0.78	7	0.30
11	0.72	8	0.46
16	0.54	9	0.39
17	0.53	10	0.57
18	0.17	11	0.50
20	0.35	13	0.57
21	0.48	15	0.54
22	0.51	22	0.58

REGRESSIVE ANALYSIS AND PROPOSAL OF A PSYCHOACOUSTIC INDEX

Regressive analysis

A regressive analysis was carried out in order to evaluate the relation between the subjective parameters and the metrics. An analysis was performed for the signals subjected to the Pair Comparison method. The following optimum relations were obtained for the parameters “No annoyance” ($NoAn_k$)and “Pleasantness” (Pl_k)
:

$$NoAn_k = -0.30 \cdot N_M - 2.05 \cdot S_{Au\,max} + 4.42 \qquad \text{(Eq. 1)}$$

$$Pl_k = 0.32 \cdot N_{10} - 1.22 \cdot N_{iM} - 0.25 \cdot S_{Au\,max} + 3.56 \qquad \text{(Eq. 2)}$$

Equation (1) shows that “No Annoyance” increases when loudness and sharpness metrics decrease. However, eq. (2) shows that “Pleasantness” may increase when the rattling signal is characterized by statistical loudness N_{10} higher than loudness mean values: thus, the rattling noise occurring in a short time lapse gives the passenger a pleasant sensation (or better, a sense of vehicle sturdiness). The comparison among values given by the Pair Comparison jury test and the ones given by the proposed relations shows that:
- the average estimation error is 0.016 and standard deviation is 0.020 for parameter “No annoyance”;
- the average estimation error is 0.018 and standard deviation is 0.019 for parameter “Pleasantness”.

Method validation

The proposed relations were validated by applying them to the signals investigated with the Semantic Differential method. The comparison between the order of preference given by the jury (Semantic Differential jury test) and the one obtained by the proposed relations is reported in Table 6. It shows that:
- the average difference between the orders of preference is 1.26 places and standard deviation is 1.78 for parameter “No annoyance”; Spearman’s rank correlation coefficient is 0.975 [6].
- the average difference between the orders of preference is 1.11 places and standard deviation is 1.47 for parameter “Pleasantness”; Spearman’s rank correlation coefficient is 0.983 [6].

CONCLUSIONS

Rattling noises produced inside a vehicle cabin were analysed by objective and subjective measurement campaigns. Psychoacoustic metrics such as loudness, sharpness, roughness and fluctuation strength were measured. A jury test was applied to a jury by a Semantic Differential method in order to evaluate noise signals in terms of annoyance and pleasantness. A limited set of signals were also evaluated by a Pair Comparison jury test. Single number indexes were proposed by analysing Pair Comparison results by a regressive analysis. The proposed indexes show that annoyance and pleasantness due to rattling noises inside vehicle cabins are mainly affected by loudness and sharpness metrics:
- annoyance due to a rattling noise increases with the loudness mean and the sharpness maximum value;
- pleasantness due to a rattling noise decreases when the loudness instantaneous mean and the sharpness maximum value increase; it decreases when the loudness statistical value N_{10} increases. Thus, a rattling noise impulse may give pleasantness.

The proposed indexes were validated by comparing the order of preference given by the regressive relations with the results obtained by Semantic Differential jury tests. Results show that the Spearman's rank correlation coefficient is:

- 0.975 for "No annoyance" parameter for rattling noises;
- 0.983 for "Pleasantness" parameter for rattling noises.

The investigated rattling noise signals are characterized by low sharpness values (S_{ZwM}<1.3). Thus, the proposed relations may be used to evaluate with high accuracy the rattling noise impact upon car passengers by using loudness and sharpness metrics, particurarly for low sharpness signals.

Table 6.- Comparison between the order of preference obtained by Semantic Differential Jury Test and the one given by the proposed Eq.1 and Eq.2

No annoyance			*Pleasantness*		
Semantic Differential Jury test Order of preference (ref.numbers)	*Eq.(1) Order of preference (ref.numbers)*	*Difference (position in the order of preference)*	*Semantic Differential Jury test Order of preference (ref.numbers)*	*Eq.(1) Order of preference (ref.numbers)*	*Difference (position in the order of preference)*
18	18	0	7	7	0
20	20	0	9	9	0
21	21	0	8	8	0
22	17	-1	15	11	-1
17	22	1	22	15	-1
16	16	0	11	22	2
11	11	0	10	10	0
9	19	-4	13	13	0
19	10	1	21	12	-3
10	8	1	20	17	-1
8	7	1	12	20	2
7	9	1	17	21	2
4	3	-1	4	4	0
3	4	1	6	6	0
1	5	-1	2	14	-2
5	1	1	14	1	1
12	6	-1	5	2	-2
15	12	-2	1	3	2
2	2	0	3	5	1
27	15	-4	16	18	-1
6	14	4	19	16	-1
13	13	0	26	19	-2
26	23	-2	18	24	3
14	27	3	24	26	1
23	26	2	27	27	0
24	25	-1	25	23	-1
25	24	1	23	25	1

References: [1] S. Kuwano, S. Namba: On the definition of loudness, noisiness, and annoyance using selected description method. Proceedings of Noise as a Public Health Problem (1988), Stockholm, Sweden, Vol. 3: 223 – 228.
[2] J.G. Snyder, C.E. Osgood. Semantic Differential Technique: A Sourcebook. Aldine, Chicago, USA, (1969).
[3] V. Kraft, T. Portele. Quality Evaluation of Five German Speech Synthesis Systems. Acta Acustica (1995), Vol. 3: 351-365.
[4] E. Zwicker, H. Fastl. Psychoacoustics - Facts and Models. Springer-Verlag (1999), Berlin, Germany.
[5] W. Aures: Berechnungsverfahren für den sensorischen Wohlklang beliebiger Schallsignale (A model for Calculating the Sensory Euphony of Various Sounds). Acustica (1985); Vol.59: 130-141.
[6] C. Spearman: The proof and measurement of association between two rings. Amer. J. Psychol. (1904); Vol.15: 72–101.