Denver, Colorado
NOISE-CON 2013
2013 August 26-28

Simulator study of indoor annoyance caused by shaped sonic boom stimuli with and without rattle augmentation

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ABSTRACT

The National Aeronautics and Space Administration's High Speed Project is developing a predictive capability for annoyance caused by shaped sonic booms transmitted indoors. The predictive capability is intended for use by aircraft designers as well as by aircraft noise regulators who are considering lifting the current prohibition on overland civil supersonic flight. The goal of the current study is to use an indoor simulator to validate two models developed using headphone tests for annoyance caused by sonic booms with and without rattle augmentation. The predictors in the proposed models include Moore and Glasberg's Stationary Loudness Level, the time derivative of Moore and Glasberg's time-varying short-term Loudness Level, and the difference between two weighted sound exposure levels, CSEL-ASEL. The indoor simulator provides a more realistic listening environment than headphones due to low-frequency sound reproduction down to 6 Hz, which also causes perceptible tactile vibration. The results of this study show that a model consisting of {PL + (CSEL-ASEL)} is a reliable predictor of annoyance caused by shaped sonic booms alone, rattle sounds alone, and shaped sonic booms and rattle sounds together.

1. INTRODUCTION

NASA's High Speed Project is developing technology to enable commercial overland supersonic flight by reducing the noise and annoyance associated with sonic booms. A "shaped" sonic boom, produced through careful design of the aircraft, creates much lower audible noise and resulting community annoyance than a conventional sonic boom. To set noise goals and quantify progress, aircraft designers and aircraft noise regulators seek a noise metric for shaped sonic booms, which should also be applicable to conventional sonic booms. However, the transient, impulsive nature and low-frequency content of shaped sonic booms exclude the use of conventional noise metrics. Furthermore, because people spend a majority of time indoors, the ideal noise metric should also predict annoyance caused by shaped sonic booms that have transmitted indoors. Indoor annoyance is affected by the transmitted waveform, but also by tactile and visual vibrations and rattle noises from doors, windows, and loose objects set into motion by the induced structural vibrations. Of the existing laboratory studies examining the annoyance caused by sonic booms shown in Table 1, the current study is the first to examine the annoyance caused by shaped sonic booms transmitted indoors in a listening environment that includes the effects of both tactile vibration and rattle. Field studies[1-4] have investigated the annoyance caused by sonic booms but control over boom levels, rattle levels, and listening conditions in the field is limited. Most importantly, shaped sonic booms cannot be tested in the field until a shaped sonic boom demonstrator is built.

Table 1: Summary of laboratory studies on annoyance caused by sonic booms.

Author	Simulator/Headphone	Signature Type	Rattle?	Vibration?
Schomer and Averbuch (1989)[5]	Simulator	Indoor	Yes	No
Leatherwood and Sullivan (1993)[6]	Simulator	Outdoor and Indoor	No	No
Fidell et al. (2002)[7]	Simulator	Indoor	Yes	No
Loubeau et al. (2013)[8]	Headphone	Indoor	Yes	No
Rathsam et al. (2012)[9]	Simulator	Indoor	No	Yes
Marshall (2012)[10]	Headphone	Outdoor	No	No
Current Study	Simulator	Indoor	Yes	Yes

The goal of this study is to use an indoor simulator to validate single-event annoyance models to rattle-augmented boom signals developed using headphone tests[8, 10]. The indoor simulator provides a more realistic listening environment than headphones due to low-frequency sound reproduction down to 6 Hz, which also causes perceptible tactile vibration. The single-event annoyance models to be validated are shown in Equations (2) and (3). The regression intercept, b_0, and regression coefficients, b_1 and b_2, are determined separately for each equation. The noise metrics used in the models include Perceived Level (PL)[11], A- and C-weighted Sound Exposure Level[12], Moore and Glasberg's stationary loudness[13] in phons, MGSLp, and dSTL, the derivative of the short-term time-varying loudness of Glasberg and Moore[14] used by Marshall[10]. As suggested by Kjellberg et al.[15] and validated by Vos[16], CSEL-ASEL is used in this study to quantify the low-frequency energy in a signal, which often corresponds to annoyance. Another predictor used is LAF_{max}, the maximum A-weighted level using exponential averaging with a time constant of 0.125 seconds. This predictor corresponds to the maximum output of a sound level meter during the transient event. Additionally, acceleration is examined as an annoyance predictor. Peak acceleration is reported after applying a weighting function, w_k, corresponding to a seated person's sensitivity to vibration in terms of comfort and perception[17]. Vibration is measured on the ground at the approximate locations of subjects' feet when seated. All other levels are calculated from waveforms measured at the approximate head location of each subject. Subjects were not present during these measurements.

$$\textbf{Existing model}\text{:}\ \text{Annoyance} = b_0 + b_1 * \text{PL} \tag{1}$$

$$\textbf{Proposed model A}\text{:}\ \text{Annoyance} = b_0 + b_1 * \text{MGSLp} + b_2 * (\text{CSEL} - \text{ASEL}) \tag{2}$$

$$\textbf{Proposed model B}\text{:}\ \text{Annoyance} = b_0 + b_1 * \text{MGSLp} + b_2 * \text{dSTL} \tag{3}$$

The research questions examined in the current study are listed below:

1. What model best predicts annoyance caused by booms alone?
2. What model best predicts annoyance caused by booms and rattles together?
3. Does CSEL – ASEL [dB] predict annoyance above and beyond loudness level?

2. TEST DESCRIPTION

The test signals, shown in Table 2, are divided into three parts: boom signals alone (Part I), rattle signals alone (Part II), and boom and rattle signals together (Part III). Each signal in Part I was played at five levels at the facility exterior, spanning a range of 65 – 81 dB PL, which may include levels eventually determined to be acceptable for shaped sonic booms. Signatures 1-6 are six proprietary shaped sonic boom predictions for commercial aircraft. The latter four signals in Part I were designed according the filtered impulse method in Rathsam et al.[9] The rattle signals in Part II were recorded as described in Loubeau et al.[8] The rattle signal amplitudes were chosen so the interior loudness level of the Boom and Rattle sounds together (in Part III) would be approximately 4-10 dB higher than the booms alone. This increment in loudness level when rattle sounds are present in addition to booms was observed in field data not yet published. In Part III, the total number of signals is 112, and not 144 (4 booms x 3 boom amplitudes x 4 rattles x 3 rattle amplitudes). To conserve time in the subjective test, only seven instead of nine boom and rattle amplitude combinations were used for each of the 16 pairings of booms and rattle signals.

Table 2: Test signals.

	Boom Signals	Exterior Boom Levels [dB PL]	Rattle Signals	Interior Rattle Levels [dB PL]
Part I: **Booms Alone** (10 booms x 5 levels = 50 signals)	Signatures 1-6 9Hz_3^{rd}_200ms **15Hz_3^{rd}_200ms** **27Hz_3^{rd}_200ms** 35Hz_3^{rd}_200ms	**65**, 69, **73**, 77, **81**		
Part II: **Rattles Alone** (9 rattles x 5 levels = 45 signals)			**wallart1** **candleglobe2** wineglass2 window3 doordamped drydengarage1 **beddoor** **fan1** window2	**52**, 56, **60**, 64, **68**
Part III: **Booms and Rattles** (112 signals)	**Signature 3** **Signature 6** **15Hz_3^{rd}_200ms** **27Hz_3^{rd}_200ms**	**65, 73, 81** (48, 56, 64 are approximate interior boom levels)	**wallart1** **candleglobe2** **beddoor** **fan1**	**52, 60, 68**

The test method was category scaling. Subjects were presented with a signal and then asked to place an 'X' on the continuous scale shown in Figure 1 using a dial input device connected to a notebook computer. The annoyance values were coded by assigning a value of 0 to "Not at all Annoying" and a value of 4 to "Extremely Annoying." Subjective judgments at intermediate points on the continuous scale were coded with values proportional to the distance from the scale's low end.

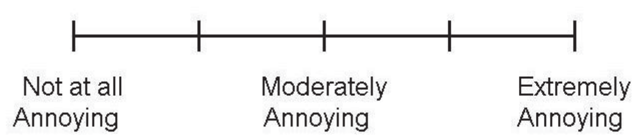

Figure 1: Category scale used for subjective responses.

Figure 2: The test subjects (seated) are briefed on the sounds they will hear.

Subjects were tested in groups of three in the Interior Effects Room[18], at the locations of the individuals seated in Figure 2. The order of the 207 test sounds was fully randomized for each group. Thirty-three subjects (11 male, 22 female) participated in the study. The subjects were obtained from a subject pool of local residents and were paid for their participation in the study. Ages of the test subjects ranged from 18 to 85 years with a median age of 55 years. All subjects were audiometrically screened prior to the test to demonstrate auditory acuity within 40 dB of audibility thresholds for tones from 500 Hz to 6 kHz.

The seating arrangement was changed from previous tests[9] to improve uniformity of signal levels among listener locations. For each sonic boom signal, the variation in PL is less than 3.5 dB across listener locations. For each rattle signal, the variation in PL is less than 0.2 dB. To achieve this uniformity in level, all rattle sounds were played over a single rattle speaker located in the larger simulator closet. Frequency content of the rattle sounds below 210 Hz was reproduced over a subwoofer located on the floor in the corner behind the flat-screen TV shown in Figure 2.

To add realism to the environment, a broadband background noise signal was used, similar to the background noise used by Vos[16] and Marshall[10]. The sound pressure level of the background noise at the chair location in the middle of Figure 2 was 38 dBA.

3. RESULTS

The research questions posed in Section 1 are answered by comparing the coefficients of determination, R^2, listed in Table 3. The coefficients of determination were found by linear regression of annoyance averaged across all test subjects against model outputs averaged across the three listener locations. The linear regression was carried out using the ‘regress’ command in Matlab’s Statistics Toolbox.

Question 1 refers to the best predictor of annoyance caused by boom alone. The highest coefficient of determination for a single predictor in the Table 3 column titled “Boom Alone” is w_k-weighted peak acceleration[17] ($R^2 = 0.87$). When loudness level is added to w_k-weighted peak acceleration as an additional predictor, the coefficient of determination increases further. The coefficient of determination for {w_k-weighted peak acceleration + PL} is 0.93 and for {w_k-weighted peak acceleration + MGSLp} is 0.94. This implies that both w_k-weighted peak acceleration and loudness levels are driving annoyance, but the dominant predictor of annoyance among those examined is vibration level. The fourth highest coefficient of determination (R^2 = 0.82) corresponds to a two-factor model containing {PL + (CSEL-ASEL)}. None of the models specified in the introduction have coefficients of determination as high: Eq. (1) (R^2 = 0.67), Eq. (2) (R^2 = 0.73), and Eq. (3) (R^2 = 0.30).

Question 2 refers to the best predictor of annoyance for booms and rattles together. The three highest coefficients of determination are found for the following three models: {w_k-weighted peak acceleration + PL} (R^2 = 0.87), {w_k-weighted peak acceleration + MGSLp} (R^2 = 0.87), and {PL + (CSEL-ASEL)} (R^2 = 0.86). Any model containing PL appears to be a good predictor of annoyance caused by boom and rattle.

Question 3 asks whether the predictor CSEL-ASEL adds a significant increment in predictive ability to models containing loudness level only. This question is tested using a partial F-test[19]. For boom alone ($F(1,47) = 33.01$, $p<0.001$), boom and rattle together ($F(1,109) = 44.56$, $p<0.001$), and all signals, including boom alone, rattle alone, and boom and rattle together, ($F(1,204) = 82.42$, $p<0.001$), CSEL-ASEL adds a significant increment in predictive ability to a model containing PL alone.

The predictive capability of PL is better than MGSLp for each signal type, as shown in Table 3. This result was contrary to expectations because MGSLp was a good predictor of annoyance in previous headphone tests[8, 10]. One explanation for this unexpected result is that the headphone tests did not reproduce sufficiently the low-frequency content of the sonic booms. In one headphone study[10], exterior sonic booms were only a subset of impulsive sounds that also included car-door slams, distant gunfire, and blast noises. The Specific Loudness function of MGSLp, which extends only as low as 40 Hz in the software implementation used for this study[20], may be sufficient for other impulsive sounds but not for sonic booms with much lower frequency content. Furthermore, the other headphone study[8] had a narrow PL range of only 7 dB (61.5 dB to 68.5 dB). This restricted range is likely to have prevented a high correlation between annoyance and PL. The range of all metrics used in the current study is much greater, as shown in the final column of Table 3.

4. CONCLUSIONS

The results show that neither of the proposed models in Equations (2) and (3) produced the highest coefficient of determination with annoyance. Instead, this study has yielded the following three major conclusions:

1. **For shaped boom signals alone, w_k-weighted peak acceleration is the best of the investigated single-predictor annoyance models.** The coefficient of determination improves if either PL or MGSL is added to w_k-weighted peak acceleration as a second predictor. If no acceleration data is available, the model of {PL+(CSEL-ASEL)} (R^2 = 0.82) predicts annoyance nearly as well as w_k-weighted peak acceleration (R^2 = 0.87) for shaped boom signals alone.
2. **For rattle sounds alone, PL and MGSLp are equivalent predictors of annoyance, and there is no benefit to adding w_k-weighted peak acceleration to the predictive model.**
3. **For any combination of shaped boom and rattle, the best of the investigated annoyance predictors are {w_k-weighted peak acceleration + PL}, {w_k-weighted peak acceleration + MGSL}, and {PL + (CSEL-ASEL)}.**

These results prompt an important question regarding annoyance caused by shaped sonic booms transmitted indoors. While w_k-weighted peak acceleration has the highest coefficient of determination with annoyance, the results do not distinguish whether subjects are responding to the tactile experience of structural vibration or to the low-frequency acoustic excitation alone, without the tactile vibration. Follow-on tests that isolate the structural vibration from the low-frequency acoustic excitation are needed to reveal the effect of acoustic vs. vibratory stimuli on the annoyance caused by shaped sonic booms transmitted indoors.

Table 3: Coefficients of Determination, R^2, between annoyance and each annoyance model. Shown in parentheses is the bootstrap 95 % Confidence Interval for R^2, calculated using N = 1000 bootstrap samples according to the procedure prescribed by Efron and Tibshirani[21].

Model	Boom Alone	Rattle Alone	Boom and Rattle Together	All Signals	Min/Max metric values across all locations
PL (Eq. 1)	**0.67** (0.56, 0.80)	**0.89** (0.85, 0.94)	**0.80** (0.74, 0.86)	**0.81** (0.77, 0.85)	43.5/75.6 dB
MGSLp	**0.30** (0.17, 0.43)	**0.83** (0.78, 0.91)	**0.54** (0.42, 0.65)	**0.54** (0.47, 0.62)	20.6/77.6 phons
w_k-weighted peak acceleration	**0.87** (0.79, 0.92)	**0.32** (0.08, 0.57)	**0.39** (0.25, 0.53)	**0.36** (0.25, 0.46)	0.01/12 cm/sec^2
dSTL	**0.12** (0.00, 0.28)	**0.45** (0.27, 0.63)	**0.17** (0.08, 0.29)	**0.25** (0.17, 0.34)	0.08/0.58 sones/sec
CSEL-ASEL	**0.20** (0.05, 0.35)	**0.01** (0.00, 0.11)	**0.01** (0.00, 0.02)	**0.01** (0.00, 0.04)	0.7/41.7 dB
LAFmax	**0.60** (0.43, 0.74)	**0.88** (0.84, 0.93)	**0.73** (0.65, 0.81)	**0.71** (0.64, 0.76)	37.1/66.2 dB
PL + (CSEL-ASEL)	**0.82** (0.77, 0.90)	**0.89** (0.86, 0.94)	**0.86** (0.82, 0.91)	**0.87** (0.84, 0.90)	
MGSLp + (CSEL-ASEL) (Eq. 2)	**0.73** (0.64, 0.82)	**0.88** (0.84, 0.92)	**0.78** (0.71, 0.85)	**0.81** (0.76, 0.84)	
PL+ dSTL	**0.67** (0.57, 0.81)	**0.89** (0.86, 0.95)	**0.82** (0.77, 0.88)	**0.82** (0.78, 0.85)	
MGSLp + dSTL (Eq. 3)	**0.30** (0.18, 0.47)	**0.84** (0.78, 0.91)	**0.58** (0.48, 0.70)	**0.54** (0.47, 0.61)	
w_k-weighted peak acceleration + PL	**0.93** (0.91, 0.96)	**0.90** (0.87, 0.95)	**0.87** (0.83, 0.91)	**0.88** (0.85, 0.90)	
w_k-weighted peak acceleration + MGSLp	**0.94** (0.91, 0.97)	**0.89** (0.85, 0.94)	**0.87** (0.83, 0.91)	**0.87** (0.84, 0.90)	

ACKNOWLEDGEMENTS

The authors acknowledge Regina Johns for recruiting and scheduling test subjects, as well as administering hearing tests.

REFERENCES

1. P. D. Schomer, J.W. Sias, and D. Maglieri. "A Comparative Study of Human Response to Blast Noise and Sonic Booms," *Noise Control Eng. J.* **45(4)**, 294-305 (1997).
2. B. M. Sullivan, J. Klos, R. D. Buehrle, D. A. McCurdy, E. A. Haering, Jr., "Human Response to Low-Intensity Sonic Booms Heard Indoors and Outdoors." NASA TM-2010-2116685, (2010).
3. J. Page, K. Hodgdon, C. Hobbs, C. Wilmer, P. Krecker, C. Koenig, T. Holmes, R. Cowart,

T. Gaugler, D. Shumway, J. Rosenberger, and D. Phillips, "Waveforms and Sonic boom Perception and Response (WSPR): Low-boom community response program pilot test design, execution and analysis", Wyle Technical Report WR12-15, submitted to NASA for publication (2012).

4. S. Fidell, R. D. Horonjeff, and M. Harris, "Pilot test of a novel method for assessing community response to low-amplitude sonic booms", NASA CR-2012-217767 (2012).
5. P. D. Schomer and A. Averbuch, "Indoor human response to blast sounds that generate rattles," *J. Acoust. Soc. Am.* **86(2)**, 665–673 (1989).
6. J. D. Leatherwood and B. M. Sullivan, "Recent laboratory studies of loudness and annoyance to sonic booms," Tech. Rep. NASA TM-107756, (1993).
7. S. Fidell, L. Silvati, and K. Pearsons, "Relative rates of growth of annoyance of impulsive and non-impulsive noises," *J. Acoust. Soc. Am.* **111(1)**, 576–585 (2002).
8. A. Loubeau, B. M. Sullivan, J. Klos, J. Rathsam, and J. R. Gavin. "Laboratory headphone studies of human response to low-amplitude sonic booms and rattle heard indoors." NASA TM-2013-217975 (2013).
9. J. Rathsam, A. Loubeau, J. Klos. "A Study in a New Test Facility on Indoor Annoyance Caused by Sonic Booms." NASA TM-2012-217332 (2012).
10. A. J. Marshall, "Development of a model of startle resulting from exposure to sonic booms," Ph.D. dissertation, Purdue University (2012).
11. K. P. Shepherd and B. M. Sullivan, "A loudness calculation procedure applied to shaped sonic booms," NASA TP-3134 (1993).
12. R. L. Bennett and K. S. Pearsons. *Handbook of aircraft noise metrics*. Technical Report N81-21871, U.S. Department of Commerce, National Technical Information Service (1981).
13. B. C. J. Moore, B.R. Glasberg, and T. Baer, "A model for the prediction of thresholds, loudness, and partial loudness," *J. Audio Eng. Soc.* **45(4)**, 224-240 (1997).
14. B. R. Glasberg and B. C. J. Moore, "A model of loudness applicable to time-varying sounds," *J. Audio Eng. Soc*, **50(5)**, 331–342 (2002).
15. A. Kjellberg, M. Tesarz, K. Holmberg, and U. Landstroem. "Evaluation of frequency-weighted sound level measurements for prediction of low-frequency noise annoyance," *Environ. Int.* **23(4)** 519-527 (1997).
16. J. Vos, "On the annoyance caused by impulse sounds produced by small, medium-large, and large firearms," *J. Acoust. Soc. Am.*, **109(1)**, 244-253 (2001).
17. *Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration–Part 1:General requirements*, 1997. ISO 2631-1:1997(E).
18. J. Klos, "Overview of an indoor sonic boom simulator at NASA Langley Research Center," *Proc. INTER-NOISE 2012*, New York, New York, USA.
19. W. Hays, *Statistics*. (Wadsworth, Belmont, CA, 1994), p. 420.
20. Genesis S.A.: Loudness Toolbox [for Matlab] (2009). Available from http://www.genesis-acoustics.com/en/index.php?page=33
21. B. Efron and R. Tibshirani, "Bootstrap Methods for Standard Errors, Confidence Intervals, and Other Measures of Statistical Accuracy." *Statistical Science*, **1(1)**, 54-77 (1986).