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Development and Validation of a Numerical Prediction Model to Estimate the Annoyance Condition at the Operation Station of Compact Loaders

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This paper describes the results of a study aimed at developing and validating a prediction model to assess the annoyance conditions at the operator station of compact loaders by using noise signal objective parameters only. For this purpose, binaural measurements were carried out on 41 compact loaders, both in stationary and real working conditions. The 62 binaural noise recordings were objectively analysed in terms of acoustic and psychoacoustic parameters and then divided into 9 groups and used in specific jury tests to obtain the subjective annoyance scores. Finally, multiple regression technique was applied to the first 6 groups of noise stimuli to develop the model while the remaining groups were used to validate it.

noise annoyance sound quality numerical models

1. INTRODUCTION

The aim of European policies concerning noise emission is that no person should be exposed to noise levels which endanger health and quality of life. For off-road machines, this approach involves the sound generated by the machine and transmitted either to the operator station or in the environment. Among the most relevant factors which can affect the safety of workers, noise is today a relevant issue. It may cause several problems resulting in a reduction in productivity or in an increase in accidents and it may cause severe physiological lesions such as a progressive loss of hearing.

It has by now been proved that the energy-oriented noise parameters, such as the *A*-weighted sound power or sound pressure levels, even if highly important to characterise the noise sources, are not adequate to describe the auditory perception of noise signals [1]. Unfortunately, they are still used by legislation to quantify the relevance of the problem. For this purpose the sound quality approach has become increasingly important and considerable research efforts have been made to describe the perceptual characteristics of sounds by means of jury tests and appropriate metrics [2, 3, 4].

As in many other fields of application, the construction machine industry is now orientated towards this approach [5]. Hence, results from studies that referred to the operator station of earth-moving machines during working conditions showed that Zwicker's loudness and sharpness are the parameters most related to the subjective perception of annoyance generated by these

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noise signals [6, 7]. This method, however, 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.

In this respect, an annoyance prediction model could be valuable in assessing the annoyance sensation perceived by operators of earth-moving machines at their working positions. The early phase of this study aimed at selecting the objective parameters to be included in the prediction model for compact loaders [8]. The first results confirmed the effectiveness of the approach based on multi-regression analyses and an annoyance prediction model was developed, even if the limited number of noise stimuli involved greatly reduced its applicability.

This paper describes the next steps of the study. The same statistical approach was applied to a significantly higher number of noise stimuli, binaurally recorded at the operator station of many families of compact loaders in different conditions. The relevant database of recorded stimuli and the high number of persons involved in jury tests allowed us to develop a model that could become an alternative and simpler way to assess the annoyance conditions at the workplace of any compact loader from objective measurements only.

2. DATABASE OF NOISE STIMULI

A sample of 41 compact loaders belonging to six families (A, B, C, D, E, F), differing in manufacturer, dimension and engine mechanical power, was involved in this experiment. All the noise acquisitions were recorded at the operation stations of the loaders, both in stationary and real working conditions to represent all the possible operations of such a machine. Measurements were carried out in the open areas generally used for testing earth-moving machines, where stockpiles of different materials could be found.

For the stationary conditions, binaural recordings were obtained using a dummy manikin (Cortex MK1; Cortex Instruments, Germany) placed at the operator station. During measurements, the tested machine was in stationary idle condition with the engine running at a fixed speed. This test involved five different loaders of the same family (F1–F5).

For the dynamic conditions, binaural recordings were obtained by means of two miniature pre-polarised condenser microphones placed at the entrance of the operator's ear canals (binaural microphones B&K 4101; Brüel & Kjær, Denmark) while the tested machine was performing the typical work cycle for loaders, which includes two main operations: the loading

stationary conditions

work cycle with loam

Figure 1. Binaural recordings.

of material from a stockpile and its discharge in a defined position. Twenty-one machines of five different families (A1–A5, B1–B5, C1–C5, D1–D3, E1–E3) repeated this work cycle with gravel and with loam. Fifteen other machines of three different families (A6–A10, B6–B10, C6–C10) performed the same work cycle without any material (simulated cycle).

In total, 62 different binaural noise signals were available for this study. Figure 1 shows the noise measurement setup both for stationary (left) and dynamic (right) conditions.

3. OBJECTIVE AND SUBJECTIVE CHARACTERISATION

The complete set of 62 binaural noise recordings was objectively analysed in terms of acoustic and psychoacoustic parameters. In addition, this set was divided into nine different groups as shown in Table 1. For each noise group a subjective assessment of annoyance was obtained with subjective listening tests carried out according to the paired comparison procedure.

3.1. Physical and Psychoacoustic Parameters

On the basis of the results of previous studies [3, 4], the following physical parameters were considered relevant for this investigation:

- overall sound pressure levels: L_{eq}, L_{Aeq}, L_{Ceq}, L_{Peak};
- overall psychoacoustic parameters: loudness N, sharpness S, roughness and fluctuation strength;
- percentile values of loudness and sharpness.

These parameters were estimated for the complete data set of noise stimuli for right and left channels separately. Then the stimulus with the highest Pearson correlation coefficient with respect to the subjective annoyance score was considered for subsequent analyses.

3.2. Listening Tests and Subjective Annoyance Scores

Eighty normal-hearing subjects (60 males and 20 females) aged 24–50 years were involved in the various listening tests. None of them were familiar with earth-moving machines but all had some knowledge in acoustics and some also had prior experience in listening tests. In addition, for each noise group, the number of subjects involved in the test was never lower than 15, with the only exception of the group 6 test which involved 9 subjects only. For each noise group, all pairs of stimuli were arranged in a random sequence according to the digram-balanced Latin square design to avoid any sequence effects. Each sequence included at least the repetition of the first pair of stimuli for checking purposes.

The noise stimuli were presented to the subjects in a quiet environment through high-quality electrostatic headphones with a flat response in the 40–40000 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. After listening to each pair of sound stimuli, the subjects were allowed to listen to the pair again as much as necessary to increase their concentration and reduce the probability of inconsistent responses. When ready to give their rating, the subjects had to choose from the pair the stimulus they considered more annoying. For each group, the preference matrices of all the test persons were analysed with respect to their consistence and agreement. Only the ratings given by the subjects satisfying the consistency tests (repeated pair and circular triads methods) were considered in the data analysis. The overall annoyance score for each stimulus was obtained by calculating the number of cases in which it was judged more annoying than all the others. Each value was normalised to the maximum score that the stimulus could have obtained. The overview of all the binaural noise stimuli belonging to each noise group and the percentage values of the subjective annoyance scores obtained for each of them are shown in Table 1.

TABLE 1. Groups of Noise Stimuli and Percentage Values of Subjective Annoyance Scores

Group 1: 10 binaural noise signals recorded from 5 loaders of family A during the working cycle with loam (L) and gravel (G)										Group 2: recordings from 5 loaders of family A during the simulated work cycle (S)				
$A1_L$	$A2_L$	$A3_L$	$A4_L$	$A5_L$	$A1_G$	$A2_G$	$A3_G$	$A4_G$	$A5_G$	$A6_S$	$A7_S$	$A8_S$	$A9_S$	$A10_S$
15.7	71.1	27.9	50.4	21.3	69.3	48.6	50.5	94.6	50.5	66.7	51.7	15.8	27.5	88.3
Group 3: 10 binaural noise signals recorded from 5 loaders of family B during the working cycle with loam (L) and gravel (G)										Group 4: recordings from 5 loaders of family B during the simulated work cycle (S)				
$B1_L$	$B2_L$	$B3_L$	$B4_L$	$B5_L$	$B1_G$	$B2_G$	$B3_G$	$B4_G$	$B5_G$	$B6_S$	$B7_S$	$B8_S$	$B9_S$	$B10_S$
18.5	18.5	57.0	47.9	13.7	75.9	64.7	86.3	65.4	52.1	55.0	30.0	70.0	65.8	29.2
Group 5: 10 binaural noise signals recorded from 5 loaders of family C during the working cycle with loam (L) and gravel (G)										Group 6: recordings from 5 loaders of family C during the simulated work cycle				
$C1_L$	$C2_L$	$C3_L$	$C4_L$	$C5_L$	$C1_G$	$C2_G$	$C3_G$	$C4_G$	$C5_G$	$C6_S$	$C7_S$	$C8_S$	$C9_S$	$C10_S$
12.1	26.0	50.0	25.5	44.4	83.4	60.0	68.4	63.9	66.2	33.3	55.8	88.3	36.7	35.8

Group 7: 6 binaural signals from 3 loaders of family D during the work cycle with gravel (G) and loam (L)						Group 8: 6 binaural signals from 3 loaders of family E during the work cycle with gravel (G) and loam (L)						Group 9: 5 binaural signals from 5 loaders of family F recorded in stationary conditions				
$D1_G$	$D2_G$	$D3_G$	$D1_L$	$D2_L$	$D3_L$	$E1_G$	$E2_G$	$E3_G$	$E1_L$	$E2_L$	$E3_L$	$F1$	$F2$	$F3$	$F4$	$F5$
43.2	77.9	98.9	18.9	22.1	38.9	35.6	77.8	93.3	6.7	46.7	40.0	77.9	76.5	70.6	2.9	22.1

4. MULTIPLE REGRESSION ANALYSIS

The first six groups of noise stimuli were used to develop the annoyance prediction model while the last three were kept aside to validate it.

To reach the proposed target, multiple regression analysis was chosen as this technique is the most commonly used for analysing multiple dependence between variables and also because the theory is well developed [9].

In this case study, the stepwise selection method was firstly applied to each group of noise stimuli to identify the smallest set of independent variables which explained the variation in the subjective annoyance scores best. In this respect, the score from subjective listening tests was entered as a dependent variable and all the objective parameters, considered to be relevant for this investigation, were used as independent variables. The results obtained for the six groups are shown in Table 2.

TABLE 2. Results of the *Stepwise* Selection Method Applied to the 6 Noise Groups

Noise Group	Predictor Variables	R^2	Adjusted R^2
1	N	.63	.58
2	S_{90}, $Peak$, N_{50}	1.00	1.00
3	N_{10}, $Peak$	.95	.94
4	$Peak$, S_5	1.00	1.00
5	N_{10}, $Peak$, N_{50}	.95	.93
6	N_{95}, S_{95}	1.00	1.00

In this table, the parameter R^2 is the square value of the correlation coefficient between the subjective scores and the predicted values of the annoyance. It quantifies the suitability of the fit of the model and shows the proportion of variation in the subjective scores, which is explained by the set of the identified parameters. In addition, the adjusted R^2 values were calculated to give a useful measure of the success of the prediction when applied to the real world. They take into account the number of variables and the number of observations. It can be seen that for each noise group the variables selected with the stepwise method account for over 93% of the variation in the subjective scores, with the exception of group 1. In addition, the set of the physical parameters which represent loudness, sharpness and peak level are very often included in the model, independently from the specific noise ensemble. On the other hand, all parameters which reflect the same quantity such as N, N_{10}, N_{50} and N_{95} for loudness, or S_5, S_{90} and

S_{95} for sharpness are strongly correlated among one another.

Consequently, to identify a common set of predictor variables for each of the six noise groups, further analyses were carried out by substituting some of the parameters shown in Table 2 with others reflecting the same acoustic features. The multiple regression analysis was then repeated on the six groups with the *Enter* variable selection method, i.e., forcing the choice of the set of predictor variables among (*Peak*, *N*, S_5), (*Peak*, *N*, S_{90}), (*Peak*, *N*, S_{95}), (*Peak*, N_{10}, S_5), etc.

The set of predictor variables which led to the highest adjusted R^2 values for the correlation between predicted and observed annoyance scores was the same as previously in the early phase of this study, i.e., (*Peak*, N_{50}, S_5). The multiple regression equations for this set of parameters are shown in Table 3.

It can be seen that for each noise group this set of variables accounts for at least 83% of the variation in the subjective scores, with the exception of noise groups 1 and 6. For the latter group, it is worth noting that the big difference between R^2 and adjusted R^2 values is due to the limited number of subjects involved in this test.

These results, which might be referred to as compromise solutions, are only slightly worse than the best solutions obtained following the stepwise variable selection method.

5. ANNOYANCE PREDICTION MODEL

To identify the best annoyance model among the regression equations obtained for the six different noise groups, and listed in Table 3, each regression equation was applied to all the other five groups and for each equation predicted annoyance values were calculated. Then the correlation between these predicted annoyance values and the observed subjective ratings was evaluated for each noise group: the better the correlation, the higher the R^2 value. In that way the best annoyance prediction model was 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 group 3 was the best and was chosen as the prediction model to assess the noise annoyance at the workplace of compact loaders:

$$PA = -5.322 + 0.038 \cdot Peak + 0.057 \cdot N_{50} + 0.412 \cdot S_5, \quad (1)$$

where *PA*—predicted annoyance.

6. VALIDATION OF THE MODEL

To verify whether this prediction model is applicable to noise signals other than those from which the equation was derived, noise groups 7, 8 and 9 were then analysed.

Referring to noise signals of groups 7 and 8, Equation 1 gave predicted annoyance values that were significantly correlated with the subjective scores (correlation coefficients .95 and .96). Referring to group 9, it included noise signals recorded in stationary conditions and then with characteristics significantly different from those recorded in working conditions. These signals had sound pressure levels and loudness values higher than those of all the other signals,

TABLE 3. Results of the *Enter* Selection Method Applied to the 6 Noise Groups

Predictor Variables	Noise Group	Multiple Regression Equation	R^2	Adjusted R^2
Peak, N_{50}, S_5	1	$Y = -9.310 + 0.057 \cdot Peak + 0.184 \cdot N_{50} + 0.216 \cdot S_5$	.79	.69
	2	$Y = -5.512 + 0.039 \cdot Peak + 0.296 \cdot N_{50} - 3.703 \cdot S_5$	.99	.97
	3	$Y = -5.322 + 0.038 \cdot Peak + 0.057 \cdot N_{50} + 0.412 \cdot S_5$	.89	.83
	4	$Y = -18.214 + 0.061 \cdot Peak + 0.018 \cdot N_{50} + 9.628 \cdot S_5$	1.00	1.00
	5	$Y = -4.241 + 0.030 \cdot Peak + 0.046 \cdot N_{50} + 0.289 \cdot S_5$	.96	.94
	6	$Y = 6.971 - 0.012 \cdot Peak + 0.312 \cdot N_{50} - 11.350 \cdot S_5$	.89	.55

~20 dB and 70 sone, respectively. Despite these differences, also this group showed quite good correlation (r = .85 corresponding to a significance level of 5.6%).

However, considering that subjective listening tests were performed on each group separately, the annoyance scores could not be compared among different groups. In this respect, a further validation was deemed necessary. Consequently, new subjective listening tests involving all the sound stimuli referred to a certain family of compact loaders (independently of the operating condition of the machine) were carried out; Table 4 reports the subjective annoyance scores obtained with these tests.

To confirm the validation of the annoyance prediction model reported in Equation 1, the predicted values were plotted against the observed values (Figure 2). The correlation between the two sets of annoyance values was still very good.

7. CONCLUSIONS

The results showed that regression analysis was a powerful approach for developing a model which could be used to objectively assess the grade of annoyance caused by noise signals at the operator station of compact loaders.

This model was built on the basis of a relevant database of noise recordings and jury tests results. It includes objective variables (*Peak*, N_{50} and S_5) and regression coefficients that best explain the variations in the subjective annoyance scores in all the noise groups used in the developing process.

The validation procedure, which involved groups of noise signals different from those used to build the model, highlighted a very good correlation between the predicted annoyance values and the subjective ratings resulting from jury tests.

In conclusion, this model could provide a real possibility for evaluating the grade of annoyance at the workplace of all types of compact loaders by using only objective parameters, with the primary advantage of avoiding time-consuming listening tests.

TABLE 4. Subjective Annoyance Scores (Percentage Values) for Tests on Loaders of Family A, B, and C

Group A: 15 binaural noise signals recorded from 10 loaders of family A during the simulated work cycle (S) and during the working cycle with loam (L) and gravel (G)

$A1_L$	$A2_L$	$A3_L$	$A4_L$	$A5_L$	$A1_G$	$A2_G$	$A3_G$	$A4_G$	$A5_G$	$A6_S$	$A7_S$	$A8_S$	$A9_S$	$A10_S$
15.7	64.9	26.6	46.5	20.7	85.0	66.7	68.4	99.2	68.4	54.3	39.3	3.5	15.1	75.9

Group B: 15 binaural noise signals recorded from 10 loaders of family B during the simulated work cycle (S) and during the working cycle with loam (L) and gravel (G)

$B1_L$	$B2_L$	$B3_L$	$B4_L$	$B5_L$	$B1_G$	$B2_G$	$B3_G$	$B4_G$	$B5_G$	$B6_S$	$B7_S$	$B8_S$	$B9_S$	$B10_S$
34.4	34.4	72.5	63.5	29.6	84.5	73.4	94.8	74.1	60.9	29.7	9.0	42.2	38.7	8.3

Group C: 15 binaural noise signals recorded from 10 loaders of family C during the simulated work cycle (S) and during the working cycle with loam (L) and gravel (G)

$C1_L$	$C2_L$	$C3_L$	$C4_L$	$C5_L$	$C1_G$	$C2_G$	$C3_G$	$C4_G$	$C5_G$	$C6_S$	$C7_S$	$C8_S$	$C9_S$	$C10_S$
30.2	45.0	70.6	44.4	64.7	89.6	64.6	73.5	68.8	71.1	13.6	29.6	52.9	16.0	15.4

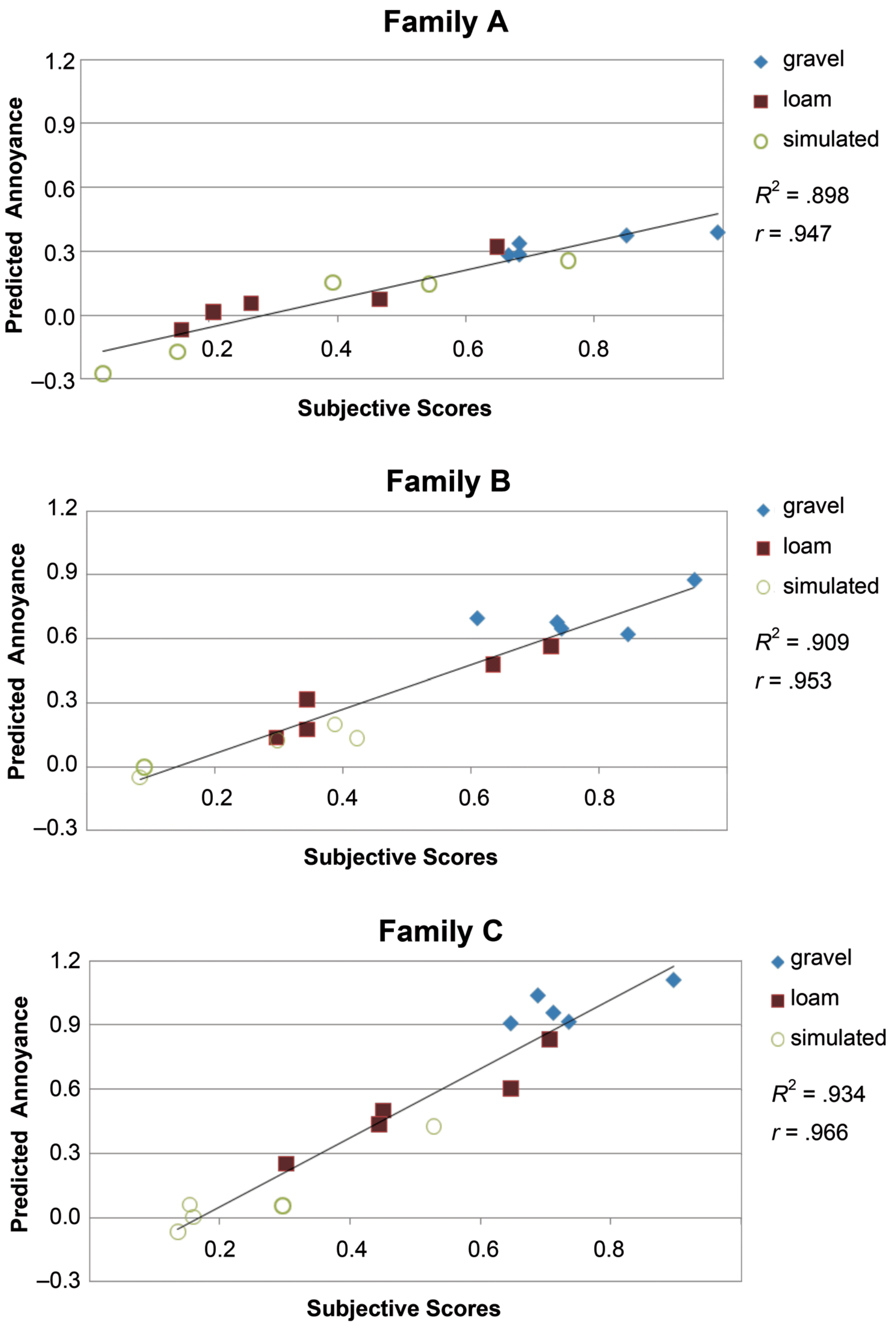

Figure 2. Comparison of predicted and observed values of annoyance.

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