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Validation of a Numerical Model for the Prediction of the Annoyance Condition at the Operator Station of Construction Machines

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Abstract: It is well-known that the reduction of noise levels is not strictly linked to the reduction of noise annoyance. Even earthmoving machine manufacturers are facing the problem of customer complaints concerning the noise quality of their machines with increasing frequency. Unfortunately, all the studies geared to the understanding of the relationship between multidimensional characteristics of noise signals and the auditory perception of annoyance require repeated sessions of jury listening tests, which are time-consuming. In this respect, an annoyance prediction model was developed for compact loaders to assess the annoyance sensation perceived by operators at their workplaces without repeating the full sound quality assessment but using objective parameters only. This paper aims at verifying the feasibility of the developed annoyance prediction model when applied to other kinds of earthmoving machines. For this purpose, an experimental investigation was performed on five earthmoving machines, different in type, dimension, and engine mechanical power, and the annoyance predicted by the numerical model was compared to the annoyance given by subjective listening tests. The results were evaluated by means of the squared value of the correlation coefficient, R^2, and they confirm the possible applicability of the model to other kinds of machines.

Keywords: annoyance; noise; numerical model; earthmoving machines; sound quality

1. Introduction

It has been proved that sound levels, sound pressure, or even sound power, although properly weighted, are not able to assess the annoyance that a sound may generate [1]. This is true especially for high sound pressure levels due both to the great difference between the A-weighting filter and the equal loudness contour curve at these levels [2] and to the necessity of using parameters that account for the time structure and the spectral variation of the signals, such as the psychoacoustics parameters. Unfortunately, almost all legislation still refers to overall A-weighted levels (L_{Aeq}, L_{WA}, L_{pA}) aimed at checking the compliance of the products.

For earthmoving machines, the Directive 2000/14/EC [3] imposes limitations on the A-weighted sound power levels emitted by the machine while the Directive 2006/42/EC [4] requires information on the airborne noise emissions, in terms of A-weighted sound pressure level at the workstation, C-weighted peak instantaneous sound pressure value at the workstation, and A-weighted sound power level emitted by the machine. As the reduction of the noise levels is not strictly linked to the reduction of the annoyance, manufacturers are facing the problem of customers' complaints concerning the noise quality of the machines with increasing frequency.

In the last ten years, great efforts have been made by the authors to better understand the relationship between the multidimensional characteristics of the noise signals at the operator station of compact loaders in different working conditions and the relevant auditory perception of annoyance [5]. Compact loaders, indeed, are critical as far as noise emission is concerned because the operator station is located just above the engine compartment, which cannot be completely insulated from the outside due to overheating problems. As a consequence, noise and vibration levels at the operator station are extremely high, causing uncomfortable conditions for workers.

Moreover, compact loaders are widely used in dwelling areas for the activities of building construction and renovation, and the study of the quality of their noise emissions may be valuable to reduce their environmental noise impact.

Results of these studies showed that loudness and sharpness are the parameters primarily related to the annoyance perception of these noise signals [6,7]. In particular, S_5 (fifth sharpness percentile) and N_{50} (fiftieth loudness percentile) were found to be closely related to the annoyance perception when the machines were operating in dynamic conditions. As to the different perception occurring with sounds having different loudness and/or sharpness values, subjective listening tests indicated that the minimum differences which are subjectively perceived (just noticeable differences, JND) for the loudness and sharpness of these machines are 0.8 sone and 0.04 acum, respectively. Results highlighted also that the loudness JND becomes greater as the overall sound pressure level of the signal increases, while the sharpness JND has very small variations related to the overall level [8].

All of these studies followed the "product sound quality" approach that, although very powerful in relating the physical characteristics of the noise to the auditory perception of annoyance, requires repeated sessions of jury listening tests, which are time-consuming [9–12]. In this respect, an annoyance prediction model could be extremely valuable to assess the annoyance sensation perceived by operators of earthmoving machines at their workplaces without repeating the full sound quality assessment but using prior knowledge of these machines.

This approach has already been applied to many other products [13–16] as well as to construction machines and some of their components [17].

The authors developed an annoyance prediction model able to evaluate the grade of annoyance at the workplace of compact loaders using objective parameters only [18]. The model was developed by multi-regression analysis based on a relevant database of binaural noise signals recorded at the operator position. Results confirmed a very good correlation between the annoyance values predicted by the model and the subjective ratings resulting from jury tests.

This paper aims at verifying the feasibility of the developed annoyance prediction model when applied to other kinds of earthmoving machines. The basic idea guiding this study is that all earthmoving machines (excavators, back-hoe loaders, dozers, etc.) have common dominant noise sources: the internal combustion engine, the engine cooling system, and the hydraulic components. Consequently, the noise signals in different working conditions should have the same temporal and spectral characteristics irrespective of the type of machine. Then, the relationship between physical/psychoacoustics descriptors and annoyance auditory perception elicited by the sound stimuli should be the same. If this is confirmed, the annoyance prediction model developed for the compact loaders could be applied to other kind of earthmoving machines.

The several experiments and analyses performed in order to validate this thesis are extensively reported in the following sections.

2. The Annoyance Prediction Model for Compact Loaders

The annoyance prediction model was developed starting from measurements on 41 compact loaders belonging to six families both in dynamic and stationary conditions in order to represent all possible operations of such machines [18].

When the machine was in a stationary idle condition, the binaural signals were recorded by means of a head and torso simulator placed in the operator station. When the machine was performing a simulated work cycle (charging and discharging gravel or loam from a stockpile to another), the binaural signals were recorded by means of a binaural headphone with miniature microphones placed at the entrance of the operator's ear canals [19].

A total amount of 62 binaural noise signals were then available. The following acoustic and psychoacoustic parameters were calculated for all these signals, using the Pulse Sound Quality software (version 10, type 7698, Bruel & Kjaer, Nærum, Denmark): overall sound pressure levels, percentile values of the sound pressure levels, overall and percentile values of loudness (N) and sharpness (S), overall values of roughness (R), and fluctuation strength (*Fl.St.*).

This huge amount of sound stimuli was divided into nine groups; for each of them, the subjective assessment of annoyance was obtained by means of subjective listening tests carried out according to the paired comparison procedure [20].

Multiple regression analysis was then used for developing the prediction model as this technique is the most commonly used for analyzing multiple dependence between variables [21,22]. Six groups of noise stimuli were used in the development phase, while the remaining three groups were used for validation purposes.

The set of predictor variables which led to the highest R^2 (squared value of the correlation coefficient between the subjective scores and the predicted values of annoyance) when applied to the six groups of sound stimuli was (Peak, N_{50}, S_5), i.e., the sound pressure Peak level, in dB, the fiftieth percentile of loudness in sone, N_{50}, and the fifth percentile of sharpness in acum, S_5.

The multiple regression equations obtained for the set of variables (Peak, N_{50}, S_5) for each group of sound stimuli are listed in Table 1.

Table 1. Results of the multiple regression analysis for the predictor variables (Peak, N_{50}, S_5).

Noise Groups	Multiple Regression Equation	R^2
Group 1	$Y_1 = -9.310 + 0.057$ Peak $+ 0.184\ N_{50} + 0.216\ S_5$	0.79
Group 2	$Y_2 = -5.512 + 0.039$ Peak $+ 0.296\ N_{50} - 3.703\ S_5$	0.99
Group 3	$Y_3 = -5.322 + 0.038$ Peak $+ 0.057\ N_{50} + 0.412\ S_5$	0.89
Group 4	$Y_4 = -18.214 + 0.061$ Peak $+ 0.018\ N_{50} + 9.628\ S_5$	1.00
Group 5	$Y_5 = -4.241 + 0.030$ Peak $+ 0.046\ N_{50} + 0.289\ S_5$	0.96
Group 6	$Y_6 = 6.971 - 0.012$ Peak $+ 0.312\ N_{50} - 11.350\ S_5$	0.89

For each noise group, this set of variables accounted for at least 89% of the variation in the subjective scores, with the only exception of Noise Group 1.

Each regression equation was finally applied to the other five groups, and the predicted annoyance values were calculated for each equation. The correlation between these predicted annoyance values and the subjective ratings was evaluated for each noise group: the better the correlation, the higher the R^2 value. In such a way, the best annoyance prediction model was identified as the one that gave the maximum sum of R^2 over all the noise groups except for the one from which that model was issued.

According to this criterion, the regression equation referred to the Noise Group 3 gave the best results, and it was chosen as the numerical prediction model able to assess noise annoyance at the workplace of compact loaders:

$$Y_3 = 5.322 + 0.038\ \text{Peak} + 0.057\ N_{50} + 0.412\ S_5 \tag{1}$$

where Y_3 indicates the predicted annoyance value.

The validation process performed on the remaining three groups of sound stimuli confirmed the reliability of this model as an alternative and simpler way for manufacturers and customers to assess the grade of annoyance at the workplace of any compact loader.

3. Experimental Investigation on Different Kinds of Earthmoving Machines

3.1. Binaural Recordings and Objective Characterizations

Five brand new earthmoving machines, different in type, manufacturer, dimension, and engine mechanical power, were selected for this test: two excavators, a back-hoe loader (used both during loader and excavator operations), a dozer, and a skid steer loader. All the binaural recordings were performed at the operator working station in an open area while the machine, in stationary idle conditions, had the engine running at one of the rotational speeds corresponding to a typical operation for that specific type of equipment. Table 2 reports the list of the machines and the codes used hereinafter for their identification and the rotational speed values during the noise recordings.

Table 2. Earthmoving machines involved in the investigation.

Machine Type	Identification Code	Rotational Speed (rpm)
Skid steer loader	A	2350
Dozer	B	2350
Excavator	C	2350
Back-hoe loader (operating as loader)	D	2700
Excavator	E	2450
Back-hoe loader (operating as excavator)	F	1600

All the binaural measurements were performed at the operator station using the Cortex System MK1 head and torso simulator (NCI, Neutrik Cortex Instruments GMBH, Regensburg, Germany). The recordings corresponding to the left and right ears were then analyzed separately, and the same physical and psychoacoustic parameters as in the previous studies were evaluated. Figure 1 shows the 1/3 octave band sound pressure spectra of the six sound stimuli recorded at the right ear of the dummy head. Similar spectra were also detected at the left ear.

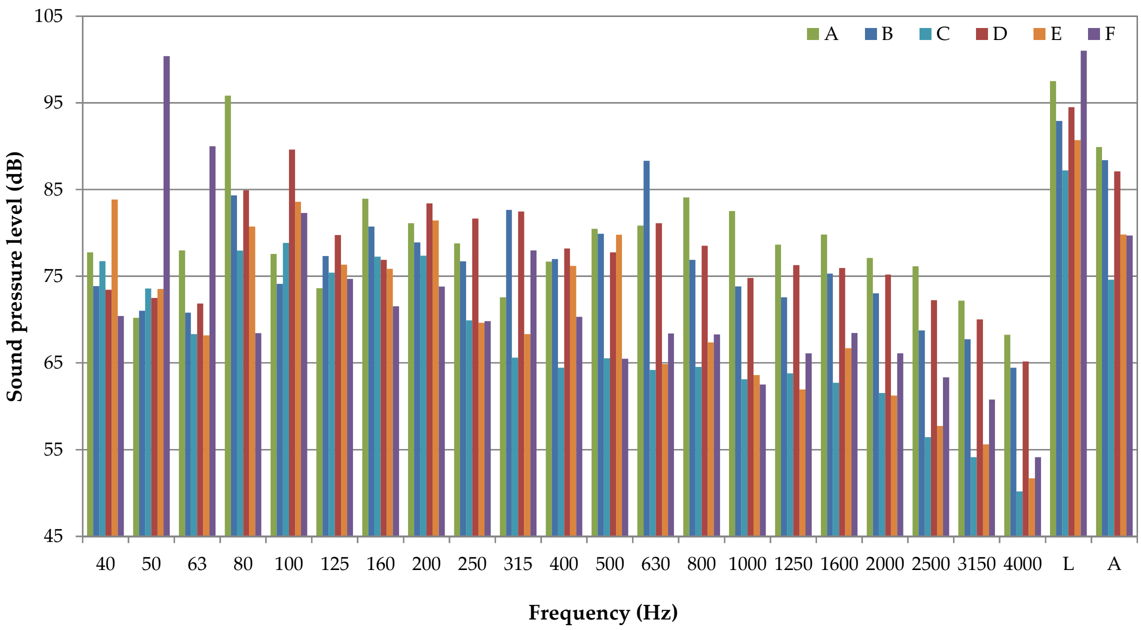


Figure 1. Sound pressure levels for all the six sound stimuli recorded at the right ear.

It is worth noting that all the noise signals except F have the first significant contribution at the engine firing frequency (80 Hz or 100 Hz depending on the rotational speed) and further significant noise contributions at higher frequencies. On the contrary, Signal F, which was recorded at 1600 rpm, still has the dominant contribution at the firing frequency (50 Hz), but this contribution is the only one responsible for the overall level. This noise spectrum feature is unusual for these kinds of machines, which generally have very similar frequency content due to the fact that most of the noise sources are the same [17,23,24].

Referring to the overall energy content of the signals, Signal F has the highest overall level, while A, D, B, E and C follow in decreasing order. Referring to the A-weighted overall level, A has the highest level and B, D, E, F and C follow in decreasing order.

Table 3 reports the most representative acoustic and psychoacoustic parameters for all the six sound stimuli.

Table 3. Acoustic and psychoacoustic parameters for the six sound stimuli.

Parameter		A	B	C	D	E	F
Peak (dB)	Left	106.0	103.0	100.0	105.0	101.0	106.0
	Right	107.0	104.0	98.2	106.0	101.0	107.0
L (dB)	Left	96.7	91.4	88.0	94.3	91.0	101.0
	Right	97.5	92.9	87.2	94.5	90.7	101.0
L_A (dB(A))	Left	89.1	84.9	76.2	86.3	78.3	79.9
	Right	89.9	88.4	74.6	87.1	79.8	79.7
N (sone)	Left	88.4	68.6	40.4	75.6	46.0	55.5
	Right	92.9	78.2	37.2	78.8	47.7	55.7
N_{50} (sone)	Left	88.8	68.9	40.6	76.0	45.9	56.0
	Right	93.4	78.6	37.3	79.2	47.8	56.0
S (acum)	Left	1.36	1.43	1.04	1.40	1.02	1.01
	Right	1.38	1.43	1.12	1.42	1.04	1.07
S_5 (acum)	Left	1.42	1.51	1.10	1.48	1.08	1.07
	Right	1.45	1.51	1.18	1.50	1.09	1.12
R (asper)	Left	1.63	1.34	1.78	1.40	1.53	1.55
	Right	1.40	1.59	1.49	1.43	1.26	1.63
$Fl.St.$ (vacil)	Left	0.30	0.32	0.29	0.29	0.31	0.32
	Right	0.31	0.27	0.29	0.28	0.27	0.30

3.2. Listening Tests and Subjective Annoyance Scores

The six binaural noise recordings were organized in pairs, and all pairs were arranged in a random sequence according to the digram-balanced Latin square design to avoid any sequence effect. In addition, each sequence included at least the repetition of the first pair of the sound stimuli for checking purposes.

Thirty-five normal-hearing subjects (28 males and 7 females) were involved in the listening test. Fifty-eight percent of the subjects were aged less than 29 years, with 32% less than 50 and only 10% over 50. The group included experts of earthmoving machines (i.e., design engineers), experts of subjective listening tests, and scientists in acoustics. No earthmoving machine operators were included. The noise stimuli were presented to the subjects in a quiet environment through high-quality electrostatic headphones with a flat response in the 40–40,000 Hz frequency range after being modified to account for the transfer function of the headphones used for playing back. Each listening session started with a learning phase, during which the experimenter provided the instructions needed to understand the correct procedure for the test. The subjects had to choose, within the pair, the stimulus they considered more annoying. The rating was given by each subject after listening to each pair of sound stimuli as many times as necessary in order to increase the concentration and reduce the probability of inconsistent responses.

According to a procedure defined in Kendall and Babington Smith [20], the consistency for each subject and the agreement among the subjects were evaluated in order to guarantee the control of the variance due to the emotional state of the judging individuals [25]. Three subjects (2 males and 1 female <29 years) did not satisfy these consistency tests, and their ratings were not used in the data analysis. The subjective responses were then arranged in matrices whose overall value is shown in Table 4.

Table 4. Overall matrix of the sound stimuli as to the subjective annoyance score (SAS).

Machine	A	B	C	D	E	F	Subjective Annoyance Score		
							Sum	Rank	%
A	-	22	32	24	31	21	130	1	81.3
B	10	-	32	10	31	12	95	4	59.4
C	0	0	-	0	5	0	5	6	3.1
D	8	22	32	-	31	13	106	3	66.3
E	1	1	27	1	-	0	30	5	18.8
F	11	20	32	19	32	-	114	2	71.3

The number reported in each cell represents how many times the sound indicated on the left hand side of the row was judged more annoying than that heading the correspondent column. The subjective annoyance score (SAS) of the sound stimuli is shown in the last three columns in terms of (1) the overall value for each sound stimulus, with respect to all the others (Sum); (2) the ranking of the subjective scores (Rank); (3) the percentage value (%) normalized to the maximum score (160) that each stimulus could have obtained.

On the basis of the subjective judgements, the noise stimulus of Machine C (excavator at 2350 rpm) turned out to be the less annoying signal, while the signal of Machine A (skid steer loader) the most annoying. This result is in full agreement with the results of previous studies that showed the relevance of the overall energy level and the energy content in the 400–5000 frequency range on the auditory perception of annoyance [7].

On the contrary, the subjective annoyance score obtained by Signal F (back-hoe loader operating as excavator at 1600 rpm) seems only to partially fit the previous results. This stimulus was ranked second as regards the annoyance score. As reported in Table 3, it has the highest Peak level but all the other acoustic and psychoacoustic descriptors are lower than those of B or D signals that were judged less annoying. Probably such a high subjective annoyance judgement could be due to two combining features: the very high overall energy content of this signal and the very high tonal component at low frequency (50 Hz) without any other significant noise component at higher frequency.

4. The Applicability of the Prediction Model to Different Kinds of Earthmoving Machines

In order to verify whether the annoyance prediction model is able to assess the annoyance conditions at the work position of any kind of earthmoving machines, all six regression equations reported in Table 1 (those originally used to develop the model for compact loaders) were considered. For each equation, Y represents the predicted annoyance value that must be calculated using the objective parameters of the six noise stimuli.

These equations were applied to the six sound stimuli recorded from the different kinds of earthmoving machines listed in Table 2. The calculation was repeated for the left and the right noise stimuli, separately. As similar results were found for both, only those of the right noise stimulus will be presented hereinafter.

Figure 2 shows the predicted values of annoyance plotted against the observed values (subjective scores) for each equation. The match of the data (predicted vs. subjectively judged) was assessed by means of the squared value of the correlation coefficient (R^2): the better the correlation, the higher the R^2 value.

At first glance, all these results seem to be a kind of "compromise solution" as the R^2 values are all lower than 0.8. However, a more careful analysis shows that all these numerical prediction models lead to an incorrect assessment of annoyance for Stimulus F. This signal was ranked second as to the annoyance score given by the subjects, while all numerical predictions lead to lower annoyance values.

It is worth emphasizing that the frequency content of this signal is very unusual for earthmoving machines, as it has an unbalanced weight between the noise contributions at low (combustion process at 50 Hz) and medium-high (hydraulic and engine cooling systems at 400–4000 Hz) frequencies. This peculiarity could suggest considering Stimulus F as an "outlier" and to exclude it from the data set.

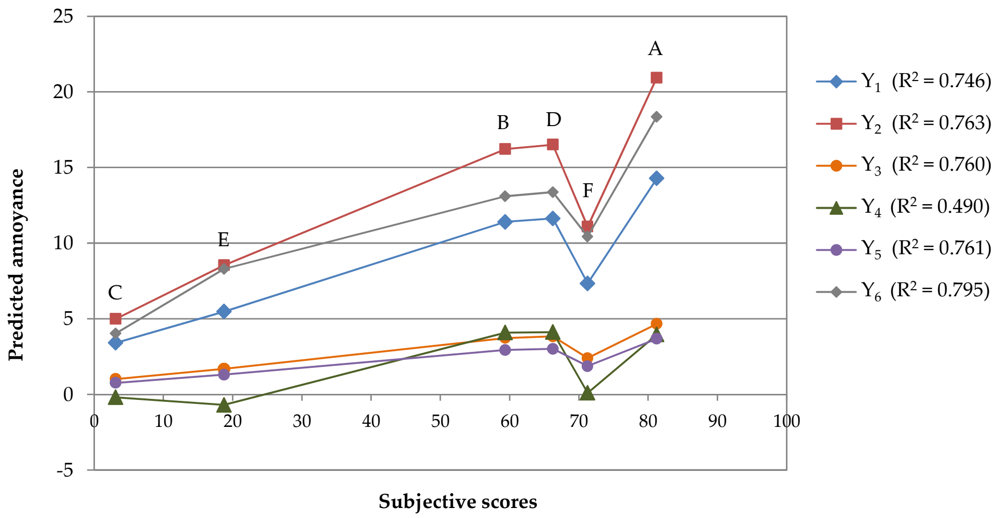
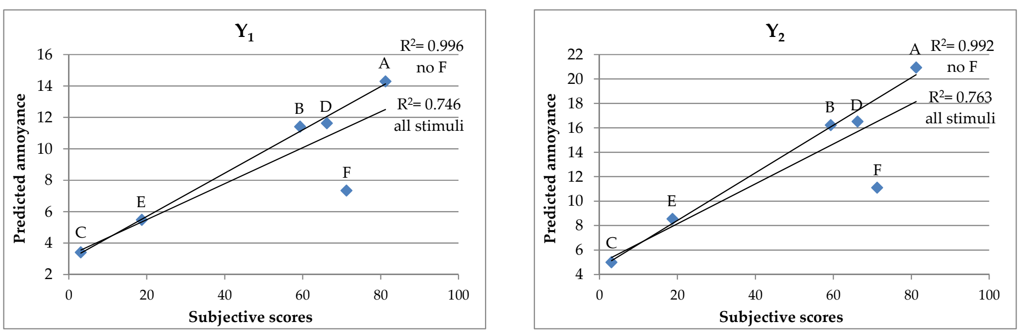


Figure 2. Comparison of the predicted and observed values of annoyance with different numerical regression models.

Figure 3 shows the regression curves and the R^2 values calculated with and without Stimulus F. This quantifies how good the relationship is between the annoyance calculated by means of a prediction model and that assessed by means of subjective evaluations. This is repeated for each of the equations in Table 1 (Y_1, Y_2, Y_3, Y_4, Y_5, Y_6).

Results show that all the regression equations lead to an R^2 value higher than 0.87 when the Signal F is not included in the data set. In particular, Y_3 and Y_5 both have very high values almost equal to 1 (R^2 = 0.997). On the basis of these considerations and results, it turns out that the annoyance prediction model developed for compact loaders (Y_3, see Equation (1)) offered a good assessment of noise annoyance at the workplace for other kinds of earth moving machines. Its validity should be further assessed with a larger number of machines.



(**a**) (**b**)

Figure 3. *Cont.*

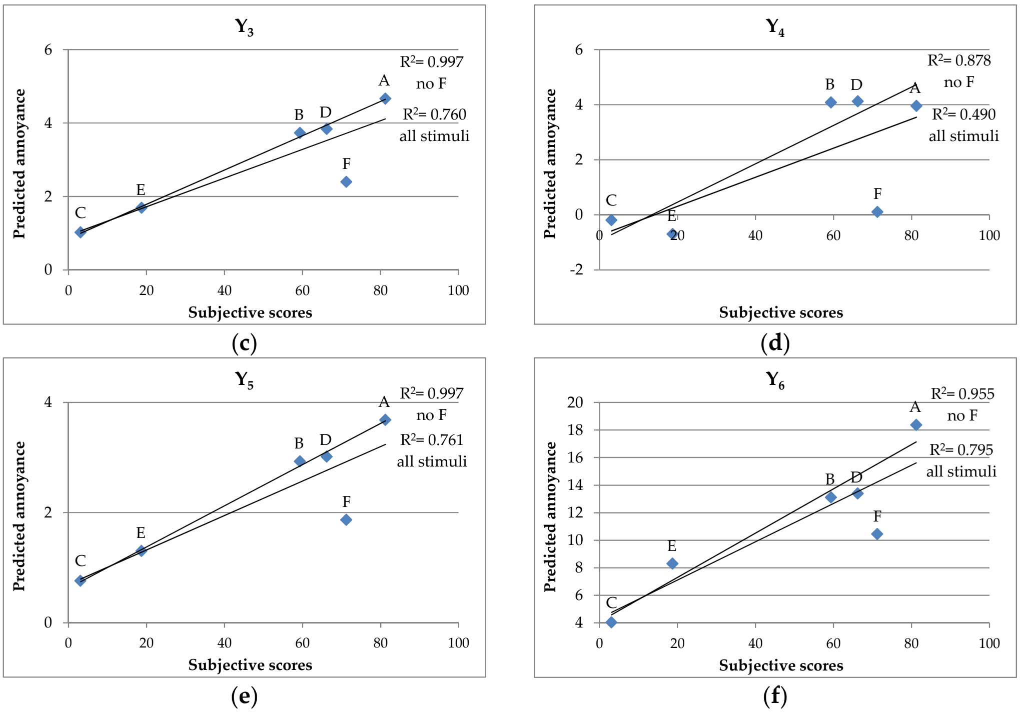


Figure 3. Comparison between the regressions obtained with and without Stimulus F, for each prediction model (**a**) Y_1; (**b**) Y_2; (**c**) Y_3; (**d**) Y_4; (**e**) Y_5; (**f**) Y_6.

Figure 4 shows a comparison between the annoyance values predicted by equation Y_3 and those obtained by subjective listening tests for all six stimuli. In order to make this comparison more understandable, the subjective annoyance values were previously normalized so that the predicted and the subjective results for the most annoying stimulus were the same. This graph shows that the prediction model leads to results in agreement with those obtained by subjective listening tests except for Stimulus F. In addition, the predicted annoyance values are slightly higher than the subjective ones. However, with the limitations due to the small number of machines under test, these results were considered satisfactory.

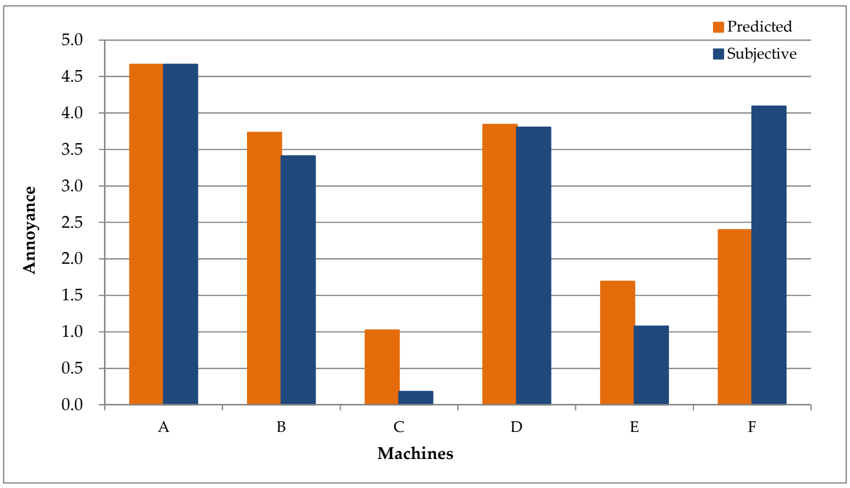


Figure 4. Comparison between the annoyance values predicted by Y_3 and those obtained by subjective listening tests.

5. Conclusions

This paper reports the results of a study aimed at verifying the feasibility of an annoyance prediction model developed for compact loaders when applied to other kinds of earth moving machines. For this purpose, six binaural noise signals were recorded at the workplace of five brand new earthmoving machines, different in type, manufacturer, dimension, and engine mechanical power: two excavators, a back-hoe loader (used both during loader and excavator operations), a dozer, and a skid steer loader.

The subjective annoyance scores of these noise stimuli were obtained by means of subjective listening tests performed according to the paired comparison procedure with more than 30 subjects. All the regression equations originally used to develop the model for compact loaders were then applied to these new binaural noise stimuli in order to obtain the annoyance predicted values. The match between the predicted annoyance and the subjective annoyance was finally assessed by means of the squared value of the correlation coefficient (R^2): the better the correlation, the higher the R^2 value.

Results showed that the regression equations led to quite low R^2 values (from 0.49 to 0.79). However, considering that Stimulus F has a frequency content very unusual for earth moving machines (a very high pick at low frequency and no significant contributions in the medium-high frequency range), it was considered as an "outlier" and excluded from the data set. This exclusion led to R^2 values higher than 0.87.

The regression equation chosen as numerical prediction model to assess noise annoyance at the workplace of compact loaders had the highest R^2 value (R^2 = 0.997). This model offered a good assessment of noise annoyance at the workplace and for other kinds of earth moving machines. It intrinsically reflected the main results of the sound quality approach although it was based on objective parameters only. Its validity should be further assessed with a larger number of machines.

Author Contributions: E.C. and F.P. conceived and designed the experiments; F.P. performed the experiments; E.C. and F.P. analyzed the data; E.C. and F.P. wrote the paper.

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