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Subjective Response to Sonic Booms Having Different Shapes, Rise Times, and Durations

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SUBJECTIVE RESPONSE TO SONIC BOOMS

HAVING DIFFERENT SHAPES, RISE TIMES, AND DURATIONS

David A. McCurdy

SUMMARY

Two laboratory experiments were conducted to quantify the subjective response of people to simulated outdoor sonic booms having different pressure signatures. The specific objectives of the experiments were (1) to compare subjective response to sonic booms when described in terms of "loudness" and "annoyance;" (2) to determine the ability of various noise metrics to predict subjective response to sonic booms; (3) to determine the effects on subjective response of rise time, duration, and level; and (4) to compare the subjective response to "N-wave" sonic boom signatures with the subjective response to "minimized" sonic boom signatures. The experiments were conducted in a computer-controlled, man-rated sonic boom simulator capable of reproducing user-specified pressure signatures for a wide range of sonic boom parameters. One hundred and fifty sonic booms; representing different combinations of two wave shapes, four rise times, seven durations, and three peak overpressures; were presented to 36 test subjects in each experiment. The test subjects in the first experiment made judgments of "loudness" while the test subjects in the second experiment judged "annoyance."

Subjective response to sonic booms was the same whether expressed in terms of loudness or in terms of annoyance. Analyses of several different noise metrics indicated that A-weighted sound exposure level (L_{AE}) and Perceived Level (PL) were the best predictors of subjective response. Further analyses indicated that, of these two noise metrics, only Perceived Level completely accounted for the effects of wave shape, rise time, and peak overpressure. Neither metric fully accounted for the effect of duration. However, the magnitude of the duration effect was small over the very wide range of durations considered.

INTRODUCTION

The proposed development of a second-generation supersonic transport has resulted in increased research efforts to provide an environmentally acceptable aircraft. One of the enviromental issues is the impact of sonic booms on people. Aircraft designers are attempting to design the transport to produce sonic boom signatures that will have minimum impact on the public.

Current supersonic commercial aircraft produce a "N-wave" sonic boom pressure signature that is considered unacceptable by the public. This has resulted in first-generation supersonic transports being banned from flying supersonically over land in the United States, a severe economic constraint. By tailoring aircraft volume and lift distributions, designers hope to produce sonic boom signatures having specific shapes other than "N-wave" that may be more acceptable to the public and could possibly permit overland supersonic flight.

In support of the efforts to develop an acceptable supersonic transport, the Langley Research Center has initiated a research program to study people's subjective response to sonic booms. To aid in this study, a sonic boom simulator was developed so that individuals could be exposed to user-specified sonic boom signatures in a controlled laboratory environment. This allows the effects on subjective response of different sonic boom parameters (e.g. rise time, duration, peak overpressure) and shapes to be determined.

The sonic boom simulator has been used to conduct a series of experiments examining an increasingly complex variety of sonic boom signatures. This paper presents the results of two of the early studies that were conducted to examine the effects of basic sonic boom parameters on subjective response and to confirm the operational status of the simulator. In the first experiment, test subjects judged the "loudness" of the simulated outdoor sonic boom test simuli. Test subjects in the second experiment judged the "annoyance" of the same sonic boom test stimuli. The specific objectives of the experiments were: (1) to compare subjective response to sonic booms when described in terms of "loudness" and "annoyance;" (2) to determine the ability of various noise metrics to predict subjective response to sonic booms; (3)

to determine the effects on subjective response of rise time, duration, and level; and (4) to compare the subjective response to "N-wave" sonic boom signatures with the subjective response to "minimized" sonic boom signatures.

SYMBOLS AND ABBREVIATIONS

d	sonic boom duration, msec
L_{AE}	A-weighted sound exposure level, dB
L_{CE}	C-weighted sound exposure level, dB
L_{linE}	unweighted sound exposure level, dB
$L_{SA(A)}$	subjective annoyance level, dB, based on transformation of mean annoyance judgments using L_{AE}
$L_{SA(PL)}$	subjective annoyance level, dB, based on transformation of mean annoyance judgments using PL
$L_{SL(A)}$	subjective loudness level, dB, based on transformation of mean loudness judgments using L_{AE}
$L_{SL(PL)}$	subjective loudness level, dB, based on transformation of mean loudness judgments using PL
p_{max}	peak overpressure, psf
PL	perceived level (Stevens Mark VII procedure), dB
rt	rise time, msec

EXPERIMENTAL METHOD

Test Facility

The Sonic Boom Simulator in the NASA Langley Acoustics Research Laboratory (fig. 1) was used as the test facility in the experiments. The simulator is an airtight booth with concrete block walls, concrete ceiling and floor, and an acoustic door with edge seals. To reduce the effects of acoustic resonances, the floor is carpeted and the walls are covered with 4-inch-thick acoustical foam. The resulting interior dimensions of 4.66 ft high, 2.82 ft deep, and 2.85 ft wide yield a usable volume of 37.5 ft^3. One side wall contains a 16-inch-wide by 8-inch-high window made of 1-inch-thick plexiglass. The door contains eight loudspeakers, four 15-inch low-frequency units and four 7-inch high-frequency units. A perforated metal screen protects the front of the loudspeakers from possible damage.

The input signal to the loudspeakers originates from a computer-driven, 16-bit, digital-to-analog converter and is then low-pass filtered to remove the digitizing frequency. A crossover network set at 420 Hz separates the low- and high-frequency components of the signal for input to the appropiate loudspeakers via DC-coupled power amplifiers. The non-uniform frequency response inherent to the simulator due to the complex interaction between the loudspeakers and the enclosed volume of air was overcome by the use of a pre-distortion scheme during the computer generation of the signal. In other words, the desired sonic boom signal was pre-distorted by the computer to correct for the non-uniformities in the transfer function between the computer and a microphone placed in the booth.

References 1 and 2 provide a more detailed description of the sonic boom simulator and the time domain equalization filter used to pre-distort the sonic boom signal.

Test Subjects

Seventy-two subjects, thirty-six for each experiment, were randomly selected from a pool of local residents with a wide range of socioeconomic backgrounds, and were paid to participate in the experiments. All test subjects were given audiograms prior to the experiment to verify normal hearing. Table I gives the sex and age data for the subjects in each experiment.

Noise Stimuli

The noise stimuli used in both experiments consisted of computer-generated, loudspeaker-reproduced simulations of outdoor sonic booms. In each experiment, 48 sonic boom signatures were presented to the test subjects at three nominal peak overpressures of 0.6, 1.2, and 1.6 psf. Six additional presentations of a reference sonic boom signature were included, for a total of 150 noise stimuli. The 48 sonic boom signatures consisted of 28 "N-wave" shapes and 20 "minimized" shapes.

N-wave sonic booms.- The 28 N-wave shapes represented the factorial combinations of four rise times and seven overall durations. The rise times were 1, 2, 4, and 8 msec. The overall durations were 25, 50, 125, 200, 275, 350, and 425 msec. (Due to an error in a computer file defining the sonic boom stimuli, the shape representing the combination of a 2 msec rise time and an overall duration of 275 msec was defined with a rise time of 1 msec. Hence, the 1-msec rise time and 275-msec overall duration combination was repeated and the 2-msec rise time and 275-msec overall duration combination was omitted during the actual experiments.) Figure 2 illustrates the four combinations of 1- and 8-msec rise times with 25- and 425-msec overall durations.

Minimized sonic booms.- The 20 minimized shapes represented the factorial combinations of four initial rise times and five overall durations. The rise times were 1, 2, 4, and 8 msec. The overall durations were 125, 200, 275, 350, and 425 msec. Figure 3 illustrates the four combinations of 1- and 8-msec rise times with 125- and 425-msec overall durations. For all the minimized shapes, the secondary rise time was 20 msec and the ratio of the front-shock overpressure to the peak overpressure was 0.6.

Reference sonic booms.- In addition to the presentations made at three peak overpressures as part of the set of N-waves, the 1-msec rise time and 275-msec duration sonic boom was also presented at six additional levels of 0.2, 0.4, 0.9, 1.4, 1.9, and 2.2 psf. These six additional presentations resulted in that sonic boom being presented a total of nine times to the test subjects. These nine stimuli were to be used as reference stimuli in the analyses to convert subjective responses to subjective decibel levels.

Experiment Design

Numerical catagory scaling was chosen as the psychophysical method for both experiments. The scale selected was a unipolar, 11-point scale from 0 to 10. In the first experiment, the end points of the scale were labeled "NOT LOUD AT ALL" and "EXTREMELY LOUD." In the second experiment, the end points were labeled "NOT ANNOYING AT ALL" and "EXTREMELY ANNOYING." The terms "LOUD" or "ANNOYING" were not defined for the test subjects in the written instructions or verbally by the test conductor.

For each experiment, every test subject listened to every stimulus. The stimuli were divided into three subsets of 50 stimuli each. The stimuli were divided between subsets so that each wave shape, rise time, duration, and peak overpressure was about equally represented in each subset. The order of the stimuli in each subset was then randomly selected. A second set of subsets was formed by reversing the order of stimuli in each of the first three subsets. The orders for each subset are given in table II. The test subjects had 5 seconds after each stimulus to make and record their judgments. Each subset lasted approximately 5 minutes. In each experiment, the first three subsets were presented to one-half of the 36 test subjects and the second three subsets were presented to the other half of the subjects. To prevent subject fatigue and other temporal effects from unduly influencing the results, the order in which the subsets were presented was varied to provide a balanced presentation. Table III gives the order of presentation of the subsets used in both experiments.

Procedure

Upon arrival at the laboratory, each group of four subjects was seated in a conference room and given instruction sheets, consent forms, practice rating sheets, and rating sheets. Copies of these items for the loudness experiment are given in the appendix. The forms were the same for the annoyance experiment, except that the word "loud" was changed to "annoying." After reading the instructions and completing the consent form, the subjects were asked if they had any questions. After answering questions, the test conductor escorted the first test subject to the test facility. While each test subject was at the test facility, the other three test subjects remained in the conference room. Test subjects were instructed not to discuss the test, the stimuli, or their judgments with other test subjects during the test.

Before the first session, each test subject heard four familiarization stimuli while standing outside the facility with the door open. Then the test subject was seated in the facility with the door closed. Six practice stimuli were presented to the subject. In order for the subject to gain experience in scoring the sounds, the subject was instructed to make and record judgments of the practice stimuli. After the practice session, the test conductor opened the door, collected the practice rating sheet, answered any additional questions, issued the rating sheet for the first half of the session, closed the door, and exited the room in which the facility was located. Then the first session began.

After the first 25 test stimuli, the test conducter re-entered the room, opened the door, collected the first rating sheet and issued a new rating sheet for the second half of the session. After completing the last 25 stimuli in the session, the test subject exited the facility and returned to the conference room to wait until his or her next session. The test subjects were rotated in this fashion until each subject had completed three sessions.

RESULTS AND DISCUSSION

Acoustic Data Analyses

A special low-frequency microphone with frequency response down to 0.10 Hz was used to obtain analog measurements of the test stimuli pressure signatures produced in the sonic boom simulator. The measurements were made with the simulator empty (i.e., no test subject and no chair) and the microphone located at approximately ear level for a seated subject. An analog to digital conversion of the measurements was then performed and the digital information was used to calculate sound levels in terms of several noise metrics.

The noise metrics considered were L_{linE}, L_{AE}, L_{CE}, and PL. L_{linE} is simply the unweighted sound exposure level, which makes no attempt to account for the frequency response characteristics of the ear. L_{AE} and L_{CE} are based on simple frequency weightings. L_{AE} is often used to assess airport community noise, while L_{CE} is often used to evaluate impulse noise sources such as piledrivers and artillery, which produce noise similar in character to sonic booms. PL is a measure of loudness that is based on more complex level-dependent frequency weightings. Peak overpressure, a traditional measure of sonic boom strength, is also included with the noise metrics in some of the analyses for comparison purposes. The calculation method used to obtain the noise metrics from the digital pressure signatures is described in reference 3. Detailed descriptions of the noise metrics can be found in reference 4.

Subjective Data Analyses

The means (across subjects) of the judgments were calculated for each stimulus in each experiment. As discussed later in this paper, these mean scores were used to assess the ability of the noise metrics to predict subjective response. In order to eliminate the rating scale curvature inherent in numercial catagory scaling and obtain a subjective scale with meaningful units of measure for use in further analyses, the mean scores were next converted to subjective loudness levels and subjective annoyance levels having decibel-like properties. The experiments were designed so that the conversions could be made using the nine reference stimuli included in the experiments for that purpose. Unfortunately, the range of subjective responses to the nine reference stimuli did not span the entire range of subjective responses to the other stimuli. Therefore, it was necessary to base the conversion in each experiment on the entire set of 150 stimuli. Also because of this problem, it was decided to calculate a separate set of subjective levels for each noise metric considered in the additional analyses (i.e., L_{AE} and PL as determined later in this report).

Third-order polynomial regression analyses were performed separately for L_{AE} and PL for each experiment on data obtained for all 150 stimuli. The dependent variable was the calculated L_{AE} or PNL, and the independent variable was the mean score for each of the stimuli in each experiment. Figures 4 and 5 present the two sets of data and the best-fit curves for each of the experiments, respectfully. The regression equations for each of the two noise metrics were then used to predict the level of a generalized sonic boom that would produce the same mean score as each of the other sonic boom stimuli in the separate experiments. These levels were then considered as the subjective loudness levels ,$L_{SL(A)}$ and $L_{SL(PL)}$, and the subjective annoyance levels, $L_{SA(A)}$ and $L_{SA(PL)}$, for each stimulus.

It is interesting to note that the four regression curves in figures 4 and 5 are nearly identical to each other. They are also nearly identical to regression curves based on the nine reference stimuli originally intended for use in the conversions. This similarity tends to validate the conversion methodology and supports some of the following results.

Comparison of Subjective Descriptors

Figure 6 shows the mean annoyance scores from the second experiment plotted against the mean loudness scores from the first experiment and the resulting first-order regression line. Although the regression intercept and slope are slightly different from 0 and 1, respectively, the agreement between the two sets of means is excellent, as indicated by a 0.99068 correlation coefficient. Examination of the residuals found no consistent trends.

As a further check for differences, the two descriptors were compared using indicator (dummy) variable analysis in conjunction with L_{AE} and PL. No significant differences in slope or intercept between the appropiate regression equations for the two descriptors were found for either noise metric. Therefore, loudness and annoyance can be represented by the same simple linear regression equation.

These comparisons indicate that subjective response to simulated outdoor sonic booms is the same whether expressed in terms of loudness or in terms of annoyance. Indeed, as is shown in the following sections of this paper, there were no significant differences in subjective response between the two experiments. However, in considering this result, it should be remembered that loudness and annoyance were not defined for the test subjects. The result may have been different if the test subjects had been given differing definitions of the two terms.

Comparison of Noise Metrics

Figures 7, 8, 9, 10, and 11 show the mean judgments for both loudness and annoyance plotted against peak overpressure and four noise metrics, respectively. The noise metrics are L_{linE}, L_{AE}, L_{CE}, and PL. Table IV gives the correlation coefficients between the mean judgments and the five noise measurements for each experiment. Also given in table IV are the coefficients of multiple determination and standard errors of estimate for the best-fitting, third-order polynominal regression equations. (Third-order equations were chosen to account for the s-shaped curve characteristic of numerical catagory scaling data. The s-shaped curvature is an artifact of the limited range of the category scale.) It is clear from the figures and the data in the table that L_{AE} and PL are significantly better predictors of subjective response for both loudness and annoyance. Statistical comparison of the correlation coefficients for L_{AE} and PL indicate no significant difference between the two noise metrics. However, as discussed in the following sections, PL did demonstrate some advantages over L_{AE}.

As previously mentioned, the subjective means were transformed into subjective levels to eliminate the s-shaped curvature. Figures 12 and 13 show the subjective levels for both loudness and annoyance plotted against L_{AE} and PL, respectively. Table V gives the correlation coefficients between the mean subjective levels and the two noise measurements for each experiment. Also given in table V are the coefficients of determination and standard errors of estimate for corresponding linear regression equations. As in the previous analysis, the differences between the two metrics are small. The subjective levels will be used in the remaining analyses in order to provide meaningful units of measure.

Effects of Wave Shape

The 150 noise stimuli in each test were divided into two groups based on the wave shape of the sonic boom pressure signature, N-wave or minimized. The two groups of stimuli were compared using indicator (dummy) variable analyses on the noise metrics L_{AE} and PL and the corresponding subjective levels. When using PL, no significant differences in subjective response were found between the two wave shapes in either experiment. However, for L_{AE}, the analyses indicated a significant difference in intercept, but not in slope, between the appropriate regressions for the two wave shape groups. For a given L_{AE} value, the minimized wave shape sonic booms were slightly less loud or annoying. The differences in subjective response were 0.85 dB for the loudness experiment and 0.96 dB for the annoyance experiment. The difference in results between L_{AE} and PL indicates an advantage for PL in predicting subjective response to sonic booms having different wave shapes.

Effects of Rise Time and Duration

The effects of rise time and duration, which are quantitative parameters, were studied in conjunction with L_{AE} and PL using multiple regression analyses with the corresponding subjective levels as the dependent variables. Regression models including the noise metric and each combination of one or both of the parameters were determined and compared by using the models comparison approach detailed in reference 5. For L_{AE}, the comparison indicated that the regression model was improved by the addition of both rise time and duration. For PL, the regression model was improved by the addition of duration. Rise time did not improve the regression model for PL. Table VI gives the best regression models as indicated by the analyses.

The difference in results between L_{AE} and PL for rise time indicates an advantage for PL in predicting subjective response to sonic booms. The results also show that neither noise metric fully accounted for the effect of sonic boom duration on subjective response. The prediction error associated with each parameter is examined in the following sections. Prediction error is defined as the subjective level minus the calculated level of the noise metric. A positive prediction error represents subjective response greater than that predicted by the noise metric.

Rise time.- Figure 14 shows plots of prediction error, averaged across wave shape, duration, and peak overpressure, as a function of rise time for L_{AE} and PL in each experiment. The curves have no linear trends, just somewhat similar u-shapes. The difference in prediction ability between L_{AE} and PL appears to be due only to L_{AE}'s greater range of prediction error, although the range difference in the annoyance experiment is extremely small.

Duration.- Figure 15 shows plots of prediction error, averaged across wave shape, rise time, and peak overpressure, as a function of duration for L_{AE} and PL in each experiment. The curves are consistent across metrics and experiments and indicate that the unexplained subjective response, as represented by the prediction error, slightly decreases as duration increases, especially above 100 msec. Examination of the average subjective rating, subjective level, and calculated level for each duration confirms an effect of duration on subjective response. As duration increases, the subjective ratings and levels decrease while the calculated levels remain constant.

The magnitude of the duration effect is extremely small (approximately 1.5 dB) over the very wide range of durations considered. Sonic boom duration is a function of aircraft length, and the durations considered in these experiments represent aircraft ranging from small fighters to very large transports. Therefore, the effect of duration on subjective response to different proposed high-speed transport configurations should be insignificant.

Effects of Level

The 144 noise stimuli in each test having peak overpressures of 0.6, 1.2, or 1.6 psf were divided into three groups according to peak overpressure. (The six reference sonic booms were omitted from these analyses due to their different peak overpressure values.) The three groups of stimuli were compared using indicator (dummy) variable analyses on the noise metrics L_{AE} and PL and the corresponding subjective levels. When using PL, no significant differences in subjective response were found between the three peak overpressure groups in either experiment. However, for L_{AE}, the analyses indicated a significant difference in intercept, but not in slope, between the appropriate regressions for the three peak overpressure groups. In the loudness experiment, for a given L_{AE} value, the 0.6-psf sonic booms were slightly less loud than the combined set of 1.2- and 1.6-psf booms. The difference in subjective loudness was 1.19 dB. In the annoyance experiment, for a given L_{AE} value, the 1.2-psf and 0.6-psf sonic booms were 0.63 dB and 1.57 dB, respectively, less annoying than the 1.6-psf sonic booms. The difference in results between L_{AE} and PL indicates an advantage for PL in predicting subjective response to sonic booms having a range of peak overpressures.

CONCLUSIONS

Two laboratory experiments were conducted to provide information on quantifying the subjective response of people to simulated outdoor sonic booms having different pressure signatures. Both experiments were conducted in a computer-controlled, man-rated sonic boom simulator capable of reproducing user-specified pressure signatures for a wide range of sonic boom parameters. One hundred and fifty sonic booms, representing different combinations of two wave shapes, four rise times, seven durations, and three peak overpressures, were presented to 36 test subjects in each experiment. The test subjects in the first experiment made judgments of "loudness" while the test subjects in the second experiment judged "annoyance." Analyses of the subjective responses were conducted in terms of peak overpressure and four conventional noise metrics (unweighted sound exposure level, A- and C-weighted sound exposure level, and perceived level).

Based on the results presented in this paper, the following conclusions were noted:

1. Subjective response to sonic booms was the same whether expressed in terms of loudness or in terms of annoyance.

2. A-weighted sound exposure level and perceived level were significantly better predictors of subjective response than peak overpressure, unweighted sound exposure level, and C-weighted sound exposure level.

3. No unexplained effect of wave shape on either loudness or annoyance was found when perceived level was used to measure the sonic booms. However, when the sonic booms were measured in terms of A-weighted sound exposure level, the sonic booms with minimized wave shapes were approximately 1 dB less loud or annoying than the N-wave shaped sonic booms.

4. No unexplained effect of rise time on either loudness or annoyance was found when perceived level was used to measure the sonic booms. However, when the sonic booms were measured in terms of A-weighted sound exposure level, regression models for subjective response prediction were improved by the addition of a rise time term.

5. Duration did have an effect on subjective response that was not accounted for by either L_{AE} or PL. As duration increased, subjective response decreased. However, the magnitude of the effect across the range of durations considered was small, approximately 1.5 to 2 dB.

6. No unexplained effect of peak overpressure on either loudness or annoyance was found when perceived level was used to measure the sonic booms. However, when the sonic booms were measured in terms of A-weighted sound exposure level, the sonic booms having the lowest peak overpressures were approximately 1 dB less loud and 1.5 dB less annoying than the sonic booms having the highest peak overpressures.

APPENDIX

Instructions, Consent Form, and Rating Sheets

INSTRUCTIONS

The experiment in which you are participating will help us understand the way people respond to various sounds produced by aircraft. We would like you to judge how LOUD some of these aircraft sounds are.

The experiment consists of six 5 minute sessions. During each session 25 aircraft sounds will be presented for you to judge. Before each session you will be given a rating sheet with 25 scales like the one below.

Not Loud At All 0 1 2 3 4 5 6 7 8 9 10 Extremely Loud

After each sound there will be a few seconds of silence. During this interval, please indicate how loud you judge the sound to be by circling the appropriate number on the scale. If you judge a sound to be only slightly loud, then circle one of the numbers close to the NOT LOUD AT ALL end of the scale, that is a low number near the left end of the scale. Similarly, if you judge a sound to be very loud, then circle a number closer to the EXTREMELY LOUD end of the scale, that is a high number near the right end of the scale. A moderately loud judgment should be marked in the middle portion of the scale. In any case, please circle only one number on each scale. There are no right or wrong answers; we are only interested in your judgment of each sound.

Before entering the test facility, four sounds will be presented to acquaint you with the sounds in the experiment. After entering the test facility, you will be given a practice rating sheet and six more sounds will be presented to familiarize you with making and recording judgments. After the practice session, I will answer any questions you may have.

Thank you for your help in conducting the experiment.

VOLUNTARY CONSENT FORM FOR SUBJECTS FOR HUMAN RESPONSE TO AIRCRAFT NOISE AND VIBRATION

I understand the purpose of the research and the technique to be used, including my participation in the research, as explained to me by the Principal Investigator (or qualified designee).

I do voluntarily consent to participate as a subject in the human response to aircraft noise experiment to be conducted at NASA Langley Research Center on

______________________________.
date

I understand that I may at any time withdraw from the experiment and that I am under no obligation to give reasons for withdrawal or to attend again for experimentation.

I undertake to obey the regulations of the laboratory and instructions of the Principal Investigator regarding safety, subject only to my right to withdraw declared above.

I affirm that, to my knowledge, my state of health has not changed since the time at which I completed and signed the medical report form required for my participation as a test subject.

____
PRINT NAME

____
SIGNATURE

PRACTICE RATING SHEET

Subject_______ Group_______

Sound		Rating Scale	
1	Not Loud At All	0 1 2 3 4 5 6 7 8 9 10	Extremely Loud
2	Not Loud At All	0 1 2 3 4 5 6 7 8 9 10	Extremely Loud
3	Not Loud At All	0 1 2 3 4 5 6 7 8 9 10	Extremely Loud
4	Not Loud At All	0 1 2 3 4 5 6 7 8 9 10	Extremely Loud
5	Not Loud At All	0 1 2 3 4 5 6 7 8 9 10	Extremely Loud
6	Not Loud At All	0 1 2 3 4 5 6 7 8 9 10	Extremely Loud

RATING SHEET

Subject_______ Group_______ Session_______ Subset_______

Sound		Rating Scale											
1	Not Loud At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Loud
2	Not Loud At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Loud
3	Not Loud At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Loud
4	Not Loud At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Loud
5	Not Loud At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Loud
6	Not Loud At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Loud
7	Not Loud At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Loud
8	Not Loud At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Loud
9	Not Loud At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Loud
10	Not Loud At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Loud
11	Not Loud At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Loud
12	Not Loud At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Loud
13	Not Loud At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Loud
14	Not Loud At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Loud
15	Not Loud At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Loud
16	Not Loud At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Loud
17	Not Loud At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Loud
18	Not Loud At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Loud
19	Not Loud At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Loud
20	Not Loud At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Loud
21	Not Loud At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Loud
22	Not Loud At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Loud
23	Not Loud At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Loud
24	Not Loud At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Loud
25	Not Loud At All	0	1	2	3	4	5	6	7	8	9	10	Extremely Loud

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Table I. Data on Test Subjects

Experiment	Sex	Number of participants	Mean age	Median age	Age range
1	Male	10	34	32	18-54
	Female	26	33	29	19-52
	All subjects	36	34	29	18-54
2	Male	10	30	28	19-45
	Female	26	38	35.5	20-63
	All subjects	36	36	34.5	19-63

Table II. Presentation Order of Stimuli in Subsets for Both Experiments

Familiarization subset	Subset 1 \/	Subset 2 \/	Subset 3 \/
	N471	N872	M242
N223	M131	M161	M441
M152	N813	N852	N163
N411	M241	N221	N833
N873	N422	M153	M872
	N262	M451	N452
Practice subset	M141	N442	N243
	M433	M871	N461
	N171	N812	N811
N141	N241	N463	M853
M852	M233	N132	M272
M233	M851	M271	N251
N452	N272	N151	M431
N413	M831	M253	M143
M131	M461	N411	N473
	N842	M473	N122
	M171	M172	N25R5
	N25R6	N861	M852
	M863	N113	N853
	M251	M163	N112
	N443	N271	N232
	M132	N252	M463
	M261	M142	N831
	N173	N25R4	N432
	N863	M432	M152
	N152	M843	N441
	N121	N871	N832
	M453	M162	M442
	N153	N213	N211
	N862	N431	M443
	N433	M833	N141
	N25R3	N161	N261
	M133	N843	N223
	N412	M842	M252
	M832	N263	N822
	N873	N131	M873
	N462	N25R2	N111
	N142	N143	M262
	M841	N421	N273
	M472	M273	N172
	N212	N233	M861
	N823	M452	N162
	M173	N472	M471
	M462	N423	M263
	N253	M231	N133
	N453	N413	N451
	N821	N242	M243
	M232	M862	N25R1
	N841	N231	N123
	N222	N851	M151
	Subset 4 /\	Subset 5 /\	Subset 6 /\

Stimuli Key			
Shape	Rise time	Duration	Nominal peak overpressure
N = N-wave	1 = 1 msec	1 = 25 msec	1 = 0.6 psf
M = minimized	2 = 2 msec	2 = 50 msec	2 = 1.2 psf
	4 = 4 msec	3 = 125 msec	3 = 1.6 psf
	8 = 8 msec	4 = 200 msec	R1 = 2.2 psf
		5 = 275 msec	R2 = 1.9 psf
		6 = 350 msec	R3 = 1.4 psf
		7 = 425 msec	R4 = 0.9 psf
			R5 = 0.4 psf
			R6 = 0.2 psf

Table III. Order of Subsets Presented to Test Subjects in Both Experiments

Test subjects	Subsets presented during session-- 1	2	3
1,13,25	1	2	3
2,14,26	1	3	2
3,15,27	2	1	3
4,16,28	2	3	1
5,17,29	3	1	2
6,18,30	3	2	1
7,19,31	4	5	6
8,20,32	4	6	5
9,21,33	5	4	6
10,22,34	5	6	4
11,23,35	6	4	5
12,24,36	6	5	4

Table IV.- Comparison of Noise Metrics Using Mean Subjective Scores

Experiment	Noise metric	Correlation coefficient	Third order regression equation - Coefficient of multiple determination	Standard error of estimate
Loudness	p_{max}	0.60855	0.37575	1.78
	L_{linE}	0.19549	0.05951	2.18
	L_{AE}	0.95724	0.95020	0.50
	L_{CE}	0.88277	0.80590	0.99
	PL	0.96646	0.96535	0.42
Annoyance	p_{max}	0.61110	0.38001	1.89
	L_{linE}	0.20332	0.05928	2.33
	L_{AE}	0.94876	0.95218	0.53
	L_{CE}	0.87345	0.80073	1.07
	PL	0.95839	0.96541	0.45

Table V.- Comparison of L_{AE} and PL Using Subjective Levels

Experiment	Noise metric	Correlation coefficient	First order regression equation - Coefficient of determination	First order regression equation - Standard error of estimate, dB
Loudness	L_{AE}	0.97494	0.95051	1.50
	PL	0.98349	0.96725	1.13
Annoyance	L_{AE}	0.97210	0.94498	1.57
	PL	0.98194	0.96420	1.18

Table VI. - Best Regression Models for Subjective Level When Given Noise Metric, Rise Time , and Duration

Experiment	Noise metric	Regression model
Loudness	L_{AE}	$L_{SL(A)} = 1.07 * L_{AE} + 0.44 * rt - 0.0044 * d - 5.49$
	PL	$L_{SL(PL)} = 0.96 * PL - 0.0036 * d + 4.84$
Annoyance	L_{AE}	$L_{SA(A)} = 1.07 * L_{AE} + 0.48 * rt - 0.0041 * d - 6.41$
	PL	$L_{SA(PL)} = 0.95 * PL - 0.0033 * d + 4.99$

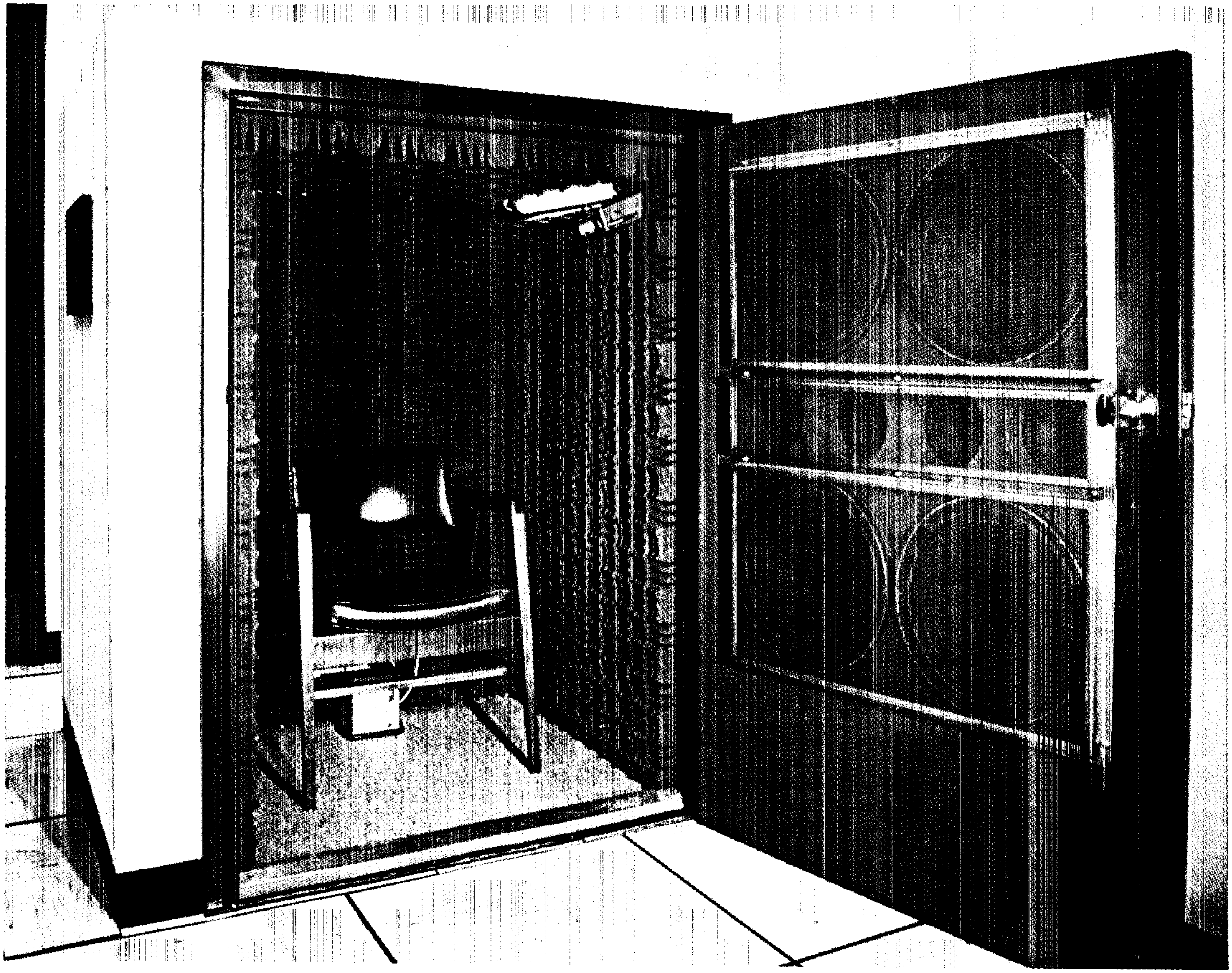
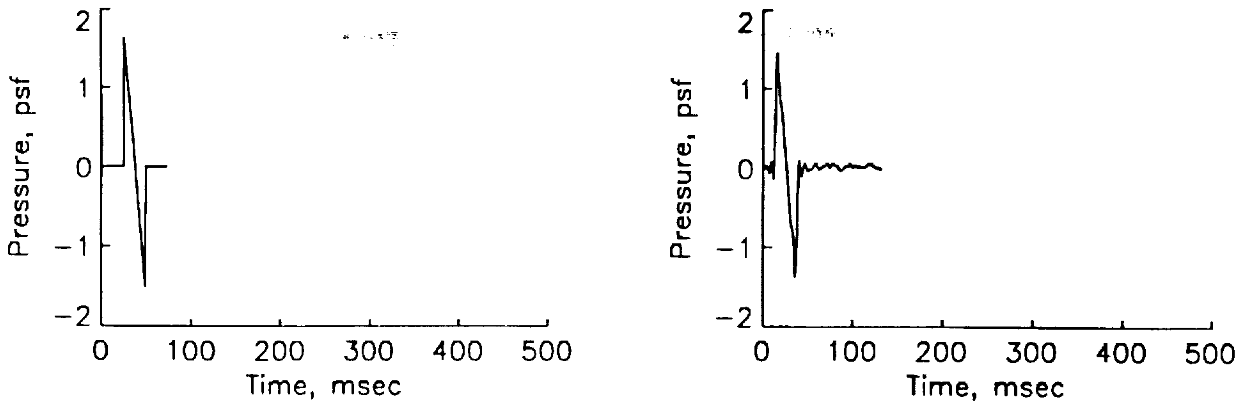
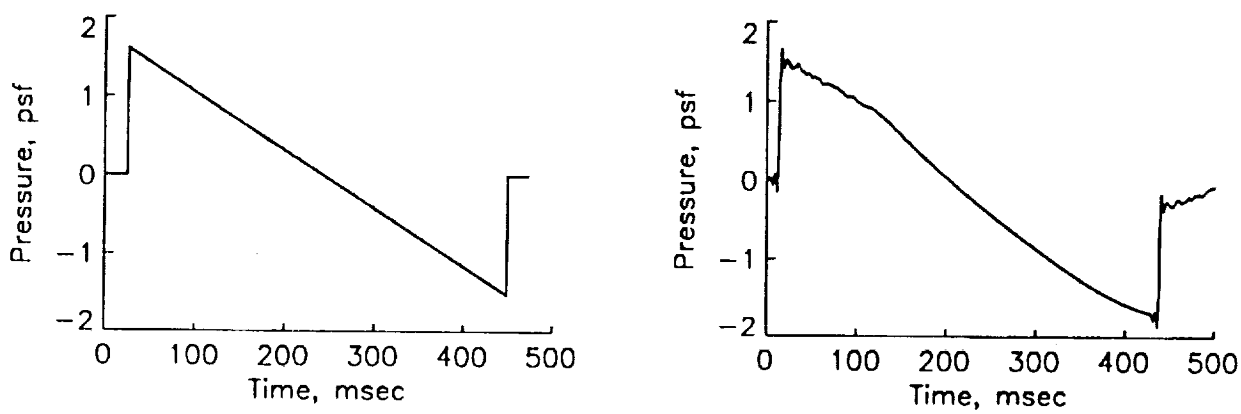


Figure 1.- Sonic Boom Simulator in the Langley Acoustics Research Laboratory.

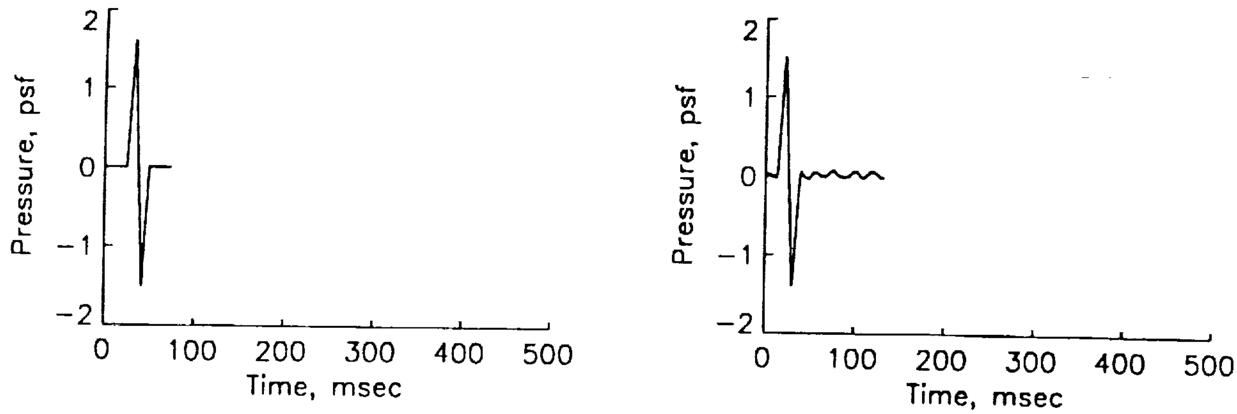


(a) rt = 1 msec, d = 25 msec.

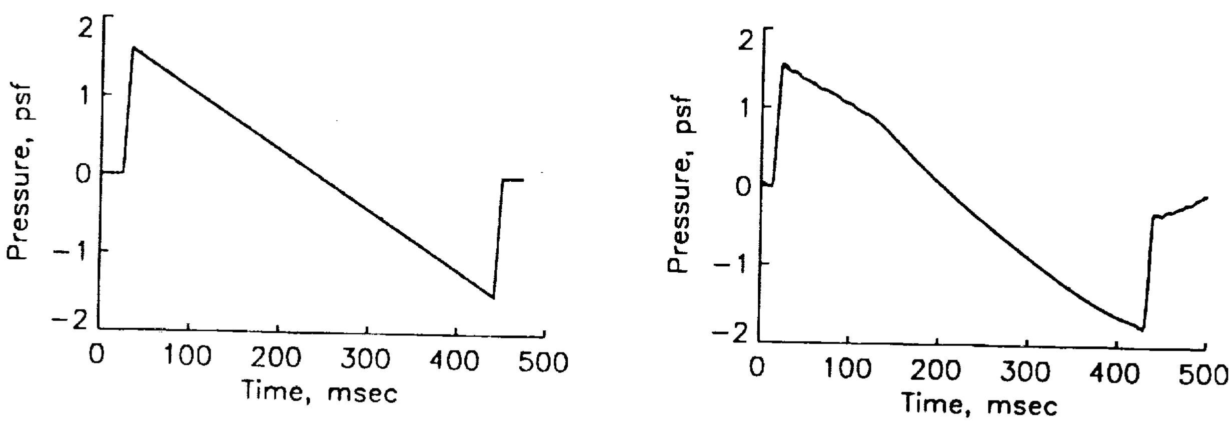


(b) rt = 1 msec, d = 425 msec.

Figure 2.- Nominal (left) and actual (right) pressure time histories of highest level N-wave sonic booms having minimum and maximum values of rise time and duration.

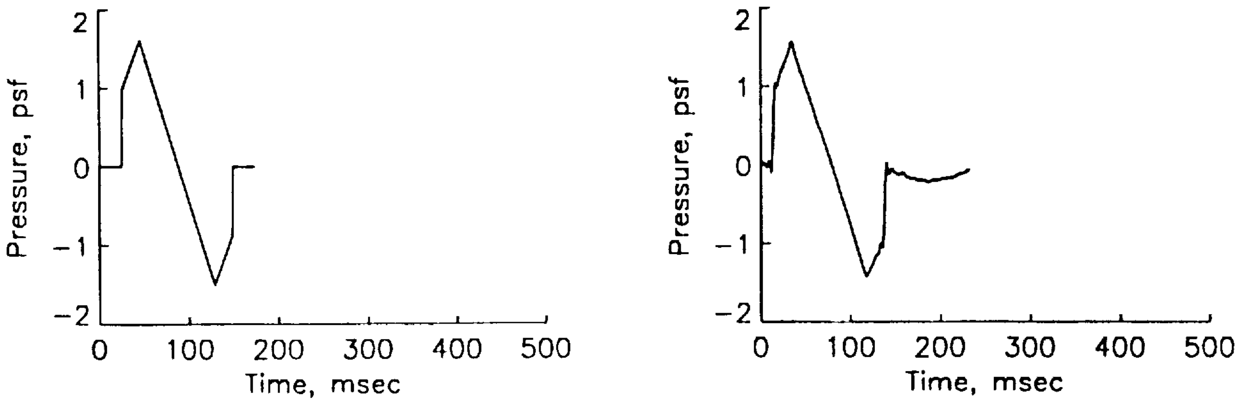


(c) rt = 8 msec, d = 25 msec.

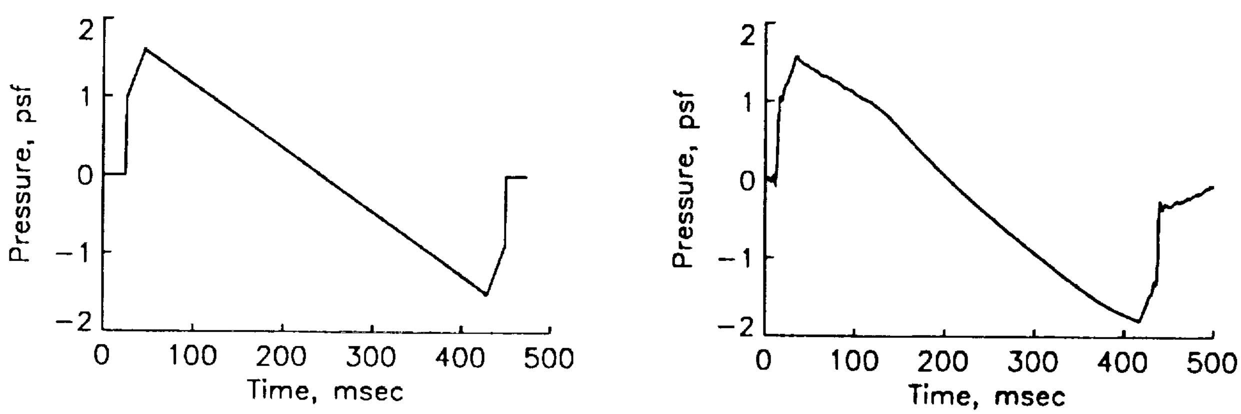


(d) rt = 8 msec, d = 425 msec.

Figure 2.- Concluded.

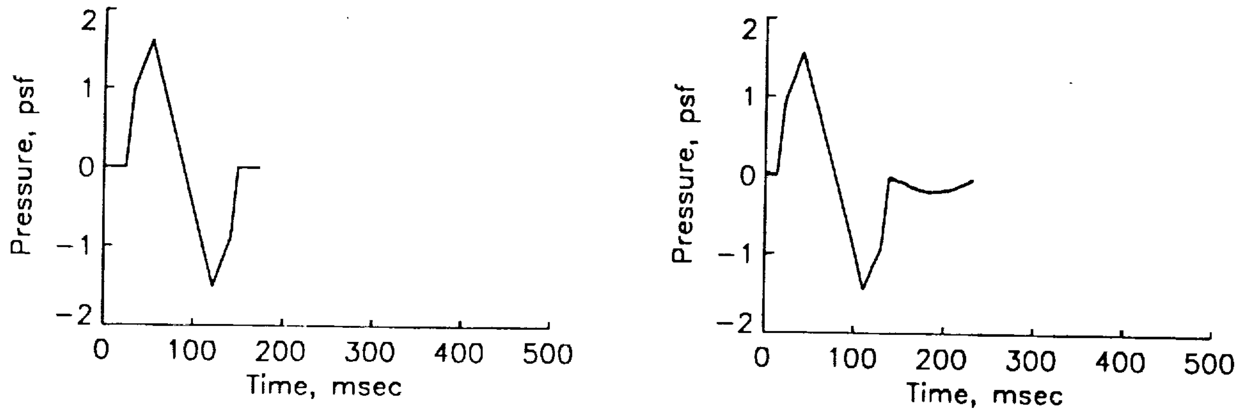


(a) rt = 1 msec, d = 125 msec.

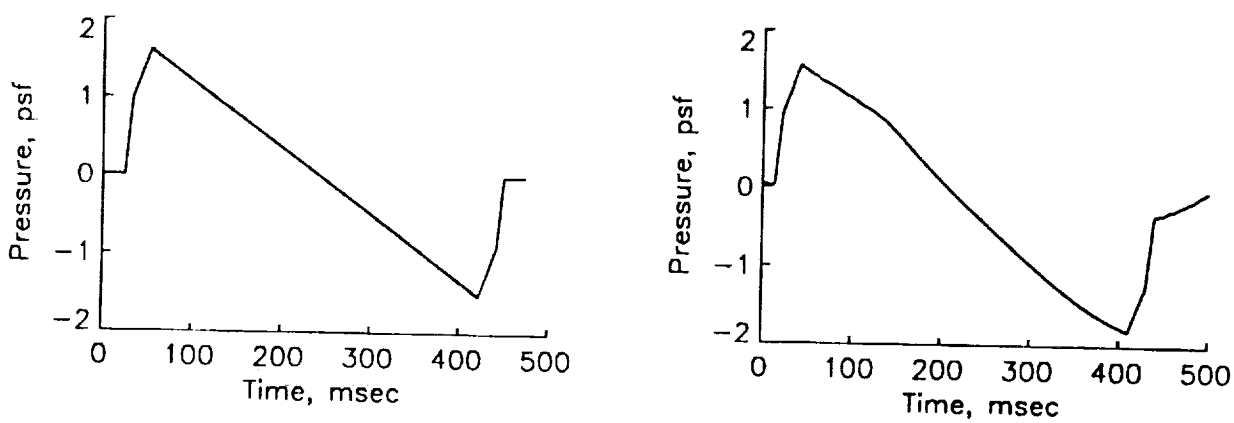


(b) rt = 1 msec, d = 425 msec.

Figure 3.- Nominal (left) and actual (right) pressure time histories of highest level minimized sonic booms having minimum and maximum values of rise time and duration.

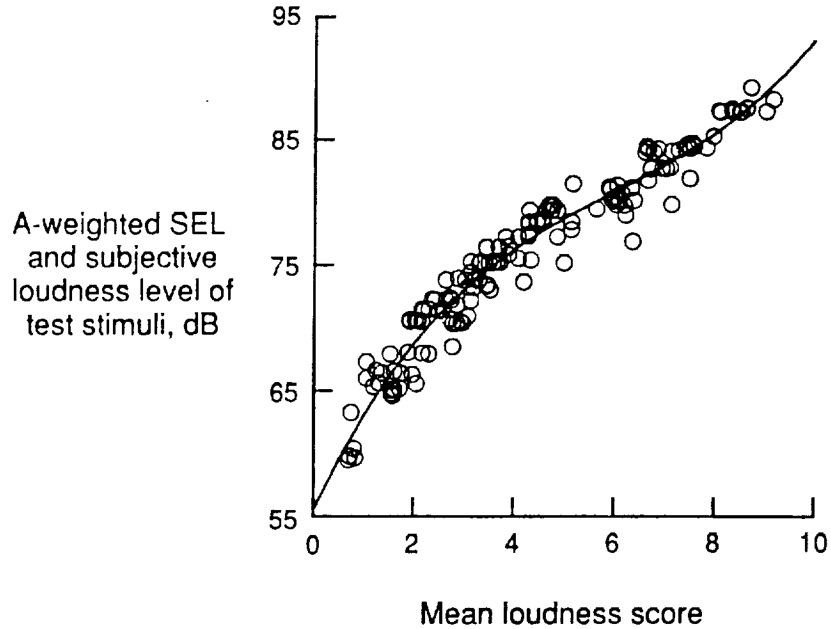


(c) rt = 8 msec, d = 125 msec.

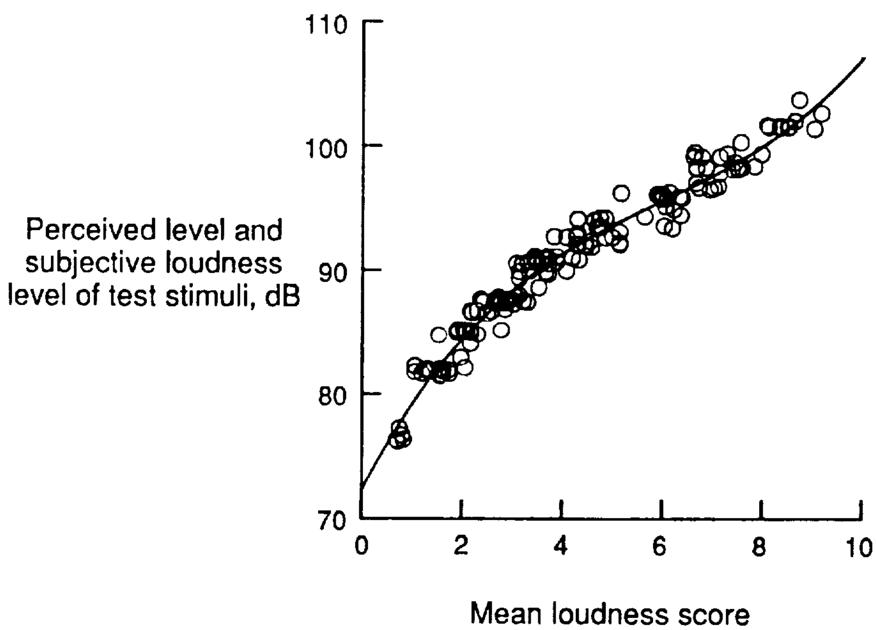


(d) rt = 8 msec, d = 425 msec.

Figure 3.- Concluded.

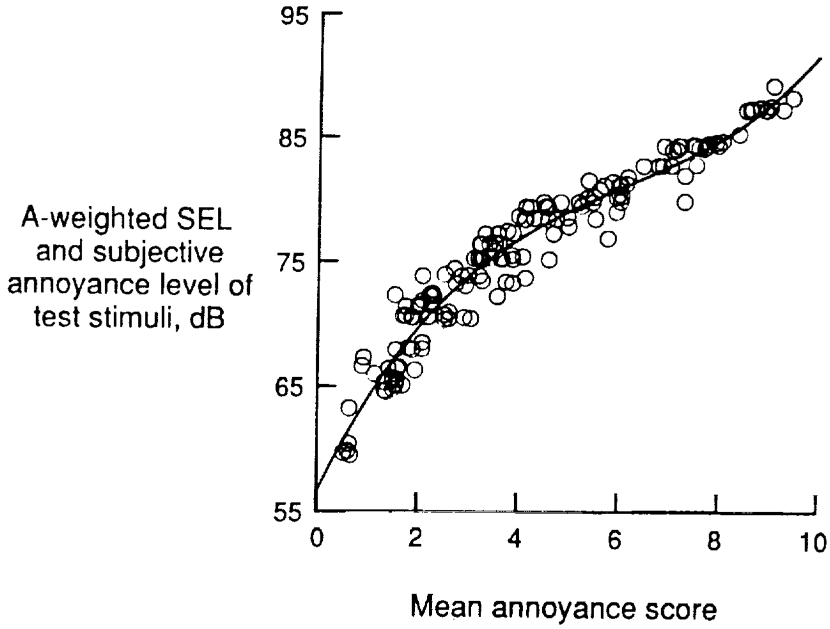


(a) L_{AE}.

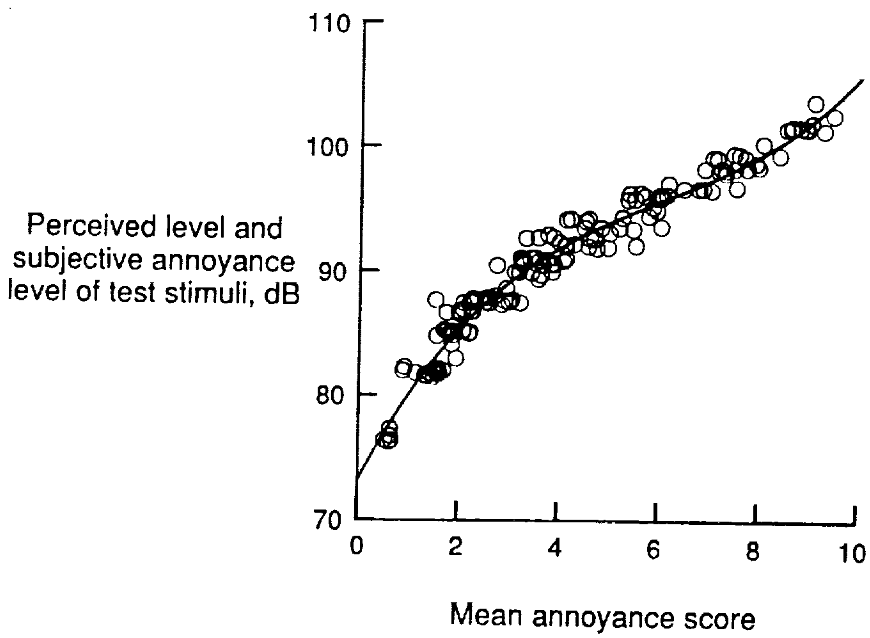


(b) PL.

Figure 4.- Regression analyses of L_{AE} and PL on mean loudness scores used to convert loudness judgments to subjective loudness levels.



(a) L_{AE}.



(b) PL.

Figure 5.- Regression analyses of L_{AE} and PL on mean annoyance scores used to convert annoyance judgments to subjective annoyance levels.

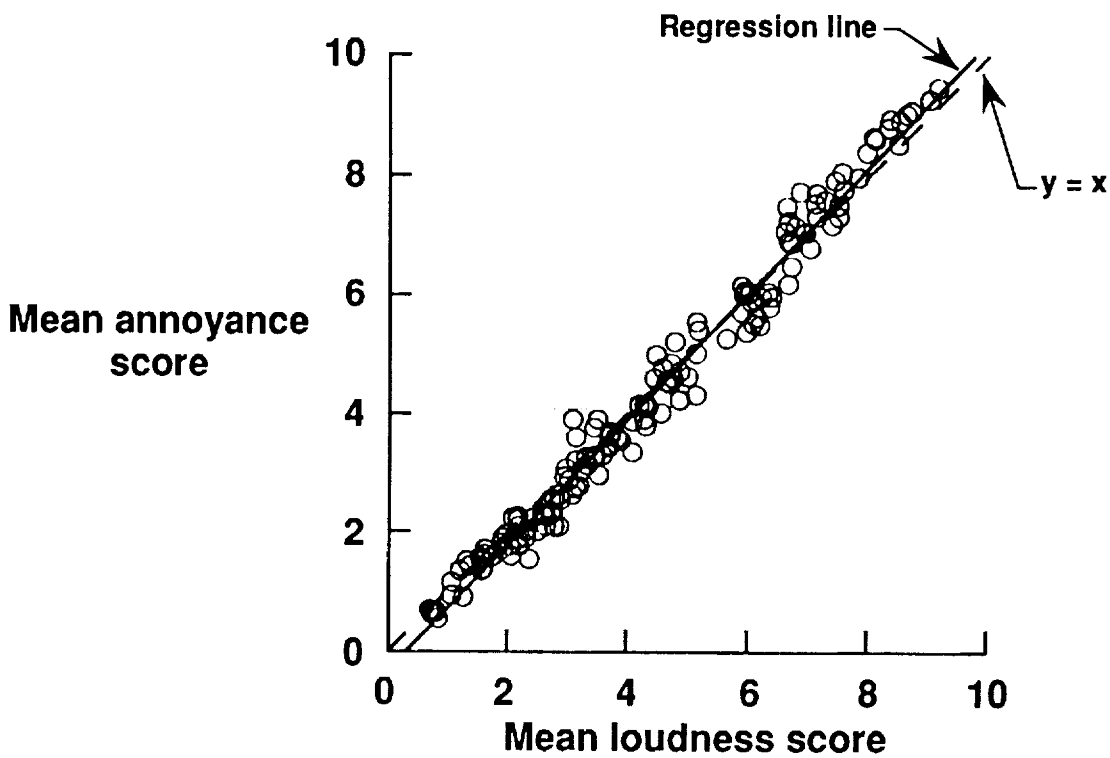
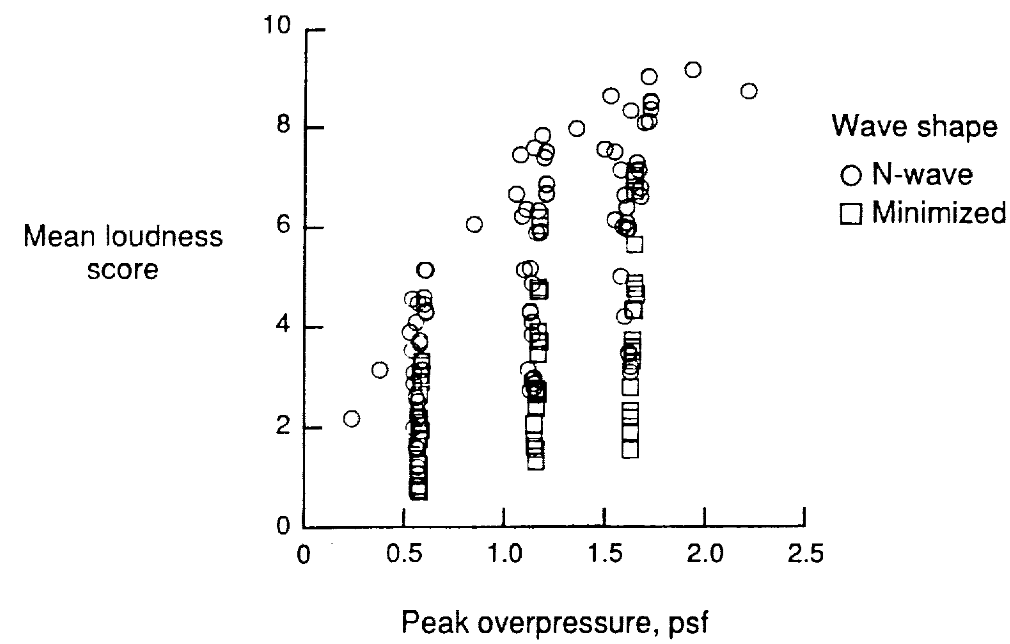
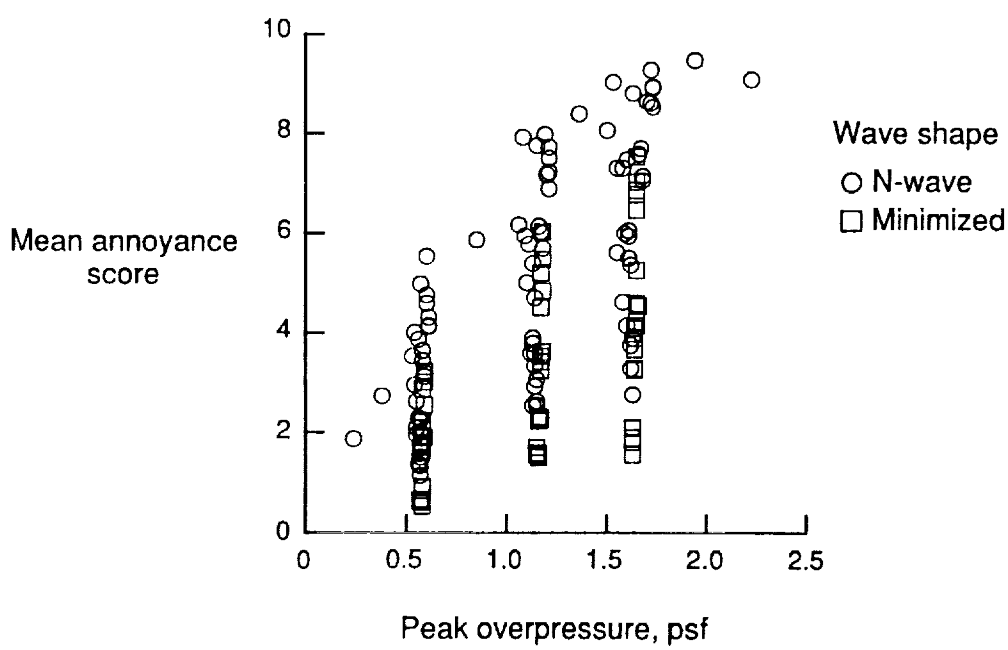


Figure 6.- Comparsion of mean annoyance scores from second experiment with mean loudness scores from first experiment.

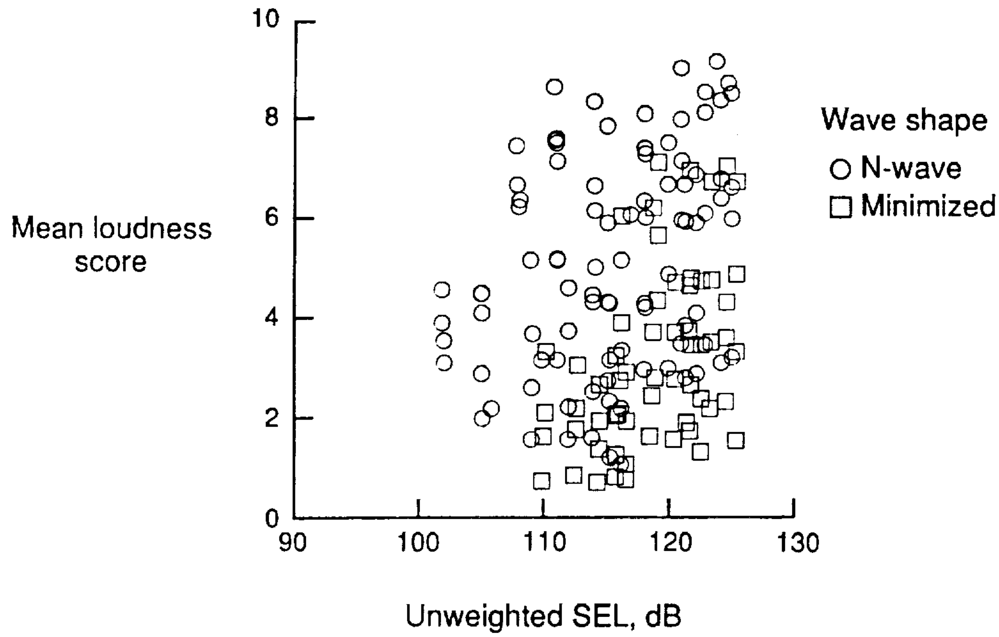


(a) Loudness experiment.

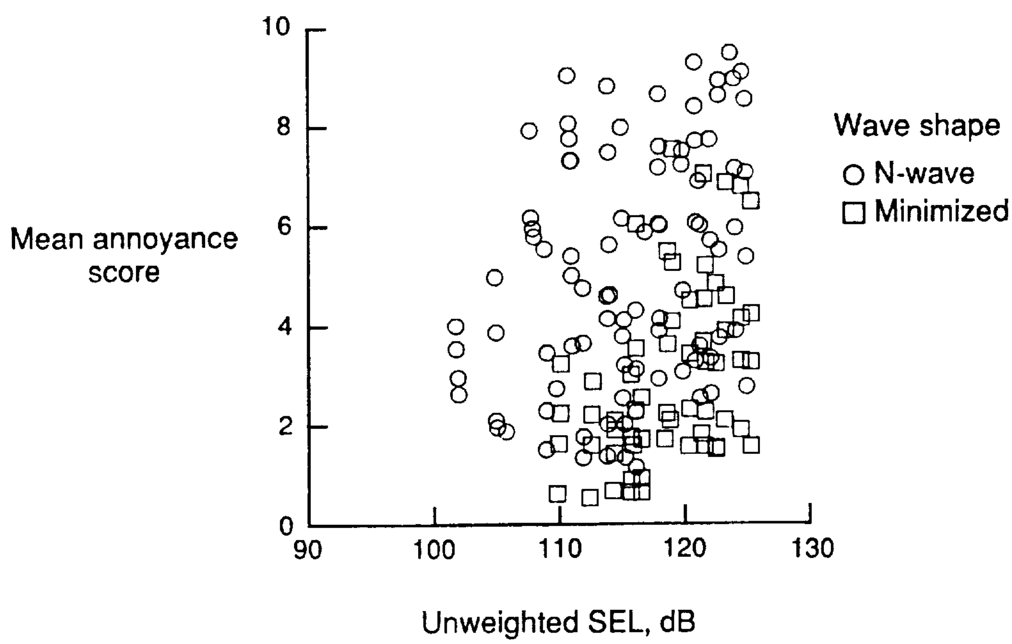


(b) Annoyance experiment.

Figure 7.- Mean subjective scores versus peak overpressure for both experiments.

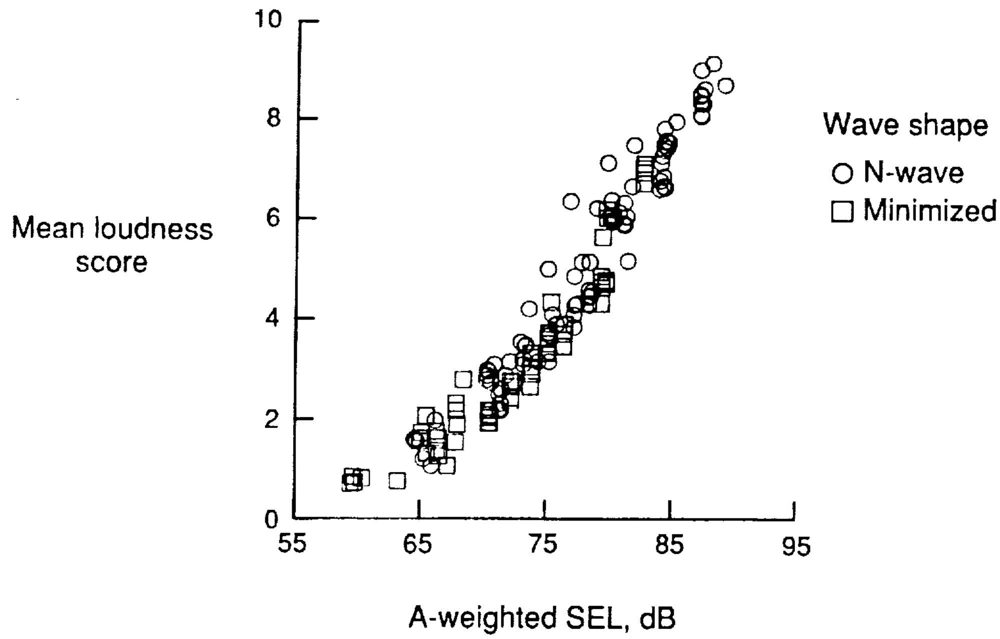


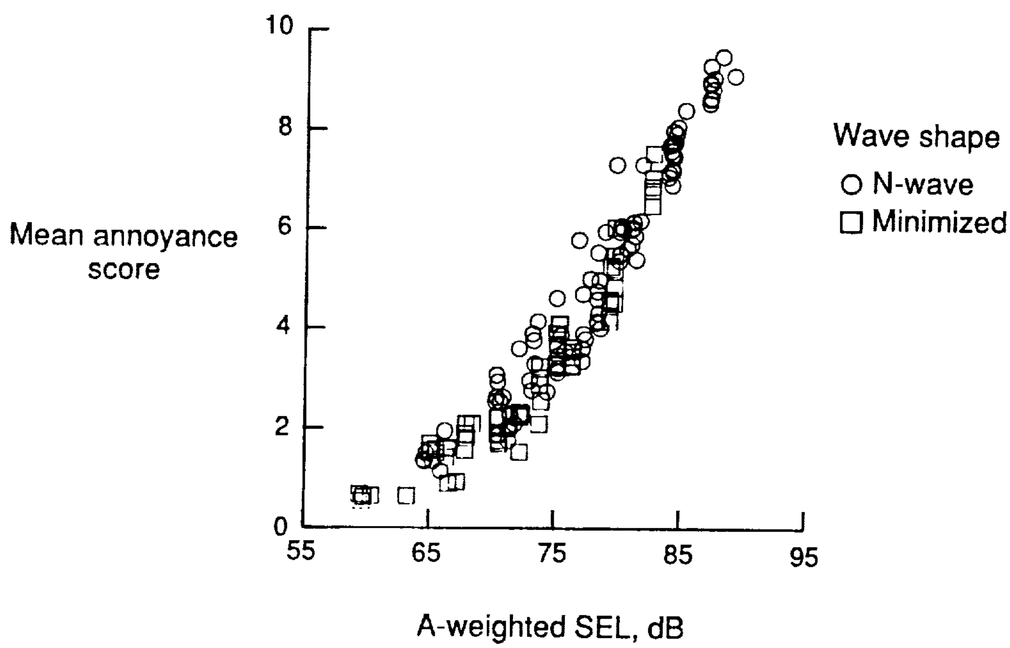
(a) Loudness experiment.



(b) Annoyance experiment.

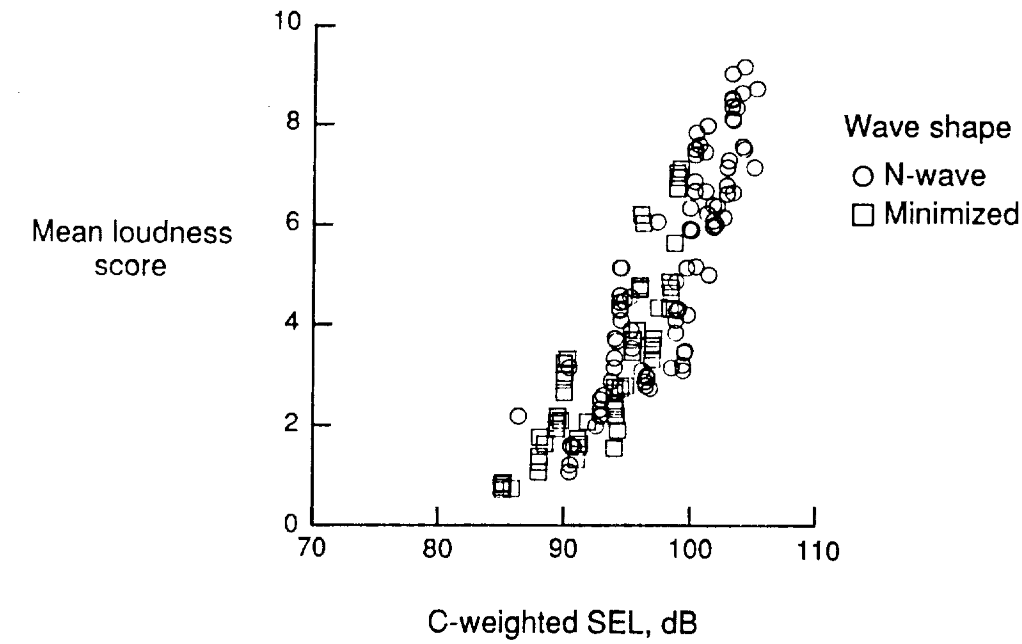
Figure 8.- Mean subjective scores versus L_{linE} for both experiments.



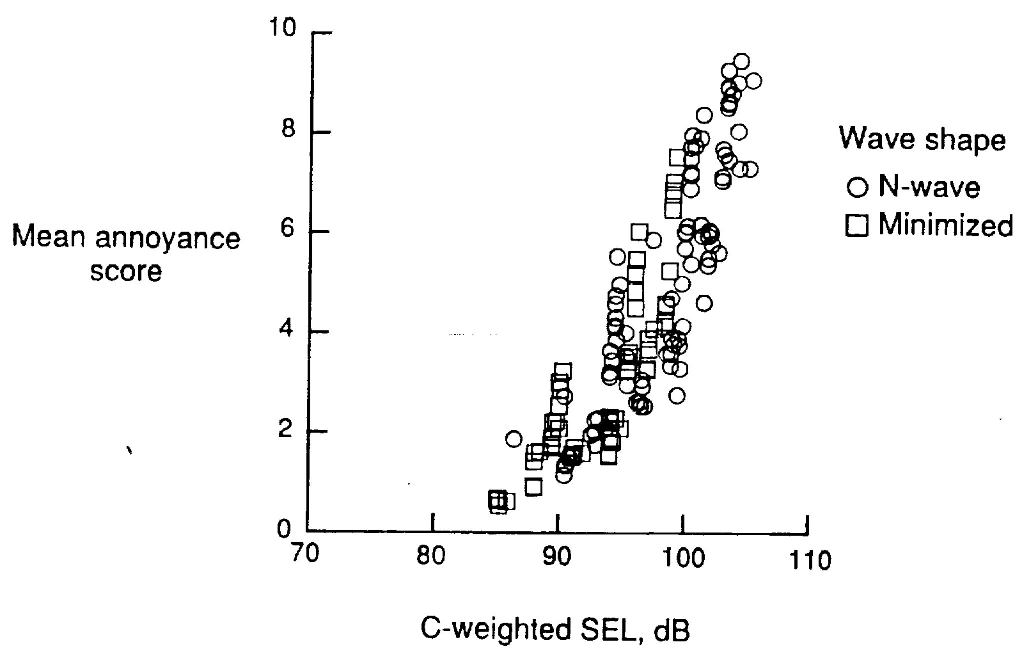


(b) Annoyance experiment.

Figure 9.- Mean subjective scores versus L_{AE} for both experiments.

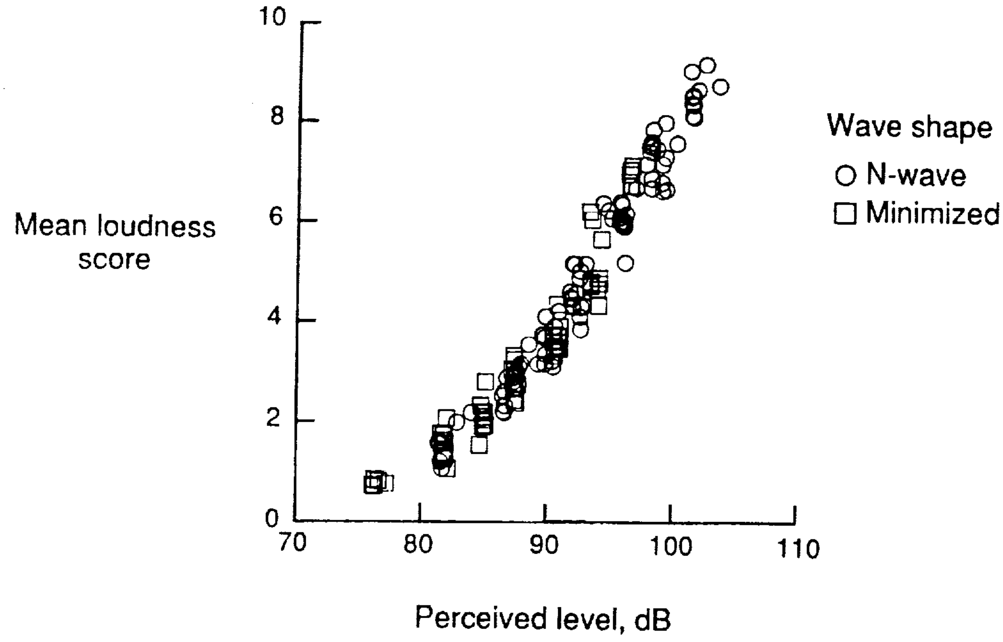


(a) Loudness experiment.

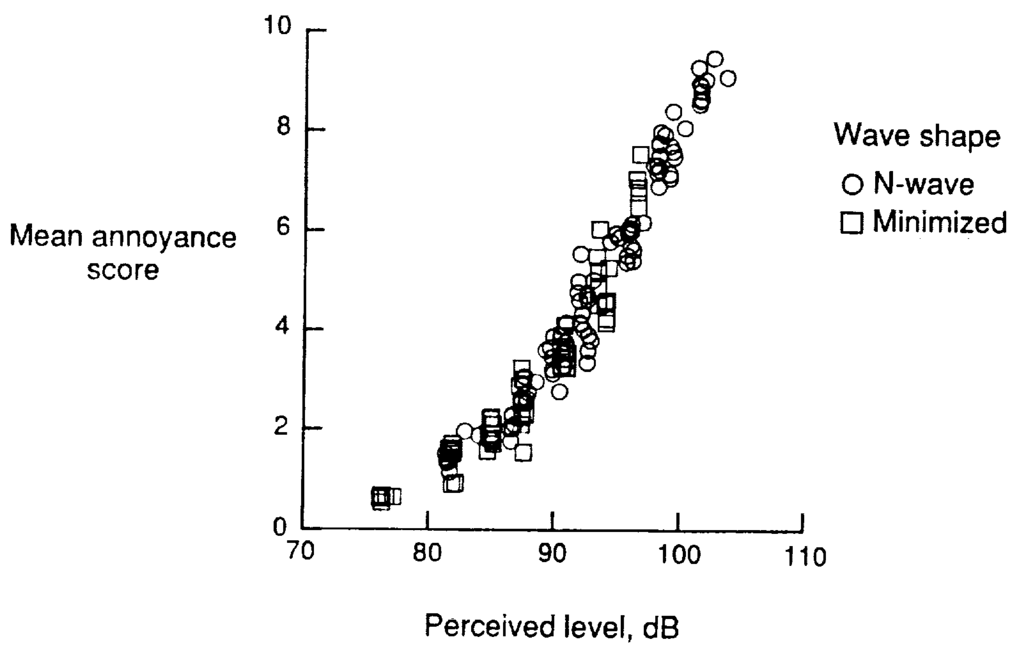


(b) Annoyance experiment.

Figure 10.- Mean subjective scores versus L_{CE} for both experiments.

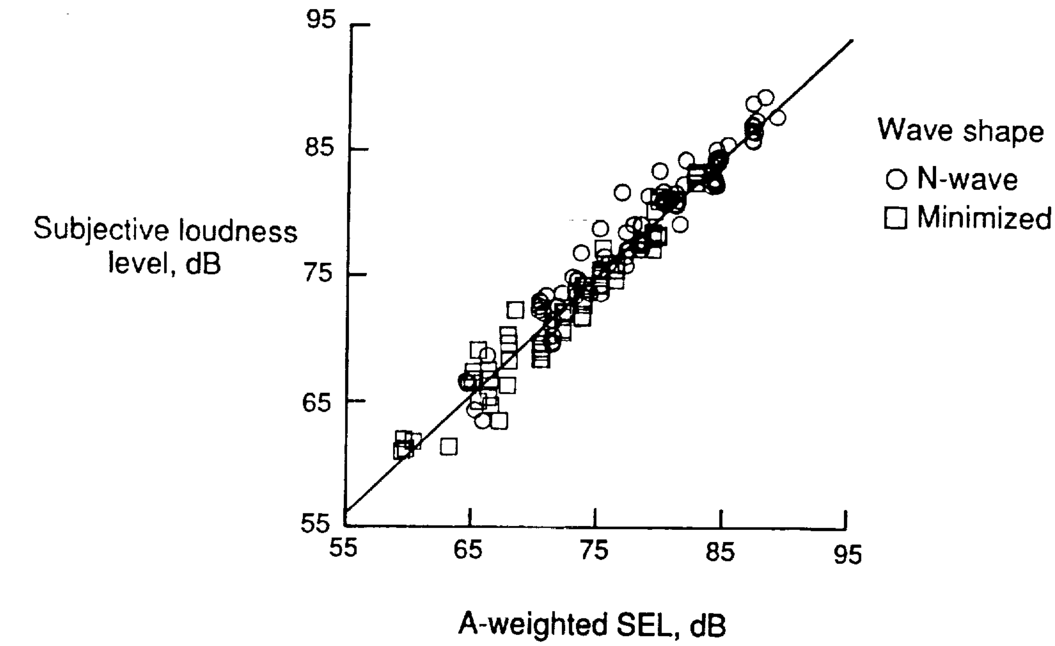


(a) Loudness experiment.

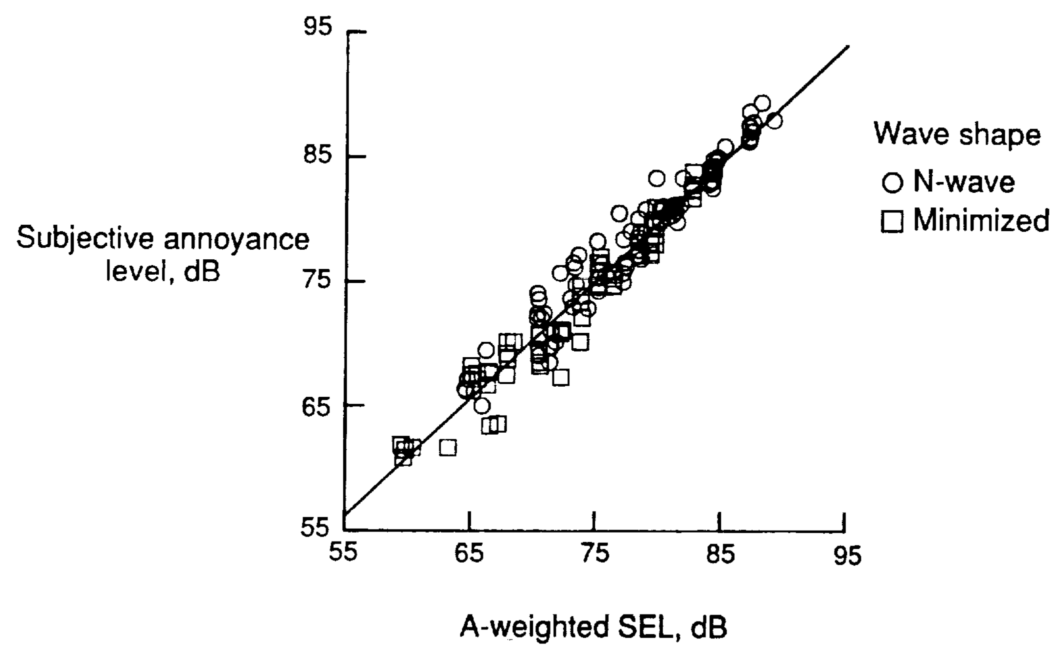


(b) Annoyance experiment.

Figure 11.- Mean subjective scores versus PL for both experiments.

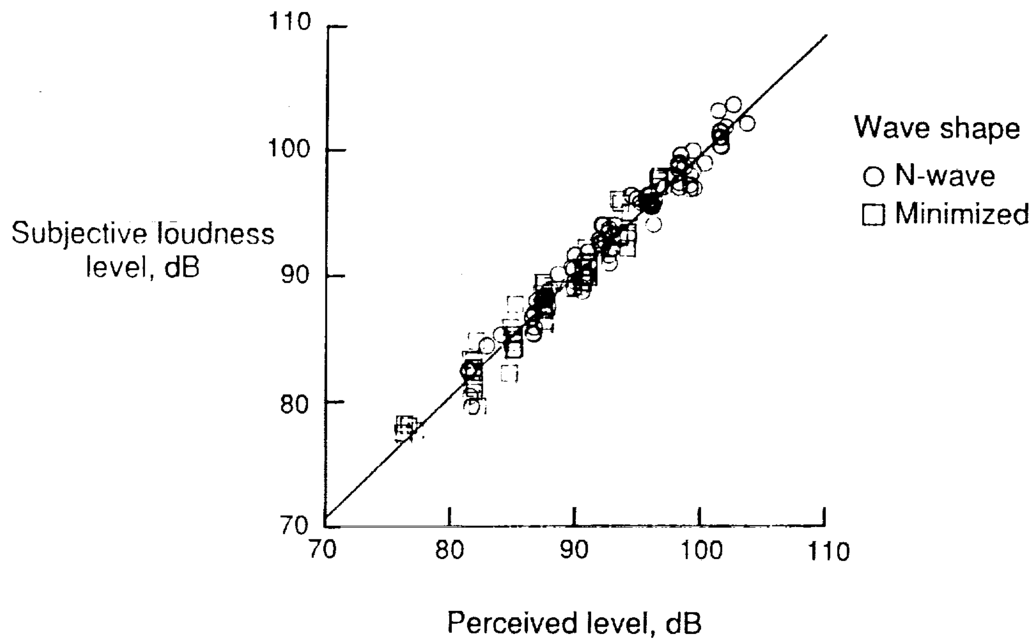


(a) Loudness experiment.

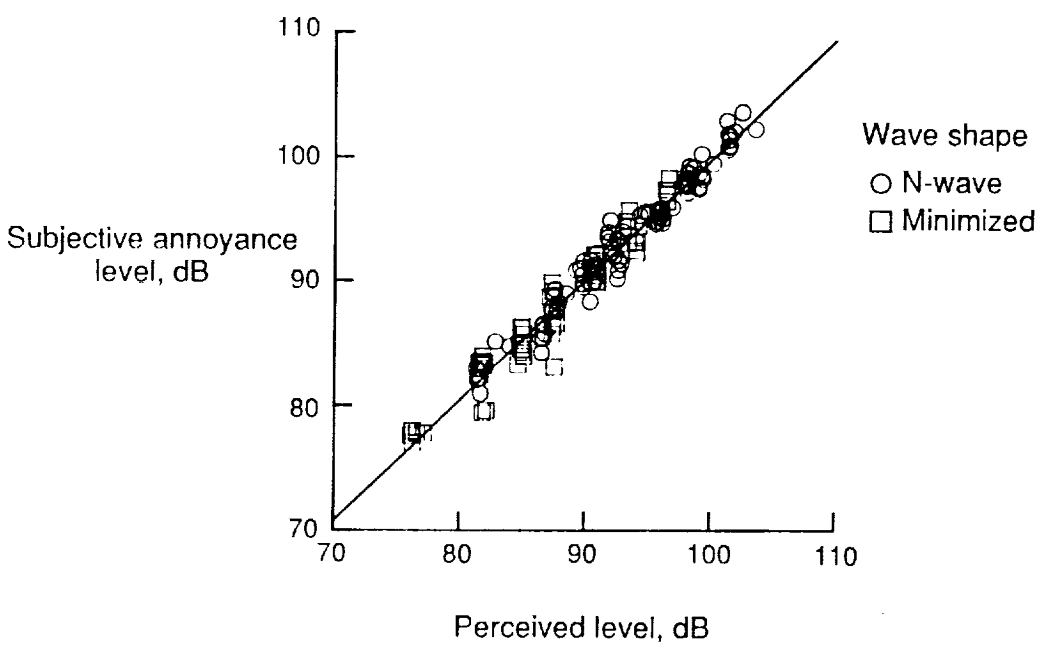


(b) Annoyance experiment.

Figure 12.- Subjective levels versus L_{AE} for both experiments.

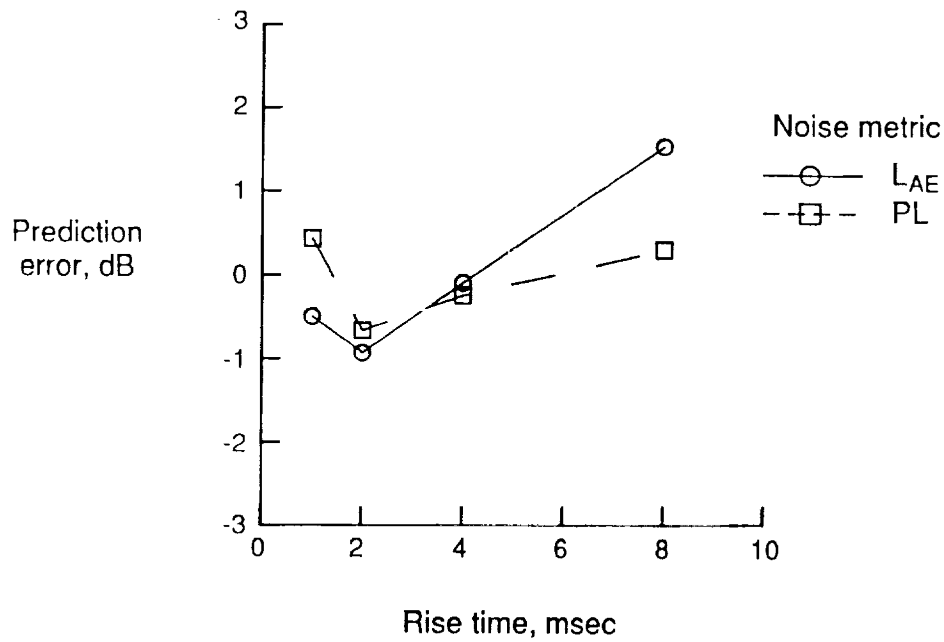


(a) Loudness experiment.



(b) Annoyance experiment.

Figure 13.- Subjective levels versus PL for both experiments.



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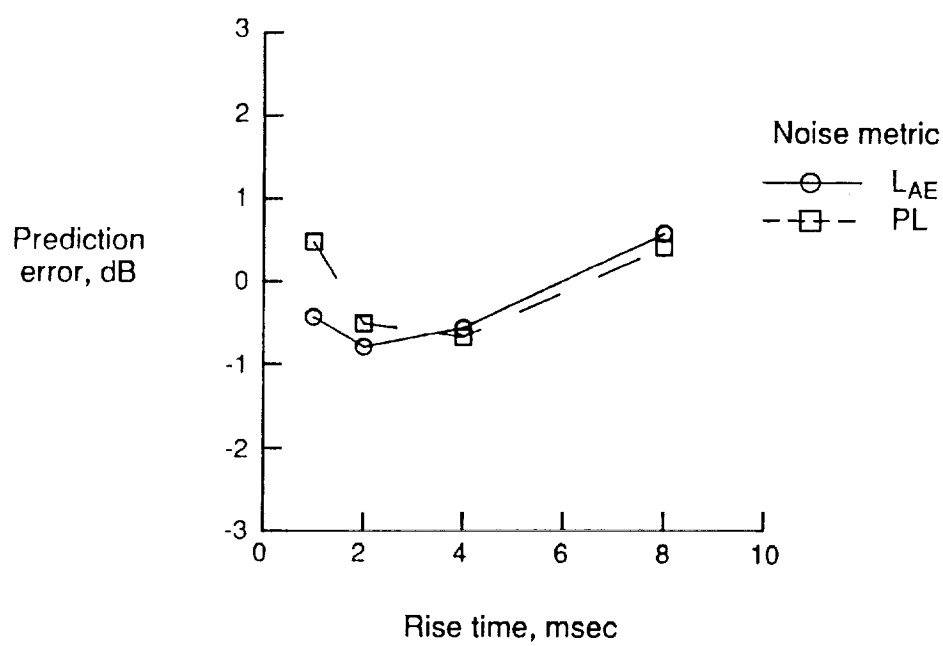
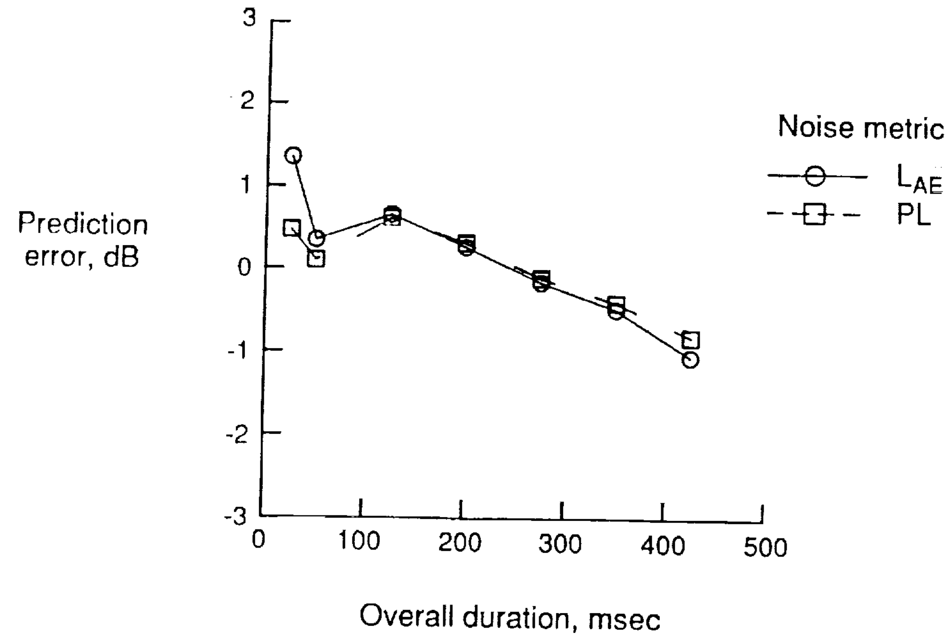
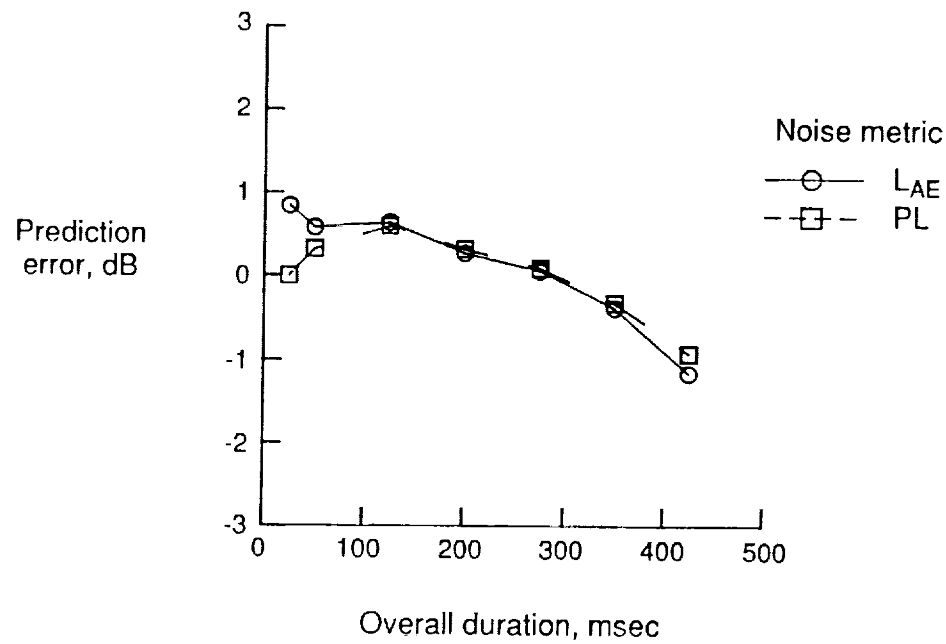


(b) Annoyance experiment.

Figure 14.- Effect of rise time on subjective response prediction for L_{AE} and PL in both experiments.



(a) Loudness experiment.



(b) Annoyance experiment.

Figure 15.- Effect of duration on subjective response prediction for L_{AE} and PL in both experiments.

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13. ABSTRACT (*Maximum 200 words*)

Two laboratory experiments were conducted to quantify the subjective response of people to stimulated outdoor sonic booms having different pressure signatures. The specific objectives of the experiments were (1) to compare subjective response to sonic booms when described in terms of "loudness" and "annoyance;" (2) to determine the ability of various noise metrics to predict subjective response to sonic booms; (3) to determine the effects on subjective response of rise time, duration, and level; and (4) to compare the subjective response to "N-wave" sonic boom signatures with the subjective response to "minimized" sonic boom signatures. The experiments were conducted in a computer-controlled, man-rated sonic boom simulator capable of reproducing user-specified pressure signatures for a wide range of sonic boom parameters. One hundred and fifty sonic booms, representing different combinations of two wave shapes, four rise times, seven durations, and three peak overpressures, were presented to 36 test subjects in each experiment. The test subjects in the first experiment made judgments of "loudness" while the test subjects in the second experiment judged "annoyance." Subjective response to sonic booms was the same whether expressed in terms of loudness or in terms of annoyance. Analyses of several different noise metrics indicated that A-weighted sound exposure level and Perceived Level were the best predictors of subjective response. Further analyses indicated that, of these two noise metrics, only Perceived Level completely accounted for the effects of wave shape, rise time, and peak overpressure. Neither metric fully accounted for the effect of duration. However, the magnitude of the duration effect was small over the very wide range of durations considered.

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