

# Psychoacoustic analysis of squeaking and rattling noises inside vehicle cabins

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**Annoyance of vehicle passengers due to squeaking and rattling noises is investigated. The investigation was carried out in the following steps: measurements, physical analysis of the measurement results and a jury test. The jury was made of 60 people with normal hearing. The participants were exposed to different noise signals generated by different sources. Two psychoacoustic parameters were evaluated by the jury test: annoyance and pleasantness, both for squeaking and rattling noises. Psychoacoustic indices depending on loudness and sharpness metrics were found by a regressive analysis. © 2010 Institute of Noise Control Engineering.**

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## 1 INTRODUCTION

Acoustic comfort for car passengers is due to many factors: vibrations, shocks, accelerations and decelerations, engine noise, cabin acoustic insulation and rolling noise<sup>1-5</sup>. Squeaking and rattling noises often give rise to acoustic discomfort<sup>6,7</sup>. They may be produced by many causes: mechanical adjustment of seats, setting of air conditioner knobs, setting of instrument panel knobs (for windscreen wipers or direction signals), safety belts hook/unhook, opening/closing of doors, centralized closing, etc<sup>8-10</sup>. However, it may be very difficult to assess the discomfort due to these noises<sup>11-15</sup>. For instance, a positive connotation may be given to the rattling noise the closing of a door makes because it may be associated with a sensation of solidity and stability of the vehicle<sup>16-19</sup>. This paper deals with the evaluation of indices of annoyance and pleasantness due to squeaking and rattling noises in vehicle cabins. Indices represent the average sensation of the participants which were subjected to a jury test<sup>20,21</sup>. The investigation was carried out in the following main steps:

- a) measurements were conducted to record squeaking and rattling noise signals near the passenger's hearing position.
- b) Squeaking and rattling noises due to noise sources inside the vehicle cabin were analyzed.

Psychoacoustic metrics were evaluated for each noise signal<sup>22,23</sup>.

- c) A jury test was conducted using binaural headphones. The participants were requested to record annoyance and pleasantness due to each noise signal<sup>24-27</sup>. Two methods were used:
  - Semantic Differential method<sup>28</sup>;
  - Paired Comparison method<sup>29</sup>.
- d) Psychoacoustic indices were found by regressive analysis. Indices were correlated to “No annoyance” and “Pleasantness” psychoacoustic metrics both for squeaking and rattling noises.

The proposed indices allow the identification of the most unpleasant and annoying noises for car passengers. The proposed relations may be useful to improve the acoustic comfort of motor vehicles and to compare different vehicles in terms of the mentioned performances.

## 2 THE MEASUREMENT CAMPAIGN

Measurements were conducted in a laboratory. The measurement equipment were a Digital Signal Recorder (DAT) and a test head for binaural recordings. Measurements were performed at CRF (Centro Ricerche Fiat—Turin—Italy) within an agreement between FIAT Auto S.p.a. and the University of Perugia (Italy). Each tape-recording time was 60 seconds with a 48 kHz sampling rate. Recordings were checked in order to detect squeaking and rattling noise signals due to mechanical and structural vehicle components. The selected noises were caused by routine activities usually occurring in the cars by drivers or passengers, such as setting the air conditioner knob or hooking and unhooking safety belts. Twenty-five squeaking noise signals and 27 rattling noise signals were found.

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Table 1—Causes of the investigated noise signals.

Kind of Signals	Reference numbers	Causes
Squeaking noise	From n.1 to n.13	Air conditioner panel
Rattling noise	From n.14 to n.25	Carpet which squeaks with the vehicle pavement
	From n.1 to n.6	Rattling noise due to a plastic panel which surrounds the gear shift
	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

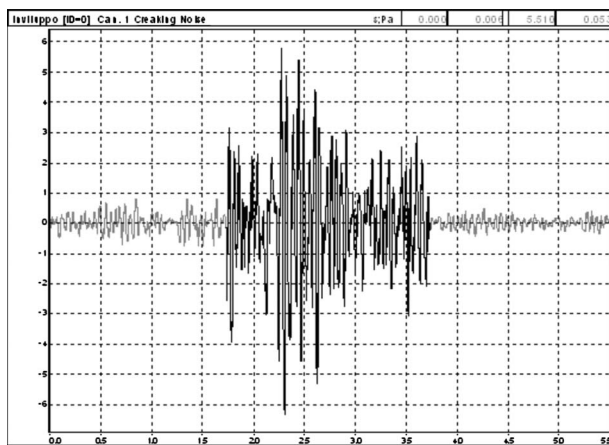


Fig. 1—Squeaking noise typical time behaviour (referred to n.16 squeaking signal).

Each noise signal time averaged 2 seconds: it was detected in the 60 s tape recording. The sources of the selected signals are shown in Table 1. Figures 1–4 present the typical time behaviour and the average spectrum of the investigated squeaking and rattling noises. It is shown and verified for each signal that rattling noises are characterized by a monotonic decreasing average spectrum with a main component in the low frequency range (100–200 Hz), while squeaking noises are characterized by a discontinuous average spectrum with medium frequency main components (300–1600 Hz).

### 3 METHODOLOGY FOR PSYCHOACOUSTIC EVALUATION

The measured noise signals were analysed in order to obtain mathematical relations among psychoacoustic metrics by a regressive analysis. The adopted

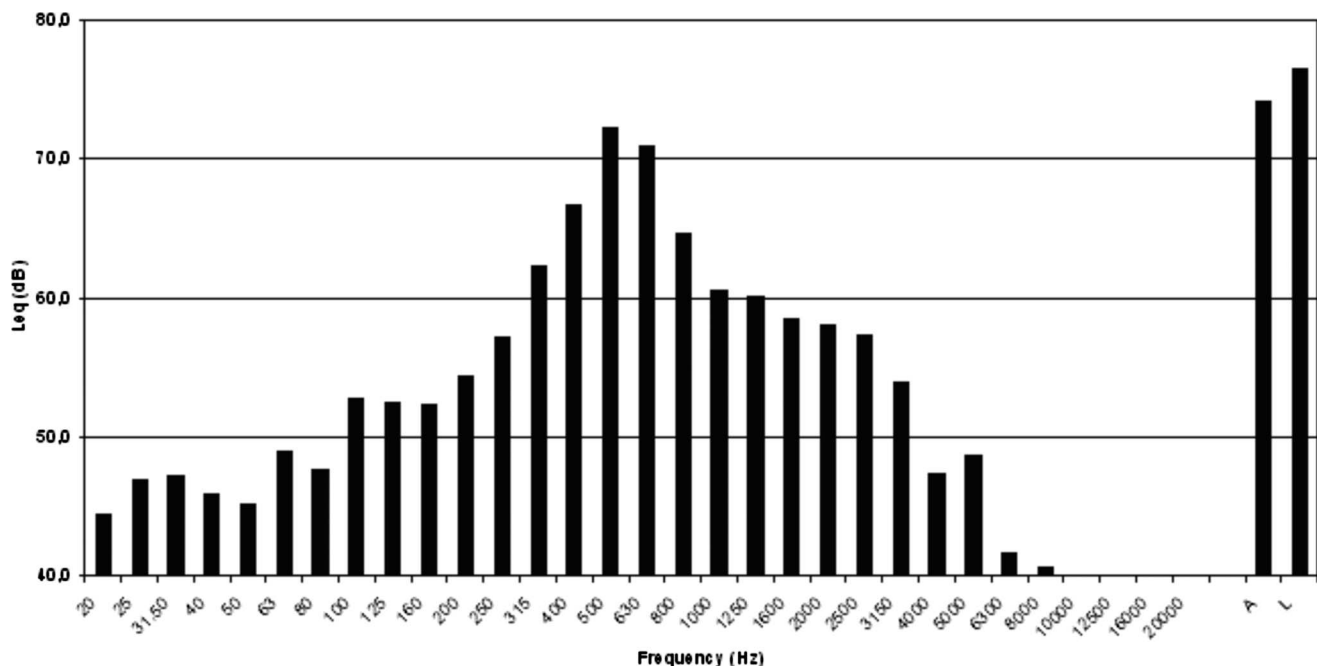


Fig. 2—Squeaking noise typical average spectrum (referred to n.16 squeaking signal).

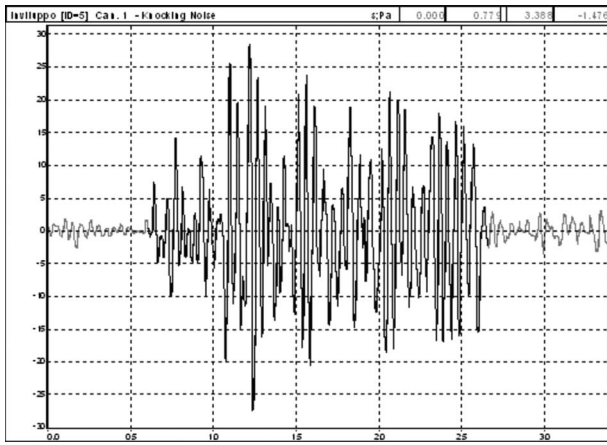
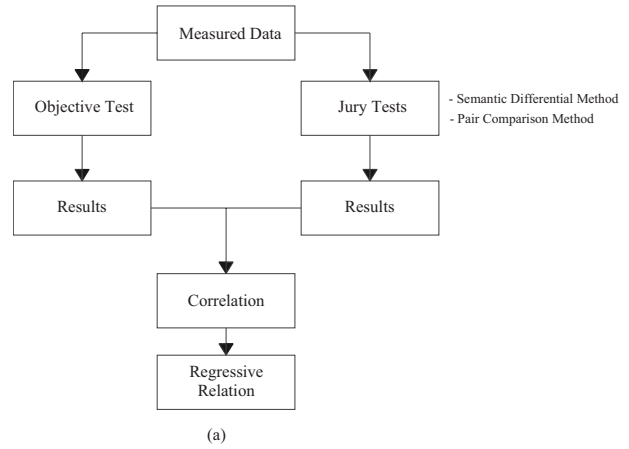


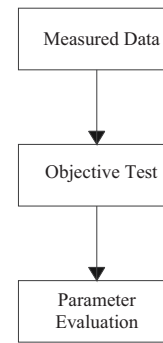
Fig. 3—Rattling noise typical time behaviour (referred to n.10 rattling signal).

methodology is based on two main phases:

- objective analyses by a numerical code (determination of the psychoacoustic metrics);
- jury tests using binaural headphones (subjective analyses). Sound Quality software by Bruel&Kjaer was used for the objective analyses and the jury tests. The correlation between the objective and subjective analyses enables the determination of relations between the psychoacoustic metrics; the obtained relations predict “No annoyance” and “Pleasantness” due to squeaking or rattling noises from objective analyses. Figure 5 shows the adopted methodology and how the obtained results may be used in order to predict “No annoyance” and “Pleasantness” due to squeaking or rattling noises.



(a)



(b)

Fig. 5—(a) The adopted methodology; (b) method for the psychoacoustic parameters evaluation.

The following metrics were evaluated by the objective analysis using the numerical code with a 1/16 Bark resolution:

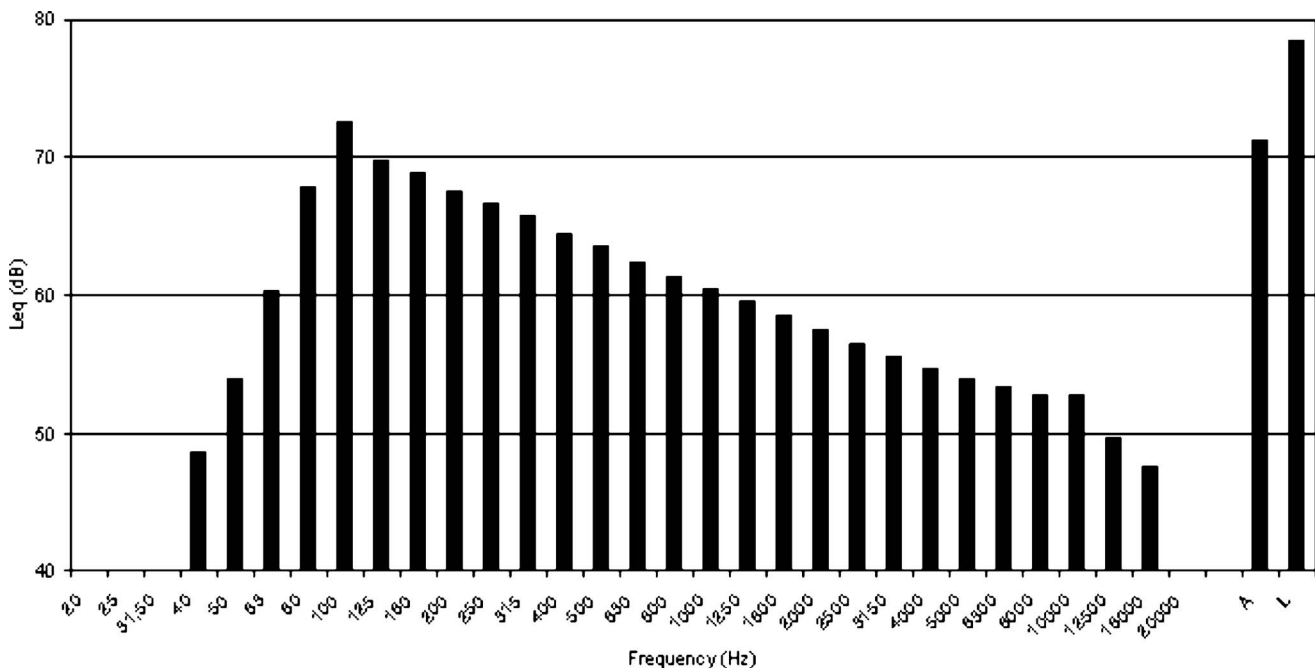


Fig. 4—Rattling noise typical average spectrum (referred to n.10 rattling signal).

- stationary loudness<sup>30,31</sup>;
- roughness<sup>30,31</sup>;
- fluctuation strength<sup>30,31</sup>;
- statistical loudness: loudness mean, maximum and minimum values, standard deviation,  $N_{10}$ ,  $N_{50}$  and  $N_{90}$ , See Refs 30 and 31;
- statistical instantaneous loudness: loudness mean, maximum and minimum values, standard deviation,  $N_{10}$ ,  $N_{50}$  and  $N_{90}$  See Refs 30 and 31;
- statistical sharpness (Zwicker method): mean, maximum and minimum values, standard deviation, 10, 50 and 90 percentiles<sup>30,31</sup>;
- statistical sharpness (Aures method): mean, maximum and minimum values, standard deviation, 10, 50 and 90 percentiles<sup>32</sup>.

The jury tests were conducted as follows:

1. 60 people (40 male, 20 female) in the 18–30 year-old range were chosen. Their hearing ability was previously verified by an audiometric analysis. No relevant acoustic differences were found between genders during the tests.
2. A Semantic Differential method was applied to the participants for the preliminary analysis<sup>28</sup>; this method was preferred for the preliminary analysis as opposed to the Paired Comparison method because the observers may have lost concentration on the test if they were subjected to too many comparisons<sup>33</sup>. Results obtained by Semantic Differential method were used to rate the investigated signals in terms of annoyance or pleasantness. A multisession method was used: the participants were subjected to three different random sessions consisting of the investigated signals. In this way, the participants are not influenced by the order of presentation of the signals.

Furthermore:

- Each participant was exposed to five sample noises before beginning the test in order to make them sensitive to the kind of noises they were going to rate.
  - Each participant evaluation time was a free choice; furthermore, each participant could listen to the proposed noise again in order to keep their concentration high.
  - Some participants were subjected to squeaking noises and then to rattling noises, others were subjected to the reverse order of presentation (in a random way).
2. The following parameters were chosen for specification by the participants:

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

- 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<sup>25</sup>.

Jury test parameter values are in the [1, 7] range for Semantic Differential method. The maximum value corresponds to the best a signal while the minimum value corresponds to the worst signal. Thus, parameter values are associated to different descriptors (see Table 2).

3. A Paired Comparison method was applied to signals characterized by similar characteristics in terms of annoyance and pleasantness<sup>29</sup>. The eight worst noises obtained by the Semantic Differential analysis were chosen for each subjective parameter and each kind of noise. It was shown that generally the same squeaking noise is disturbing on both the annoyance and pleasantness scales (an annoying squeaking noise gives a sense of vehicle fragility). An inhomogeneous trend is shown for rattling noises.

Both for squeaking and rattling noises the participants were asked the following questions:

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

Jury test parameter values are in the [0, 1] range for Paired Comparison method, where 0 corresponds to a signal which was never chosen by the participants and 1 to a signal which was always chosen by the participants. Thus, small values are associated with negative characteristics, in a way close to the Semantic Differential scale. No problems occur for the order of presentation in this case. The only caution was to avoid always presenting the same signal as the first or second in the proposed pair. Each participant was free to choose the delay time between the first and second signal in the proposed pair and the delay time between two different signals.

A regressive analysis was performed in order to find

Table 3—Values of the psychoacoustic metrics (squeaking noises, ref. number from 1 to 9).

Metrics	Squeaking Noise (Ref. Number)								
	1	2	3	4	5	6	7	8	9
$N_{SM}$ (sone)	5.81	6.23	8.27	6.17	6.4	6.93	8.61	8.48	6.99
R (asper)	2.02	2.27	2.84	2.74	2.61	2.39	2.52	2.52	2.41
F (vacil)	2.02	2.91	2.84	2.78	2.61	2.82	2.75	2.52	2.33
$N_{max}$ (sone)	7.78	7.86	10.56	7.85	9.09	8.46	10.24	9.77	8.93
$N_{min}$ (sone)	2.38	2.47	2.45	2.43	2.43	2.38	2.35	2.33	2.41
$N_M$ (sone)	3.68	3.93	4.46	4.04	3.58	4.06	4.27	5.05	4.23
$N_\sigma$ (sone)	1.71	1.81	2.26	1.96	1.81	2.00	2.10	2.22	2.10
$N_5$ (sone)	6.89	7.41	8.23	7.45	6.94	7.91	7.95	8.52	7.96
$N_{10}$ (sone)	6.86	7.13	8.06	7.32	6.84	7.65	7.88	8.47	7.90
$N_{50}$ (sone)	2.63	2.86	3.40	2.69	2.64	2.71	3.29	4.73	2.89
$N_{90}$ (sone)	2.46	2.55	2.50	2.53	2.51	2.50	2.57	2.60	2.50
$N_{imax}$ (sone)	11.98	12.57	17.43	11.40	15.86	14.05	17.86	15.87	14.37
$N_{imin}$ (sone)	2.00	2.06	2.11	2.09	1.94	2.05	2.09	1.85	1.99
$N_{iM}$ (sone)	3.67	3.92	4.46	3.96	3.57	4.05	4.26	5.04	4.22
$N_{i\sigma}$ (sone)	2.06	2.12	2.92	2.20	2.27	2.53	2.93	2.98	2.57
$N_{i10}$ (sone)	6.80	7.51	9.13	8.02	5.90	7.77	7.62	9.83	8.34
$N_{i50}$ (sone)	2.69	2.85	3.16	2.79	2.68	2.81	3.10	3.91	2.90
$N_{i90}$ (sone)	2.36	2.42	2.45	2.42	2.38	2.39	2.46	2.52	2.40
$S_{Zwmax}$ (acum)	1.94	2.07	2.01	1.59	1.80	2.10	2.17	1.99	1.93
$S_{Zwmin}$ (acum)	0.72	0.73	0.74	0.70	0.71	0.74	0.69	0.69	0.77
$S_{ZwM}$ (acum)	1.13	1.10	1.09	1.11	1.14	1.12	1.08	1.04	1.10
$S_{Zw\sigma}$ (acum)	0.20	0.19	0.20	0.19	0.18	0.20	0.20	0.20	0.19
$S_{ZwN10}$ (acum)	1.35	1.31	1.32	1.32	1.33	1.34	1.31	1.31	1.33
$S_{ZwN50}$ (acum)	1.19	1.15	1.10	1.17	1.18	1.17	1.11	1.00	1.14
$S_{ZwN90}$ (acum)	0.83	0.83	0.83	0.82	0.84	0.84	0.81	0.81	0.84
$S_{Aumax}$ (acum)	2.55	2.60	2.65	1.86	2.39	2.63	2.84	2.46	2.52
$S_{Aumin}$ (acum)	0.79	0.80	0.81	0.77	0.77	0.81	0.78	0.77	0.82
$S_{AuM}$ (acum)	1.29	1.26	1.26	1.26	1.30	1.28	1.25	1.19	1.26
$S_{Au\sigma}$ (acum)	0.23	0.23	0.25	0.23	0.21	0.24	0.25	0.26	0.23
$S_{AuN10}$ (acum)	1.54	1.51	1.54	1.52	1.52	1.55	1.51	1.52	1.53
$S_{AuN50}$ (acum)	1.35	1.31	1.27	1.34	1.35	1.33	1.26	1.15	1.30
$S_{AuN90}$ (acum)	0.92	0.91	0.94	0.90	0.96	0.95	0.93	0.90	0.93

relations between the selected subjective parameters (“No annoyance” and “Pleasantness”) and the objective psychoacoustics metrics<sup>34</sup>. The relations were obtained from the Paired Comparison results. The proposed relations were tested by applying them to the signals which were evaluated by the Semantic Differential method.

## 4 SQUEAKING NOISE ANALYSIS

### 4.1 Objective Analysis

An objective analysis was carried out to evaluate the psychoacoustics metrics for the investigated noises. Results given by the investigated squeaking noises are shown in Tables 3–5.

### 4.2 Subjective Analysis

#### 4.2.1 Semantic differential jury test

The Semantic Differential method was applied in the jury test. The average results of the three sessions are reported in Table 6 for each parameter (“No annoyance” and “Pleasantness”).

The eight signals characterized by the smallest values for each parameter were chosen for the Paired Comparison jury test. This method was applied for the following reasons:

- to limit the number of tests. Too many tests may make the participants lose their concentration;
- the signals for the Paired Comparison analysis were chosen close together in terms of the

Table 4—Values of the psychoacoustic metrics (squeaking noises, ref. number from 10 to 17).

Metrics	Squeaking Noise (Ref. Number)							
	10	11	12	13	14	15	16	17
N <sub>SM</sub> (sone)	9.59	5.93	8.03	4.71	7.55	11.77	9.79	6.92
R (asper)	2.63	2.16	2.93	2.50	3.79	4.60	3.73	3.91
F (vacil)	2.63	2.16	3.65	2.50	2.56	4.60	3.73	2.58
N <sub>max</sub> (sone)	12.95	9.22	10.57	8.05	11.94	14.73	12.50	9.48
N <sub>min</sub> (sone)	2.40	2.38	2.47	2.41	2.80	2.74	2.61	2.72
N <sub>M</sub> (sone)	5.13	2.90	5.36	2.92	3.98	5.45	4.50	4.05
N <sub>σ</sub> (sone)	2.75	1.16	2.08	1.08	2.18	3.68	2.36	1.92
N <sub>5</sub> (sone)	11.14	3.34	7.89	3.71	7.42	12.01	8.86	7.71
N <sub>10</sub> (sone)	9.11	3.24	7.69	3.63	7.35	11.48	8.64	7.69
N <sub>50</sub> (sone)	4.08	2.57	5.34	2.58	3.09	3.08	3.26	3.06
N <sub>90</sub> (sone)	2.51	2.47	2.64	2.45	2.93	2.83	2.85	2.77
N <sub>imax</sub> (sone)	20.16	14.14	15.74	12.59	18.87	26.65	23.16	16.39
N <sub>imin</sub> (sone)	1.81	1.95	2.13	1.99	2.39	2.22	2.26	2.31
N <sub>iM</sub> (sone)	5.13	2.89	5.28	2.91	3.97	5.44	4.49	4.04
N <sub>iσ</sub> (sone)	3.66	1.40	2.72	1.24	2.56	4.82	3.54	2.44
N <sub>i10</sub> (sone)	10.89	3.13	9.33	3.46	6.42	11.89	7.89	7.05
N <sub>i50</sub> (sone)	3.62	2.59	4.32	2.59	3.12	3.15	3.18	3.09
N <sub>i90</sub> (sone)	2.49	2.30	2.62	2.32	2.80	2.75	2.72	2.67
S <sub>Zwmax</sub> (acum)	2.37	1.80	1.95	1.70	1.70	1.96	2.25	1.82
S <sub>Zwmin</sub> (acum)	0.68	0.79	0.71	0.76	0.76	0.70	0.73	0.75
S <sub>ZwM</sub> (acum)	1.06	1.22	1.00	1.21	1.08	1.07	1.07	1.08
S <sub>Zwσ</sub> (acum)	0.21	0.13	0.18	0.13	0.12	0.17	0.17	0.14
S <sub>ZwN10</sub> (acum)	1.30	1.37	1.26	1.36	1.21	1.23	1.23	1.24
S <sub>ZwN50</sub> (acum)	1.05	1.24	0.95	1.22	1.09	1.09	1.07	1.10
S <sub>ZwN90</sub> (acum)	0.80	1.07	0.80	1.05	0.92	0.84	0.84	0.89
S <sub>Aumax</sub> (acum)	2.99	2.14	2.57	2.14	2.23	2.91	3.20	2.44
S <sub>Aumin</sub> (acum)	0.75	0.84	0.78	0.82	0.83	0.76	0.81	0.80
S <sub>AuM</sub> (acum)	1.23	1.39	1.15	1.38	1.24	1.24	1.23	1.24
S <sub>Auσ</sub> (acum)	0.28	0.16	0.24	0.16	0.16	0.25	0.25	0.18
S <sub>AuN10</sub> (acum)	1.52	1.57	1.45	1.55	1.40	1.43	1.43	1.42
S <sub>AuN50</sub> (acum)	1.22	1.41	1.10	1.39	1.24	1.24	1.22	1.25
S <sub>AuN90</sub> (acum)	0.90	1.22	0.88	1.19	1.04	0.94	0.95	0.99

evaluation given by the Semantic Differential Method. Thus, they are probably similar in terms of disturbance experienced by the car passenger. In this way, the relations obtained by the regressive analysis are accurate.

#### 4.2.2 Paired comparison jury test

The average results obtained by the Paired Comparison jury tests are shown in Table 7 for each parameter.

#### 4.3 Regressive Analysis and Proposal for a Psychoacoustic Index

##### 4.3.1 Regressive analysis

A regressive analysis was carried out in order to evaluate the relation between the subjective parameters

and the metrics. The signals subjected to the Paired Comparison method were analysed. The following optima relations were obtained for the parameters “No annoyance” and “Pleasantness:”

$$\text{NoAn}_s = -0.32 \cdot N_M - 0.41 \cdot S_{\text{Au max}} + 3.22 \quad (1)$$

$$\text{Pl}_s = -0.10 \cdot N_{\text{max}} - 0.30 \cdot N_M + 0.39 \cdot N_{\sigma} + 2.08 \quad (2)$$

where

- N<sub>M</sub>: Stat. Loudness Mean;
- N<sub>max</sub>: Stat. Loudness Max;
- N<sub>σ</sub>: Stat. Loudness Stand. Dev;
- S<sub>Au max</sub>: Aures Sharpness Max;

Table 5—Values of the psychoacoustic metrics (squeaking noises, ref. number from 18 to 25).

Metrics	Squeaking Noise (Ref. Number)							
	18	19	20	21	22	23	24	25
$N_{SM}$ (sone)	9.31	6.04	10.13	7.55	9.47	6.47	7.82	2.33
R (asper)	2.90	2.51	2.97	3.20	2.66	3.11	5.56	1.83
F (vacil)	2.90	2.51	2.97	3.20	2.66	2.98	3.05	2.41
$N_{max}$ (sone)	10.43	7.77	11.83	10.34	11.68	9.86	15.54	2.46
$N_{min}$ (sone)	2.69	2.75	2.65	2.75	2.83	2.76	2.63	2.01
$N_M$ (sone)	4.25	3.81	4.63	3.91	4.34	3.70	4.07	2.20
$N_\sigma$ (sone)	2.10	1.46	2.60	1.85	2.20	1.69	3.00	0.10
$N_5$ (sone)	9.11	6.72	10.12	6.91	8.42	6.79	7.15	2.52
$N_{10}$ (sone)	8.18	6.67	9.04	6.83	8.39	6.77	7.00	2.33
$N_{50}$ (sone)	3.08	3.02	3.06	3.09	3.20	3.03	3.04	2.18
$N_{90}$ (sone)	2.83	2.85	2.78	2.88	2.95	2.87	2.84	2.09
$N_{imax}$ (sone)	22.77	15.07	24.95	21.77	25.24	15.62	17.29	2.78
$N_{imin}$ (sone)	2.30	2.35	2.30	2.41	2.45	2.28	2.33	1.68
$N_{iM}$ (sone)	4.25	3.78	4.63	3.91	4.33	3.70	4.06	2.19
$N_{i\sigma}$ (sone)	3.20	1.93	3.83	2.53	3.36	2.06	3.18	0.20
$N_{i10}$ (sone)	7.16	6.02	8.64	5.74	6.92	5.54	5.38	2.46
$N_{i50}$ (sone)	3.15	3.08	3.12	3.11	3.20	3.05	3.05	2.20
$N_{i90}$ (sone)	2.73	2.74	2.69	2.80	2.84	2.72	2.73	1.93
$S_{Zwmax}$ (acum)	2.23	1.62	2.23	2.00	2.26	1.53	1.68	1.84
$S_{Zwmin}$ (acum)	0.74	0.73	0.73	0.73	0.73	0.74	0.74	1.20
$S_{ZwM}$ (acum)	1.07	1.09	1.08	1.08	1.07	1.10	1.10	1.47
$S_{Zw\sigma}$ (acum)	0.17	0.12	0.18	0.13	0.16	0.12	0.11	0.11
$S_{ZwN10}$ (acum)	1.24	1.23	1.27	1.22	1.21	1.24	1.24	1.61
$S_{ZwN50}$ (acum)	1.09	1.10	1.10	1.09	1.08	1.10	1.10	1.47
$S_{ZwN90}$ (acum)	0.85	0.91	0.84	0.90	0.87	0.94	0.98	1.34
$S_{Aumax}$ (acum)	3.14	2.06	3.20	2.70	3.02	1.99	2.25	2.09
$S_{Aumin}$ (acum)	0.81	0.77	0.80	0.78	0.78	0.79	0.82	1.33
$S_{AuM}$ (acum)	1.24	1.24	1.25	1.24	1.23	1.25	1.27	1.65
$S_{Au\sigma}$ (acum)	0.24	0.15	0.26	0.18	0.22	0.16	0.14	0.13
$S_{AuN10}$ (acum)	1.43	1.41	1.47	1.41	1.40	1.43	1.43	1.83
$S_{AuN50}$ (acum)	1.24	1.25	1.25	1.24	1.23	1.25	1.26	1.65
$S_{AuN90}$ (acum)	0.96	1.02	0.95	1.02	0.99	1.06	1.11	1.48

Equations (1) and (2) show that both “No annoyance” and “Pleasantness” increase when loudness and sharpness means or maximum values decrease. Furthermore, a squeaking signal characterized by a wide range of loudness values (high  $N_\sigma$  values) may give a sense of solidity and stability to the passenger. Table 8 shows the comparison among values given by the Paired Comparison jury test and the ones given by the proposed relations. It is shown that:

- the average estimation error is 0.018 and the standard deviation is 0.021 for the parameter “No annoyance;”
- the average estimation error is 0.020 and the standard deviation is 0.021 for the parameter “Pleasantness.”

### 4.3.2 Method validation

Equations (1) and (2) were validated by applying them to the signals investigated with the Semantic Differential method. The order of preference given by the participants (Semantic Differential jury test) and the one obtained by the proposed relations were compared. Results show that:

- the average difference between the orders of preference is 1.24 places and the standard deviation is 1.65 for the parameter “No annoyance;” the Spearman’s rank correlation coefficient is 0.980<sup>35</sup>.
- the average difference between the orders of preference is 1.20 places and the standard de-

Table 6—Semantic Differential jury test results (squeaking noises).

Squeaking Noise Reference Number	No annoyance	Pleasantness
1	4.26	5.01
2	3.86	4.11
3	3.34	3.57
4	4.21	4.52
5	4.10	4.00
6	3.47	3.95
7	3.41	3.66
8	3.22	3.10
9	3.67	3.91
10	2.78	3.03
11	5.36	4.45
12	2.71	3.00
13	5.66	4.69
14	4.09	3.58
15	2.53	3.29
16	2.83	3.15
17	3.92	3.88
18	3.28	3.64
19	4.36	4.29
20	3.02	3.34
21	3.62	3.86
22	3.45	3.55
23	4.55	3.75
24	3.92	3.38
25	6.28	5.19

viation is 1.66 for the parameter “Pleasantness;” the Spearman’s rank correlation coefficient is 0.975<sup>35</sup>.

Table 7—Paired Comparison results for squeaking noises.

No annoyance		Pleasantness	
Squeaking Noise Reference Number	Jury Test results	Squeaking Noise Reference Number	Jury Test results
3	0.68	8	0.48
8	0.62	10	0.30
10	0.38	12	0.24
12	0.44	15	0.44
15	0.29	16	0.38
16	0.50	20	0.51
18	0.59	22	0.49
20	0.43	24	0.50

A quantitative description of psychoacoustic annoyance due to synthetic and technical sounds (such as car noise, air conditioner noise, sawing noise and drilling noise) may be obtained also by the following well-known model proposed by Widmann<sup>30</sup>:

$$PA = N_5(1 + \sqrt{w_S^2 + w_{FR}^2}) \quad (3)$$

where

$$w_S = (S_{ZWM} - 1.75) \cdot 0.25 \cdot \log(N_5 + 10) \quad \text{for } S_{ZWM} > 1.75 \quad (4)$$

$$w_{FR} = \frac{2.18}{(N_5)^{0.4}} \cdot (0.4 \cdot F + 0.6 \cdot R) \quad (5)$$

Each analysed squeaking signal is characterized by  $S_{ZWM} < 1.75$ . Thus, the model given by Eqn. (3) was applied with  $w_S = 0$ . Values of  $N_5$  were evaluated and reported in Tables 3–5. The comparison between the order of preference given by the participants (Semantic Differential jury test) and the one obtained by Eqn. (3) model gives 0.944 as Spearman’s rank correlation coefficient value. The correlation coefficient is less than the one obtained by the proposed Eqn. (1). This is due to the fact that the investigated squeaking noises are characterized by low sharpness values. High main component frequencies (higher than 1600 Hz) don’t occur in the investigated signals. This fact induces low sharpness values. Thus, the proposed model gives a better annoyance evaluation compared to Eqn. (3) for low sharpness noise signals.

## 5 RATTLING NOISE ANALYSIS

### 5.1 Objective Analysis

An objective analysis of the rattling noises enabled the evaluation of the psychoacoustics metric values. Results are shown in Tables 9–11.

### 5.2 Subjective Analysis

#### 5.2.1 Semantic differential jury test

The Semantic Differential method was applied as first step of the jury test. The average results obtained in the three sessions are reported in Table 12 both for “No annoyance” and “Pleasantness” parameters. Eight noise signals for each parameter were chosen for the Paired Comparison jury test in the same way described for the squeaking noise analysis.

#### 5.2.2 Paired comparison jury test

Results obtained by the Paired Comparison method for the investigated signals are shown in Table 13. It is shown that the most annoying rattling signals are mainly due to safety belts hooking/unhooking, while

Table 8—Comparison among the Paired Comparison results and the values given by the proposed relations.

No Annoyance				Pleasantness			
Squeaking Noise Ref. Number	Paired Comparison Jury test	Eqn. (1) values	$\Delta$	Squeaking Noise Ref. Number	Paired Comparison Jury test	Eqn. (2) values	$\Delta$
3	0.68	0.71	-0.03	8	0.48	0.45	0.03
8	0.62	0.60	0.02	10	0.30	0.32	-0.02
10	0.38	0.35	0.03	12	0.24	0.23	0.01
12	0.44	0.45	-0.01	15	0.44	0.41	0.03
15	0.29	0.28	0.01	16	0.38	0.40	-0.02
16	0.50	0.47	0.03	20	0.51	0.52	-0.01
18	0.59	0.57	0.02	22	0.49	0.47	0.02
20	0.43	0.43	0.00	24	0.50	0.48	0.02

the most unpleasant rattling signals are due to the empty plastic car radio container jittering.

### 5.3 Regressive Analysis and Proposal for a Psychoacoustic Index

#### 5.3.1 Regressive analysis

A regressive analysis was carried out to evaluate the relation between the subjective parameters and the metrics. An analysis was performed for the signals subjected to the Paired Comparison method. The following optimum relations were obtained for the parameters “No annoyance” and “Pleasantness:”

$$\text{NoAn}_r = -0.30 \cdot N_M - 2.05 \cdot S_{\text{Au max}} + 4.42 \quad (6)$$

$$\text{Pl}_r = 0.32 \cdot N_{10} - 1.22 \cdot N_{iM} - 0.25 \cdot S_{\text{Au max}} + 3.56 \quad (7)$$

where

- $N_M$ : Stat. Loudness Mean;
- $S_{\text{Au max}}$ : Aures Sharpness Max;
- $N_{10}$ : Stat. Loudness  $N_{10}$ ;
- $N_{iM}$ : Stat. Inst. Loudness Mean;
- $S_{\text{Au max}}$ : Aures Sharpness Max;

Equation (6) shows that “No Annoyance” increases when loudness and sharpness metrics decrease. However, Eqn. (7) shows that “Pleasantness” may increase when the rattling signal is characterized by a statistical loudness ( $N_{10}$ ) higher than loudness mean values: thus, the rattling noise occurring in a short time lapse gives a pleasant sensation (or better, a sense of vehicle sturdiness) to the passenger.

Table 14 shows the comparison between the values given by the Paired Comparison jury test and the ones given by the proposed relations. It is shown that:

- the average estimation error is 0.016 and the standard deviation is 0.020 for the parameter “No annoyance;”
- the average estimation error is 0.018 and the standard deviation is 0.019 for the parameter “Pleasantness.”

#### 5.3.2 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 participants (Semantic Differential jury test) and the one obtained by the proposed relations shows that:

- the average difference between the orders of preference is 1.26 places and the standard deviation is 1.78 for the parameter “No annoyance;” Spearman’s rank correlation coefficient is 0.975<sup>35</sup>.
- the average difference between the orders of preference is 1.11 places and the standard deviation is 1.47 for the parameter “Pleasantness;” Spearman’s rank correlation coefficient is 0.983<sup>35</sup>.

The model for psychoacoustic annoyance described in Eqns. (3)–(5) was also applied to the investigated rattling signals. Each analysed rattling signal is characterized by  $S_{\text{ZwM}} < 1.75$ . Thus, the model given by Eqn. (3) was applied with  $w_s = 0$ . Values of  $N_5$  were evaluated and reported in Tables 9–11. The comparison between the order of preference given by the participants (Semantic Differential jury test) and the one obtained by Eqn. (3) gives a Spearman’s rank correlation coefficient equal to 0.941. The correlation coefficient is lower than the one obtained by the proposed Eqn. (6) due to the very low sharpness values of the investigated signals. In fact,

Table 9—Values of the psychoacoustic metrics (rattling noises, ref. number from 1 to 9).

Metrics	Rattling Noise (Ref. Number)								
	1	2	3	4	5	6	7	8	9
$N_{SM}$ (sone)	3.72	2.95	4.34	5.04	3.60	3.21	5.47	4.74	5.05
R (asper)	1.82	2.04	1.87	2.10	1.61	1.77	1.71	1.81	1.90
F (vacil)	1.88	2.04	1.72	1.84	1.82	1.77	2.03	1.81	1.90
$N_{max}$ (sone)	6.97	5.01	8.89	9.62	6.70	5.73	11.47	8.70	8.31
$N_{min}$ (sone)	2.45	2.44	2.40	2.52	2.49	2.51	2.41	2.43	2.47
$N_M$ (sone)	2.93	2.77	3.02	3.15	2.89	2.86	3.01	3.04	3.04
$N_\sigma$ (sone)	0.73	0.38	1.10	1.23	0.69	0.50	1.12	1.08	0.98
$N_5$ (sone)	3.62	3.13	4.16	4.35	3.82	3.29	3.71	4.12	3.98
$N_{10}$ (sone)	3.48	3.02	4.03	4.28	3.61	3.18	3.42	3.89	3.79
$N_{50}$ (sone)	2.70	2.69	2.65	2.70	2.66	2.73	2.69	2.67	2.72
$N_{90}$ (sone)	2.55	2.53	2.52	2.59	2.55	2.60	2.56	2.50	2.54
$N_{imax}$ (sone)	9.70	6.29	12.14	13.51	9.28	7.41	18.36	13.88	14.22
$N_{imin}$ (sone)	2.14	2.15	2.07	2.22	2.11	2.15	2.06	2.14	2.10
$N_{iM}$ (sone)	2.92	2.77	3.02	3.14	2.89	2.86	3.01	3.03	3.04
$N_{i\sigma}$ (sone)	0.86	0.49	1.24	1.39	0.82	0.60	1.44	1.35	1.24
$N_{i10}$ (sone)	3.50	3.08	3.96	4.20	3.51	3.20	3.55	3.74	3.59
$N_{i50}$ (sone)	2.72	2.68	2.69	2.74	2.68	2.74	2.70	2.67	2.73
$N_{i90}$ (sone)	2.43	2.41	2.40	2.45	2.41	2.46	2.43	2.38	2.43
$S_{Zwmax}$ (acum)	1.52	1.55	1.54	1.55	1.57	1.49	2.02	2.06	1.92
$S_{Zwmin}$ (acum)	0.76	0.77	0.71	0.69	0.75	0.83	0.73	0.68	0.69
$S_{ZwM}$ (acum)	1.17	1.20	1.17	1.15	1.18	1.18	1.20	1.20	1.18
$S_{Zw\sigma}$ (acum)	0.13	0.11	0.15	0.16	0.13	0.11	0.13	0.14	0.13
$S_{ZwN10}$ (acum)	1.32	1.34	1.32	1.32	1.33	1.31	1.35	1.35	1.33
$S_{ZwN50}$ (acum)	1.18	1.19	1.19	1.17	1.19	1.18	1.21	1.21	1.19
$S_{ZwN90}$ (acum)	0.99	1.07	0.97	0.92	1.01	1.05	1.05	1.03	1.03
$S_{Aumax}$ (acum)	1.78	1.79	1.79	1.82	1.81	1.73	2.75	2.66	2.58
$S_{Aumin}$ (acum)	0.83	0.83	0.78	0.81	0.86	0.91	0.81	0.75	0.75
$S_{AuM}$ (acum)	1.34	1.36	1.34	1.32	1.35	1.35	1.36	1.36	1.34
$S_{Au\sigma}$ (acum)	0.15	0.13	0.17	0.18	0.15	0.13	0.16	0.18	0.17
$S_{AuN10}$ (acum)	1.52	1.53	1.52	1.52	1.53	1.51	1.55	1.55	1.53
$S_{AuN50}$ (acum)	1.35	1.36	1.36	1.34	1.36	1.35	1.37	1.37	1.35
$S_{AuN90}$ (acum)	1.14	1.21	1.12	1.08	1.16	1.18	1.16	1.15	1.16

rattling signals are characterized by lower sharpness values than squeaking signals: this is due to the low frequency main components which characterize the investigated rattling signals. Thus, the proposed model also gives very good annoyance estimation for rattling noise inside vehicle cabins.

## 6 CONCLUSIONS

Squeaking and rattling noises produced inside a vehicle cabin were analysed by objective and subjective measurements. Psychoacoustic metrics such as loudness, sharpness, roughness and fluctuation strength were measured. A jury test was applied to the participants by a Semantic Differential method in order to evaluate noise signals in terms of annoyance and pleas-

antness. A limited set of signals were also evaluated by a Paired Comparison jury test. Single number indices were proposed by analysing the Paired Comparison results by a regressive analysis. The proposed indices show that annoyance and pleasantness due to squeaking and rattling noises inside vehicle cabins are mainly affected by loudness and sharpness metrics:

- annoyance due to a squeaking noise or a rattling noise increases with the loudness mean and the sharpness maximum value;
- pleasantness due to a squeaking noise decreases when the loudness mean and the loudness maximum value increase; it increases with the loudness standard deviation;
- pleasantness due to a rattling noise decreases

Table 10—Values of the psychoacoustic metrics (rattling noises, ref. number from 10 to 18).

Metrics	Rattling Noise (Ref. Number)								
	10	11	12	13	14	15	16	17	18
$N_{SM}$ (sone)	4.07	5.12	4.73	3.47	4.52	4.07	8.43	8.57	12.15
R (asper)	1.86	1.35	1.98	1.73	1.76	2.18	1.67	1.59	1.94
F (vacil)	2.12	1.96	1.98	1.73	1.76	1.94	1.67	1.59	1.94
$N_{max}$ (sone)	7.39	9.18	8.32	4.90	4.37	6.35	13.67	13.41	19.25
$N_{min}$ (sone)	2.35	2.36	2.53	2.62	2.47	2.67	2.32	2.43	2.50
$N_M$ (sone)	2.84	2.98	3.06	3.01	2.89	3.05	5.02	5.11	6.43
$N_\sigma$ (sone)	0.82	1.10	0.92	0.43	0.35	0.60	3.66	3.66	5.72
$N_5$ (sone)	3.50	3.84	3.71	3.52	3.38	3.62	13.12	12.58	18.21
$N_{10}$ (sone)	3.04	3.51	3.60	3.43	3.34	3.55	12.48	12.01	17.90
$N_{50}$ (sone)	2.61	2.65	2.80	2.88	2.80	2.89	2.80	2.83	2.88
$N_{90}$ (sone)	2.49	2.51	2.64	2.73	2.59	2.72	2.58	2.55	2.60
$N_{imax}$ (sone)	10.65	14.85	13.36	6.53	5.53	9.93	16.92	15.63	22.03
$N_{imin}$ (sone)	2.00	1.95	2.15	2.22	2.13	2.36	2.02	2.07	2.03
$N_{iM}$ (sone)	2.84	2.97	3.05	3.01	2.89	3.05	4.98	5.08	6.39
$N_{i\sigma}$ (sone)	1.01	1.40	1.11	0.53	0.45	0.73	3.70	3.72	5.78
$N_{110}$ (sone)	3.10	3.45	3.31	3.40	3.29	3.49	12.22	11.99	17.86
$N_{150}$ (sone)	2.63	2.67	2.81	2.89	2.80	2.87	2.89	2.89	2.96
$N_{190}$ (sone)	2.37	2.36	2.54	2.59	2.53	2.62	2.46	2.47	2.49
$S_{Zwmax}$ (acum)	1.62	1.86	1.47	1.48	1.50	1.50	1.69	1.96	1.95
$S_{Zwmin}$ (acum)	0.76	0.74	0.79	0.81	0.86	0.84	0.35	0.36	0.32
$S_{ZwM}$ (acum)	1.22	1.21	1.16	1.13	1.16	1.14	0.97	0.97	0.94
$S_{Zw\sigma}$ (acum)	0.13	0.14	0.12	0.10	0.10	0.11	0.32	0.32	0.35
$S_{ZwN10}$ (acum)	1.36	1.36	1.30	1.26	1.28	1.27	1.30	1.30	1.28
$S_{ZwN50}$ (acum)	1.23	1.22	1.16	1.12	1.16	1.15	1.12	1.11	1.11
$S_{ZwN90}$ (acum)	1.08	1.06	1.03	1.01	1.02	1.01	0.45	0.47	0.40
$S_{Aumax}$ (acum)	2.06	2.34	1.72	1.72	1.75	1.75	2.30	2.52	2.57
$S_{Aumin}$ (acum)	0.82	0.82	0.84	0.87	0.94	0.93	0.52	0.53	0.49
$S_{AuM}$ (acum)	1.39	1.38	1.32	1.29	1.32	1.31	1.15	1.15	1.13
$S_{Au\sigma}$ (acum)	0.15	0.17	0.14	0.12	0.13	0.13	0.33	0.33	0.35
$S_{AuN10}$ (acum)	1.55	1.56	1.50	1.45	1.47	1.47	1.50	1.48	1.48
$S_{AuN50}$ (acum)	1.39	1.38	1.33	1.28	1.32	1.31	1.27	1.26	1.26
$S_{AuN90}$ (acum)	1.22	1.20	1.17	1.14	1.15	1.14	0.63	0.65	0.60

when the loudness instantaneous mean and the sharpness maximum value increase; it increases when the loudness statistical value  $N_{10}$  increases. Thus, a rattling noise impulse may produce pleasantness.

The proposed indices 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:

- 0.980 for the “No annoyance” parameter for squeaking noises;
- 0.975 for the “Pleasantness” parameter for squeaking noises;
- 0.975 for the “No annoyance” parameter for rattling noises;

- 0.983 for the “Pleasantness” parameter for rattling noises;

Furthermore, the proposed models for psychoacoustic annoyance were compared to a well-known model proposed for synthetic and technical sounds. The comparison showed that the proposed models are correlated more to the obtained results than the bibliographic model for the investigated signals (squeaking and rattling noises inside vehicle cabins) because these signals are characterized by low sharpness values. Thus, the proposed relations may be used to accurately evaluate the squeaking or rattling noise impact upon car passengers by using loudness and sharpness metrics.

Table 11—Values of the psychoacoustic metrics (rattling noises, ref. number from 19 to 27).

Metrics	Rattling Noise (Ref. Number)								
	19	20	21	22	23	24	25	26	27
$N_{SM}$ (sone)	6.33	9.30	8.93	8.58	4.36	2.81	2.23	4.26	3.33
R (asper)	1.52	2.18	1.70	1.97	1.16	1.12	1.07	0.90	1.04
F (vacil)	1.52	2.18	1.70	1.97	1.05	1.12	1.07	0.90	1.04
$N_{max}$ (sone)	9.82	15.75	14.14	16.23	5.26	3.43	3.31	3.75	4.43
$N_{min}$ (sone)	2.43	2.39	2.48	2.37	1.46	1.65	1.45	1.58	1.62
$N_M$ (sone)	4.15	5.73	5.28	4.97	2.56	2.26	2.16	2.30	2.38
$N_\sigma$ (sone)	2.38	4.48	3.83	3.67	1.02	0.47	0.45	0.65	0.67
$N_5$ (sone)	9.21	15.34	13.21	11.78	4.42	3.01	2.85	3.30	3.68
$N_{10}$ (sone)	8.99	14.39	12.57	11.32	4.33	2.87	2.77	3.20	3.55
$N_{50}$ (sone)	2.81	2.99	2.87	2.86	2.16	2.07	1.99	2.00	2.10
$N_{90}$ (sone)	2.54	2.50	2.60	2.56	1.60	1.73	1.62	1.66	1.75
$N_{imax}$ (sone)	11.98	16.60	17.17	17.96	6.18	4.15	3.90	4.43	5.26
$N_{imin}$ (sone)	2.09	2.10	2.24	2.08	1.22	1.44	1.11	1.26	1.41
$N_{iM}$ (sone)	4.13	5.69	5.24	4.94	2.54	2.25	2.12	2.29	2.37
$N_{i\sigma}$ (sone)	2.43	4.50	3.88	3.74	1.03	0.50	0.48	0.66	0.70
$N_{i10}$ (sone)	8.90	14.20	12.47	11.09	4.19	2.92	2.79	3.23	3.46
$N_{i50}$ (sone)	2.85	3.06	2.92	2.92	2.14	2.11	1.99	2.07	2.13
$N_{i90}$ (sone)	2.46	2.45	2.52	2.44	1.54	1.70	1.59	1.59	1.71
$S_{Zwmax}$ (acum)	1.54	1.88	1.78	1.90	0.90	0.78	0.82	0.80	0.78
$S_{Zwmin}$ (acum)	0.43	0.34	0.34	0.36	0.33	0.38	0.41	0.37	0.37
$S_{ZwM}$ (acum)	1.02	0.95	0.97	0.99	0.57	0.59	0.61	0.58	0.58
$S_{Zw\sigma}$ (acum)	0.28	0.34	0.34	0.36	0.33	0.38	0.41	0.37	0.37
$S_{ZwN10}$ (acum)	1.30	1.29	1.29	1.30	0.73	0.69	0.71	0.72	0.69
$S_{ZwN50}$ (acum)	1.13	1.10	1.11	1.13	0.60	0.59	0.61	0.58	0.58
$S_{ZwN90}$ (acum)	0.54	0.41	0.47	0.48	0.40	0.47	0.49	0.43	0.45
$S_{Aumax}$ (acum)	1.91	2.54	2.39	2.43	0.93	0.81	0.85	0.82	0.79
$S_{Aumin}$ (acum)	0.60	0.52	0.51	0.52	0.38	0.42	0.44	0.42	0.41
$S_{AuM}$ (acum)	1.20	1.13	1.16	1.17	0.59	0.59	0.61	0.60	0.59
$S_{Au\sigma}$ (acum)	0.29	0.35	0.33	0.32	0.10	0.07	0.07	0.09	0.08
$S_{AuN10}$ (acum)	1.50	1.48	1.48	1.49	0.72	0.69	0.70	0.71	0.69
$S_{AuN50}$ (acum)	1.29	1.26	1.27	1.28	0.60	0.60	0.61	0.60	0.60
$S_{AuN90}$ (acum)	0.72	0.61	0.66	0.66	0.45	0.50	0.52	0.48	0.49

**APPENDIX: NOMENCLATURE**

*Symbol Description*

- $\Delta$ : Estimation Error
- F: Fluctuation Strength (vacil)
- $N_{iM}$ : Statistical instantaneous loudness mean (sone)
- $N_{imax}$ : Statistical instantaneous loudness maximum value (sone)
- $N_{imin}$ : Statistical instantaneous loudness minimum value (sone)
- $N_{i\sigma}$ : Statistical instantaneous loudness standard deviation (sone)
- $N_{i10}$ : 10 percentile statistical instantaneous loudness (sone)

- $N_{i50}$ : 50 percentile statistical instantaneous loudness (sone)
- $N_{i90}$ : 90 percentile statistical instantaneous loudness (sone)
- $N_M$ : Statistical loudness mean (sone)
- $N_{max}$ : Statistical loudness maximum value (sone)
- $N_{min}$ : Statistical loudness minimum value (sone)
- NoAn<sub>s</sub>: “No annoyance” for squeaking noises
- NoAn<sub>r</sub>: “No annoyance” for rattling noises
- $N_{SM}$ : Stationary loudness (sone)
- $N_\sigma$ : Statistical loudness standard deviation (sone)
- $N_5$ : 5 percentile statistical loudness (sone)
- $N_{10}$ : 10 percentile statistical loudness (sone)
- $N_{50}$ : 50 percentile statistical loudness (sone)
- $N_{90}$ : 90 percentile statistical loudness (sone)

Table 12—Semantic Differential jury test results (rattling noises).

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

PA: Psychoacoustic annoyance defined by Eqn. (3)

Table 13—Paired Comparison results for rattling noises.

No Annoyance		Pleasantness	
Rattling Noise Reference Number	JuryTest results	Rattling Noise Reference Number	JuryTest 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

- PI<sub>s</sub>: “Pleasantness” for squeaking noises
- PI<sub>r</sub>: “Pleasantness” for rattling noises
- R: Roughness (asper)
- S<sub>AuM</sub>: Aures statistical sharpness mean (acum)
- S<sub>AuMax</sub>: Aures statistical sharpness maximum value (acum)
- S<sub>AuMin</sub>: Aures statistical sharpness minimum value (acum)
- S<sub>Auσ</sub>: Aures statistical sharpness standard deviation (acum)
- S<sub>AuN10</sub>: 10 percentile Aures statistical sharpness (acum)
- S<sub>AuN50</sub>: 50 percentile Aures statistical sharpness (acum)
- S<sub>AuN90</sub>: 90 percentile Aures statistical sharpness (acum)
- S<sub>ZwM</sub>: Zwicker statistical sharpness mean (acum)
- S<sub>ZwMax</sub>: Zwicker statistical sharpness maximum value (acum)
- S<sub>ZwMin</sub>: Zwicker statistical sharpness minimum value (acum)
- S<sub>Zwσ</sub>: Zwicker statistical sharpness standard deviation (acum)
- S<sub>ZwN10</sub>: 10 percentile Zwicker statistical sharpness (acum)
- S<sub>ZwN50</sub>: 50 percentile Zwicker statistical sharpness (acum)
- S<sub>ZwN90</sub>: 90 percentile Zwicker statistical sharpness (acum)
- w<sub>FR</sub>: Coefficient describing the effect of F and R on PA
- w<sub>S</sub>: Coefficient describing the effect of S<sub>ZwM</sub> on PA

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Table 14—Comparison among the Paired Comparison results and the values given by the proposed relations.

No annoyance				Pleasantness			
Rattling Noise Ref. Number	Paired Comparison Jury test	Eqn. (6) values	$\Delta$	Rattling Noise Ref. Number	Paired Comparison Jury test	Eqn. (7) values	$\Delta$
9	0.78	0.76	0.02	7	0.30	0.29	0.01
11	0.72	0.70	0.02	8	0.46	0.44	0.02
16	0.54	0.56	-0.02	9	0.39	0.42	-0.03
17	0.53	0.53	0.00	10	0.57	0.55	0.02
18	0.17	0.17	0.00	11	0.50	0.47	0.03
20	0.35	0.38	-0.03	13	0.57	0.56	0.01
21	0.48	0.46	0.02	15	0.54	0.54	0.00
22	0.51	0.53	-0.02	22	0.58	0.55	0.03

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