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## NOISE AND VIBRATION RIDE COMFORT CRITERIA

By

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October 1976



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16. Abstract

A program is underway at Langley Research Center to develop a comprehensive ride quality model based upon the various physical and psychological factors that most affect passenger ride comfort. Two of the most important factors, namely, vibration and noise were studied to (1) determine whether composite or separate noise and vibration criteria are needed for the prediction of ride quality, (2) determine a noise correction for the previously-defined vibration criteria of the ride quality model, (3) assess whether these noise corrections depend on the nature of the vibration stimuli, i.e., deterministic as opposed to random, and (4) specify noise-vibration criteria for this combined environment. The stimuli for the study consisted of octave bands of noise centered at 500 or 2,000 Hz and vertical vibrations composed of either 5 Hz sinusoidal vibration or random vibrations centered at 5 Hz and with a 5 Hz bandwidth. The noise stimuli were presented at levels ranging from ambient to 95 dB(A) and the vibrations at levels ranging from 0.02 to $0.13g_{rms}$.

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# NOISE AND VIBRATION RIDE COMFORT CRITERIA

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# INTRODUCTION

The accurate prediction of passenger discomfort in various transportation vehicles necessitates appropriate empirical integration of the key factors (e.g., noise, vibration, etc.) known to influence ride quality. Previous work at NASA Langley Research Center has concentrated upon that portion of information needed in a comprehensive multifactor ride quality model (refs. 1-12) for prediction of discomfort associated with vibration. This paper represents an extension of this vibration work and a continuation of a preliminary study (ref. 13) of noise and vibration with the goal of predicting passenger discomfort within a complex environment. The initial investigation (ref. 13) of discomfort associated with a noise and vibration environment supplied information that (1) passengers can separate the influence of noise and vibration on discomfort when using separate noise discomfort and vibration discomfort category scales; the remaining problem being apparently to determine how the separate subjective reactions combined for prediction of overall discomfort and (2) that when passengers provide an overall discomfort response, there is an interactive influence of noise and vibration on overall discomfort; the implication of these results being that mere summation of noise and vibration effects will never accurately predict overall discomfort. These latter results are important because they imply that composite noise-vibration criteria are needed for the prediction of ride quality rather than separate noise and vibration criteria (perhaps successive in nature). Therefore, the present study, as a continuation of this initial investigation, included objectives to (1) verify and document the interactive effect of noise and vibration on overall discomfort through the use of different subjects and experimental methods, (2) determine a noise correction for the ride quality model based upon the psychophysical relationship between noise discomfort and noise level (dB(A)) within a vibration environment, (3) assess whether this noise correction depends upon the nature of the vibration stimuli, and (4) specify initial noise-vibration discomfort criteria.

## METHOD

The objectives of the investigation were achieved through exposure of subjects to noise and vibration combinations. The following sections provide a review of the NASA Langley Passenger Ride Quality Apparatus (PRQA) which was used in the investigation as well as a short description of the subjects and procedure.

### Simulator

The apparatus used was the Langley Passenger Ride Quality Apparatus (PRQA). The PRQA is described briefly in this section and a detailed description is presented in references 14 and 15. The PRQA and associated programing and control instrumentation are shown in the photographs of figure 1 on the next page. Figure 1(a) shows the waiting room where subjects are instructed as to their participation in the experiment, complete questionnaires, etc. Figures 1(b) and 1(c) are photographs of the exterior of PRQA, and it should be noted that the actual mechanisms which drive the simulator are located beneath the pictured floor. Shown in figure 1(d) is a model of the PRQA indicating the supports, actuators, and restraints of the three-axis drive system. The control console is shown in figure 1(e) and is located at the same level as the simulator to allow the console control operator to constantly monitor subjects within the simulator. An interior view of PRQA fitted with tourist-class aircraft seats is shown in figure 1(f). Additional interior views (with front or back panels removed) of PRQA are displayed in figures 1(g), 1(h), and 1(i). Noise was produced by a noise generator and played through an octave filter into the sound system.

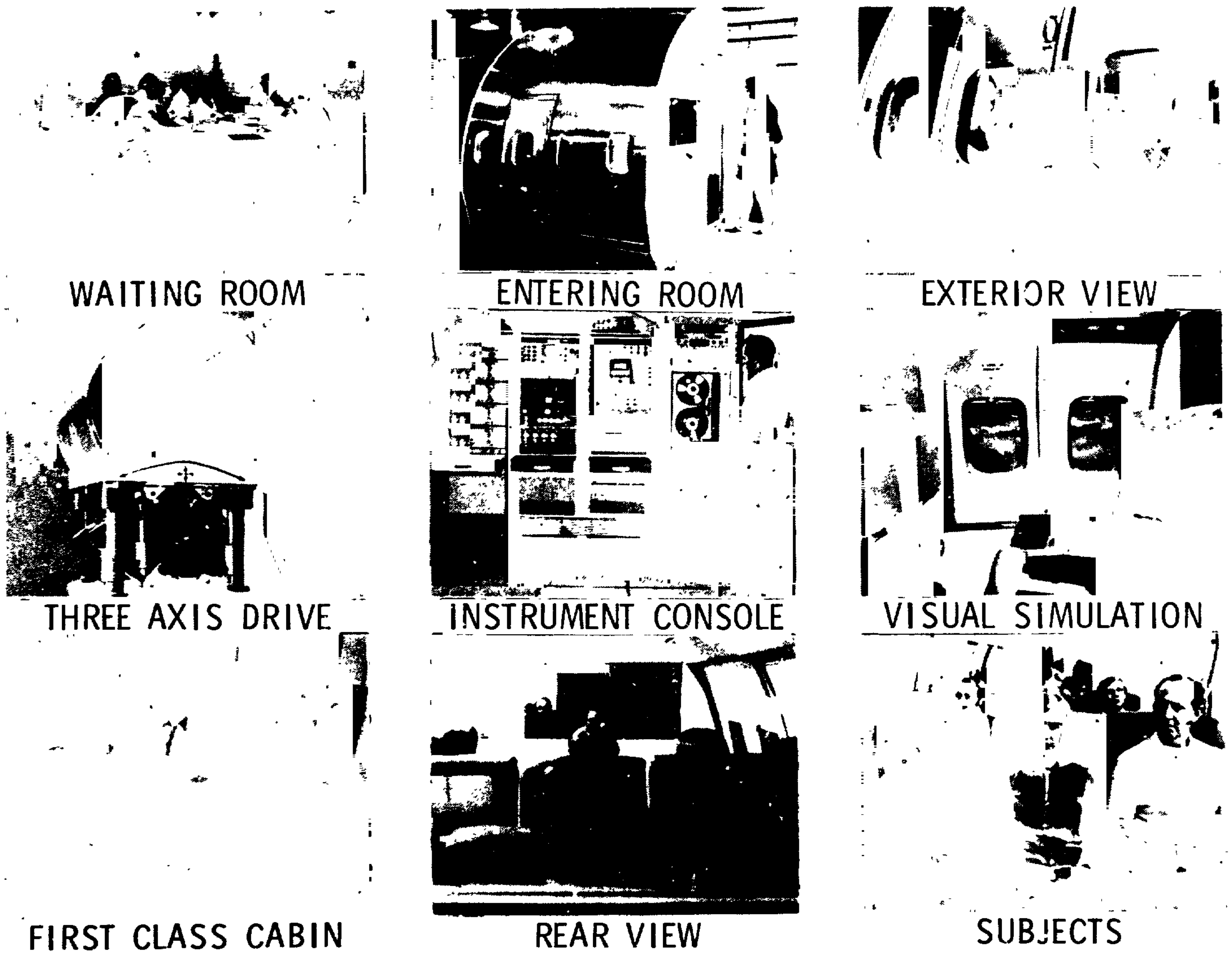


Figure 1.- Passenger Ride Quality Apparatus.

## SUBJECTS

A total of 48 subjects (8 males and 40 females) participated in the study. The volunteer subjects were obtained from a contractual subject pool and were paid for their participation in the study. The ages of the subjects ranged from 18 to 55 years, with a median age of 28 years. The mean weight of the subjects was 62 kg (136.67 lb), with a standard deviation of 11 kg (24.04 lb). All subjects were audiometrically screened and had normal hearing.

### Procedure

The task for each subject (six subjects concurrently) was to provide magnitude estimations of successive "comparison ride segments" relative to a "standard ride segment" assigned the numerical value of 100. Table I displays the design of the present investigation and indicates a comparison ride segment is defined as a particular experimental condition that resulted from a parametric combination of selected vibrations and noise. The comparison ride segments were vertical 5 Hz vibrations, either sinusoidal or random (with a 5 Hz bandwidth) in nature, each presented at 0.02, 0.042, 0.064, 0.085, 0.106, or 0.130$g_{rms}$. The noises were octave bands of random noise centered at 500 or 2,000 Hz and each presented at ambient ($\approx$65), 75, 85, and 95 dB(A). The "standard" ride segment was always sinusoidal in nature, presented at 0.074$g_{rms}$ at ambient noise conditions. Through the use of a red indicator light, the subjects were informed of the time period (ride segment duration) on which to base their evaluation (magnitude estimation). The subjects were instructed to ignore rise and decay vibrations (and noise) that occurred prior to and subsequent to illumination of the indicator light. Each of the comparison ride segments lasted 15 seconds, the standard ride segments 10 seconds, with an additional 2 seconds each of rise and decay time (for both comparison and standard ride segments), and a 5 second time period between successive ride segments. Appropriate randomization and counterbalancing were used for presentation of the noise-vibration stimuli to subjects.

TABLE I.- EXPERIMENTAL DESIGN

| VIBRATION | | NOISE | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | dB(A) - Oct. Band CTR. Freq. | | | | | | |
| TYPE | $g_{rms}$ | AMBIENT | 75 | | 85 | | 95 | |
| | | | 500 | 2K | 500 | 2K | 500 | 2K |
| SINUSOIDAL 5 Hz | 0.020 | | | | | | | |
| | 0.042 | | | | | | | |
| | 0.064 | | | | | | | |
| | 0.085 | | | | | | | |
| | 0.106 | | | | | | | |
| | 0.130 | | | | | | | |
| RANDOM 5 Hz | 0.020 | | | | | | | |
| | 0.042 | | | | | | | |
| | 0.064 | | | | | | | |
| | 0.085 | | | | | | | |
| | 0.106 | | | | | | | |
| | 0.130 | | | | | | | |

## RESULTS AND DISCUSSION

This section provides results and discussion related to the four objectives listed in the introduction. The implication of these results for the ride quality model (refs. 1-3) are briefly discussed

### Physical Stimulus Effects

In order to provide an overall summary of the effects of noise and vibration on passenger discomfort, an analysis of variance was computed. The analysis of variance (2 x 6 x 3 x 2) consisted of factorial combinations of two types of vibration (random or sinusoidal) each at six levels of acceleration (0.020, 0.042, 0.064, 0.085, 0.106, and $0.130g_{rms}$), with three levels of noise (75, 85, or 95 dB(A)) each for two different octave bands of noise (500 and 2,000 Hz center frequencies), with repeated measures on all dimensions. Table II provides a summary of this analysis. Note that all the main effects (except vibration type) as well as most of their double and triple interactions were significant. The discomfort variation associated with these main effects and interactions are discussed in subsequent sections. An initial implication, however, is that all four of the physical characteristics (type of vibration, acceleration level of vibration, noise level, and octave bandwidth of noise) either singularly (main effects) or in combination (interactive effects) cause variation in passenger discomfort. The importance of these interactions for the ride quality model is discussed in successive sections.

TABLE II.- SUMMARY OF ANALYSIS OF VARIANCE FOR OVERALL DISCOMFORT RESPONSES

| Source | Sum of Squares | df | Mean Sq. | F |
|---|---|---|---|---|
| T Vibration Type<br>Error (SXT) | $1.10 \times 10^5$ | 1 | $1.10 \times 10^5$ | .68 |
| A Accel. Level, $g_{rms}$<br>Error (SXA) | 609.67 | 5 | 121.93 | 72.62* |
| D Noise Level, dB(A)<br>Error (SXD) | 837.01 | 2 | 418.51 | 93.89* |
| F Octave Bands<br>Error (SXF) | 210.94 | 1 | 210.94 | 60.81* |
| S Subjects | 1472.19 | 47 | 31.32 | ---- |
| TXA Interaction<br>Error (SXTXA) | 9.90 | 5 | 1.98 | 4.15* |
| TXD Interaction<br>Error (SXTXD) | 2.77 | 2 | 1.38 | 2.58 |
| AXD Interaction<br>Error (SXAXD) | 35.92 | 10 | 3.59 | 9.18* |
| TXF Interaction<br>Error (SXTXF) | 1.76 | 1 | 1.76 | 5.54* |
| AXF Interaction<br>Error (SXAXF) | 9.91 | 5 | 1.98 | 6.27* |
| DXF Interaction<br>Error (SXDXF) | 179.68 | 2 | 89.84 | 39.96* |
| TXAXD Interaction<br>Error (SXTXAXD) | 7.01 | 10 | .70 | 1.84* |
| TXAXF Interaction<br>Error (SXTXAXF) | .85 | 5 | .17 | .39 |
| TXDXF Interaction<br>Error (SXTXDXF) | .68 | 2 | .34 | .78 |
| AXDXF Interaction<br>Error (SXAXDXF) | 13.60 | 10 | 1.36 | 3.63* |
| TXAXDXF Interaction<br>Error (SXTXAXDXF) | 4.22 | 10 | .42 | 1.05 |

*$p<0.05$

## Interaction: Noise Level x Vibration Level

This section addresses the effect on overall passenger discomfort of noise and vibration level variations. In order to allow interpretation of these results within the ride quality model, the subjective responses are displayed in terms of both magnitude estimations of discomfort and DISC (discomfort) values. The DISC values merely represent an anchoring of the magnitude estimations relative to the "standard ride segment" which was 5 Hz @ $0.074g_{rms}$ and received a DISC value equal to 2.147 based on previous research (e.g., ref. 9).

Figures 2 and 3 display for sinusoidal and random vibration the DISC values (and magnitude estimations) that occurred as a function of noise level (dB(A)) for different levels of vibration acceleration. These figures represent a division of variance associated with the significant TxAxD interaction (vibration type x acceleration level x noise level). The main effects and double interactions associated with the triple TxAxD interaction are discernible within the figures. These figures and the analysis of variance show that discomfort is a function of (1) vibration type (indicated only through interactions), (2) acceleration level of vibration, (3) noise level, and (4) various interactions of these variables. Simply stated, the significant interactions mean that systematic variations of responses occur that can not be predicted from the sum of the effects of the two variables (e.g., noise level and vibration acceleration level) considered separately. Thus, a need for composite criteria for noise and vibration in a ride quality model is implied. This result is qualified in a subsequent section.

The existence or lack of interactions can depend upon the scale of subjective measurement. Based on this fact and the apparent power-type relationship (logarithmic by logarithmic) between the discomfort data and noise level, an analysis of variance was based on the logarithms of the discomfort responses. This analysis reduced but did not remove the interactions. Given this information, plus the rather systematic linear increase of discomfort with acceleration level (for a constant noise level) the possibility exists that different psychophysical relationships (e.g., power for noise and linear for vibration) are embedded within a passenger's overall discomfort reaction to the combined environment. If this is the case, the existence of interactions (e.g., noise and vibration) may simply be an artifact of analyses of overall reactions. The possibility of several different psychophysical relationships is explored in a subsequent section.

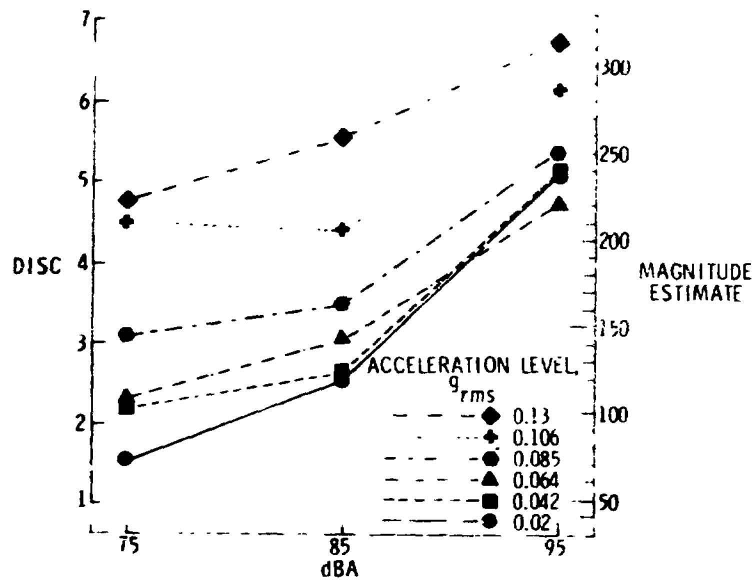


Figure 2.- Discomfort as a function of noise level for various levels of sinusoidal vibration.

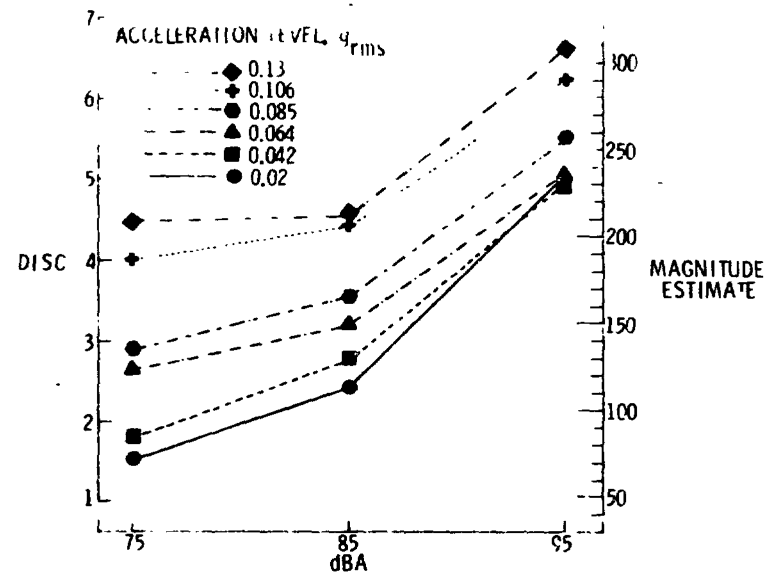


Figure 3.- Discomfort as a function of noise level for various levels of random vibration.

## Interaction: Noise Level x Octave Band

Figures 4 and 5 display for sinusoidal and random vibration the DISC values (and magnitude estimations) that occurred as a function of noise level (dB(A)) for different octave bands of noise. The similarity of these figures and previous results (Table II) indicate that despite the significance of the main effects of noise level and octave bands, as well as their interaction, these effects are common to random or sinusoidal vibration conditions. Implications of these results are that (1) distinctions between vibration types (random or sinusoidal) are not needed for the assessment of noise characteristics on overall discomfort, and (2) information of both the noise level and spectrum content of a noise are needed for the prediction of ride quality. Relative to this latter point, since different octave band conditions produced systematic response differences, information regarding spectrum content may not be needed if an appropriate physical noise-level measure other than the A-weighting is derived.

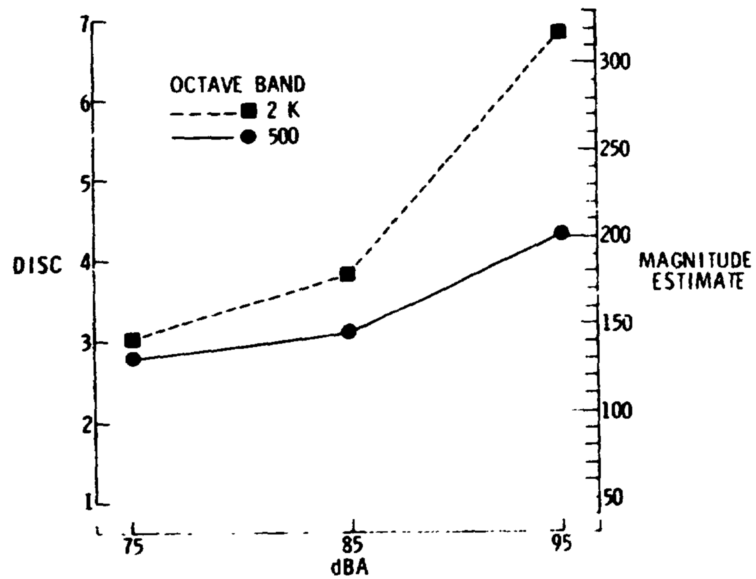


Figure 4.- Discomfort as a function of noise level for different octave bands of noise in a sinusoidal vibration environment.

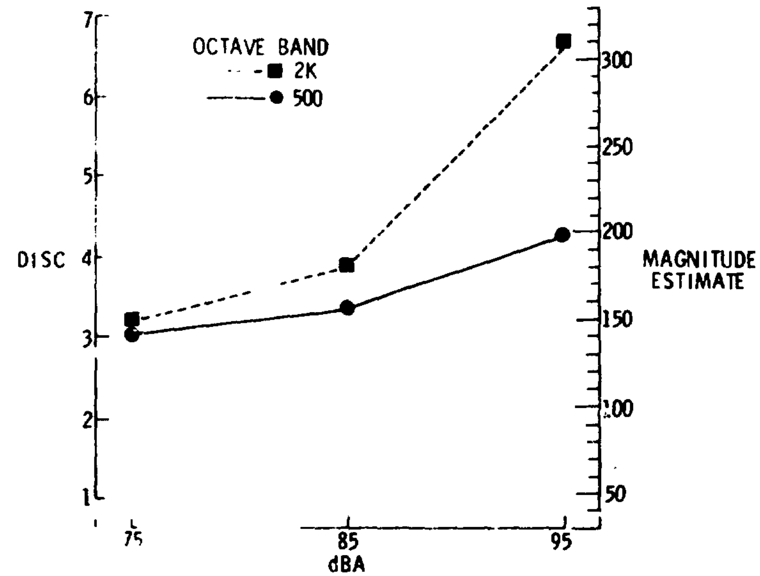


Figure 5.- Discomfort as a function of noise level for different octave bands of noise in a random vibration environment.

### Interaction: Acceleration Level x Octave Band

Figures 6 and 7 display for sinusoidal and random vibrations the DISC values (and magnitude estimations) that occurred as a function of vibration acceleration level for different octave bands of noise. These figures represent a division of variance associated with the TxAxF (vibration type x acceleration level x octave band) interaction which was not significant. The only source of variance represented in the figures and not discussed previously is the TxF (vibration type x octave band) interaction. Due to the similarity of the two figures, this interaction is based on a small amount of variability and for practical purposes is not of major importance.

### Summary of Interactions

Analyses of overall discomfort responses obtained in this study indicated that various characteristics of noise and vibration, as well as the interaction of these factors, influenced ride quality. The major implication of these interactive effects being that composite noise and vibration criteria rather than separate criteria are needed for the prediction of ride quality. This conclusion is qualified in a subsequent section. In addition in order to understand overall discomfort responses, attention was called to the need for (1) division of overall discomfort responses into components of noise discomfort and vibration discomfort and exploration of the psychophysical relationship between each type of response and its respective physical factor, and (2) determination of the approprirate physical measure of noise for accurate prediction of subjective reactions in the combined noise-vibration environment.

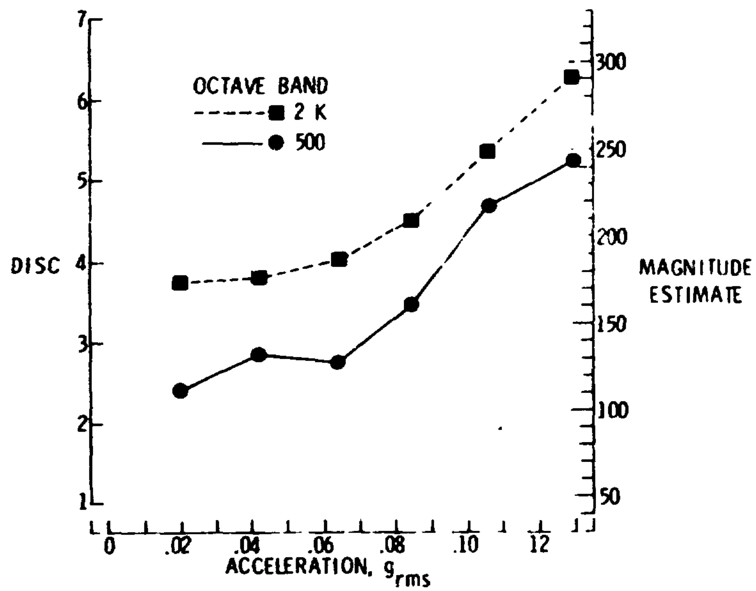


Figure 6.- Discomfort as a function of sinusoidal vibration acceleration levels for different octave bands of noise.

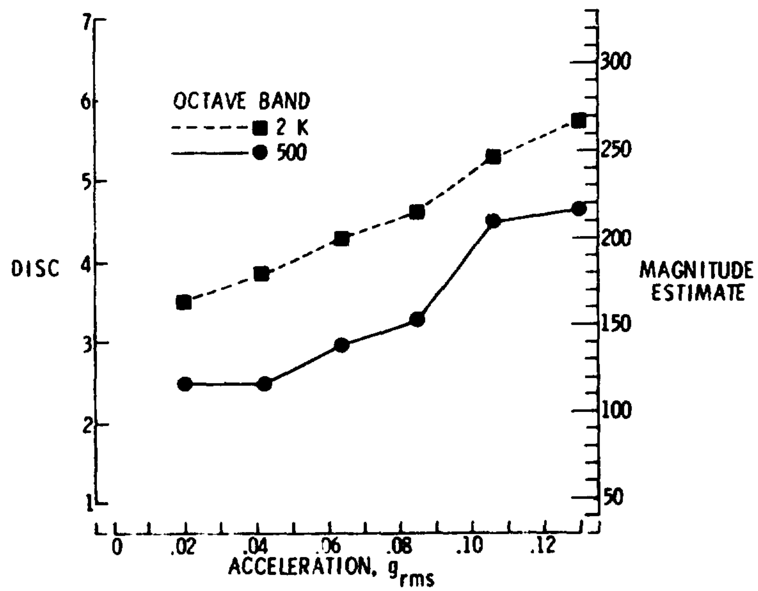


Figure 7.- Discomfort as a function of random vibration acceleration levels for different octave bands of noise.

## Noise Discomfort Modeling

The second and third objectives given in the introduction which relate to a noise correction for the ride quality model are addressed in this section. The experimental design provided for exposing passengers to the same vibrations (e.g., acceleration level x frequency) under ambient and various noise-level conditions. Therefore, theoretically the discomfort attributable to noise could be represented as the difference in discomfort between ride segments with and without noise exposure as displayed in formula (1):

$$DISC_{noise} = DISC_{vibration + ndB(A)} - DISC_{vibration\ only} \qquad (1)$$

where DISC is discomfort.

This formula is meaningful if noise and vibration do not interact and consequently the influence of each physical factor is specifiable as a certain contributor of overall discomfort. Evaluation and use of formula (1) is, therefore, dependent upon the reduction or removal of these statistically significant interactions (e.g., noise level x acceleration level). Earlier analyses in this paper provided suggestive information that (1) these interactions may be an artifact of the linear analyses of overall discomfort responses, and (2) there may be two psychophysical relationships embedded in overall discomfort responses; namely, the logarithm of noise discomfort increases linearly with dB(A) (e.g., power relationship) and there is a simple linear relationship between vibration discomfort and vibration acceleration level. These latter relationships formed the basis for evaluation of formula (1).

Table III displays a summary of analyses of variance (ref. 16) of noise discomfort responses (computed according to formula (1)) as well as logarithmic values of these same responses. These analyses were computed to determine the degree of interaction (nonadditivity) of noise and vibration. The analyses of variance were for factorial (6x3) combinations of vibration (six levels) with noise (three levels). The noise discomfort responses were averaged across octave bands because of the likelihood that the systematic difference between these conditions is a problem of physical measure specification (for noise level) rather than related to the interaction of interest. In addition, noise discomfort responses were averaged for random and sinusoidal vibrations because there was no statistical difference between the noise discomfort responses obtained under random or sinusoidal vibration. The latter results are of importance to development of the ride quality model. The implication of these results being that a noise correction could be obtained under either conditions of vibration, i.e., deterministic or random.

TABLE III.- SUMMARY OF ANALYSES OF VARIANCE FOR BOTH LINEAR AND LOGARITHMIC VALUES OF NOISE DISCOMFORT RESPONSES

| Source | Degrees of Freedom | Linear | | | Logarithmic | | |
|---|---|---|---|---|---|---|---|
| | | Sum of Squares | Mean Square | F | Sum of Squares | Mean Square | F |
| A Vibration Level | 5 | 2.1602 | | | .5041 | | |
| B Noise Level | 2 | 21.6025 | | | 3.9180 | | |
| AXB Interaction | 10 | 1.0096 | | | .1949 | | |
| Nonadditivity | 1 | .8858 | .8858 | 64.1884* | .0003 | .0003 | .0139 |
| Balance | 9 | .1238 | .0138 | | .1946 | .0216 | |

*$p<0.05$

The results of Table III indicate there is a significant interaction of noise and vibration for noise discomfort responses (linear data) but not for logarithms of these same responses. Logarithms of noise discomfort responses are displayed in figure 8 as a function of noise level (dB(A)) for each level of vibration acceleration. The other component of overall discomfort, vibration discomfort, is displayed in figure 9 as a function of vibration acceleration level, for both random and sinusoidal vibrations. The results of Table III and figures 8 and 9 indicate (1) the use of formula (1) is appropriate for the division of overall discomfort into components associated with noise discomfort and vibration discomfort; the use of logarithms of the noise discomfort component removed the interaction of noise and vibration, the implication being that separate but successive noise and vibration criteria are sufficient for the prediction of ride quality, (2) the subjective responses of vibration discomfort increase linearly as a function of vibration acceleration level (linear relationship), and (3) the logarithms of subjective noise discomfort responses increase linearly with dB(A) (power relationship). This power-type psychophysical function defines the noise correction for the ride quality model.

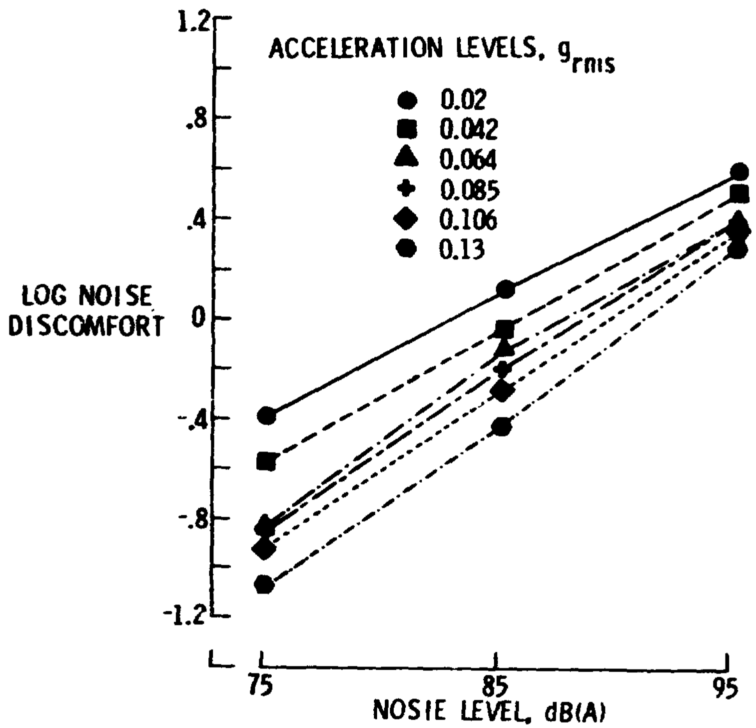


Figure 8.- Logarithms of noise discomfort as a function of noise level for various vibration acceleration levels.

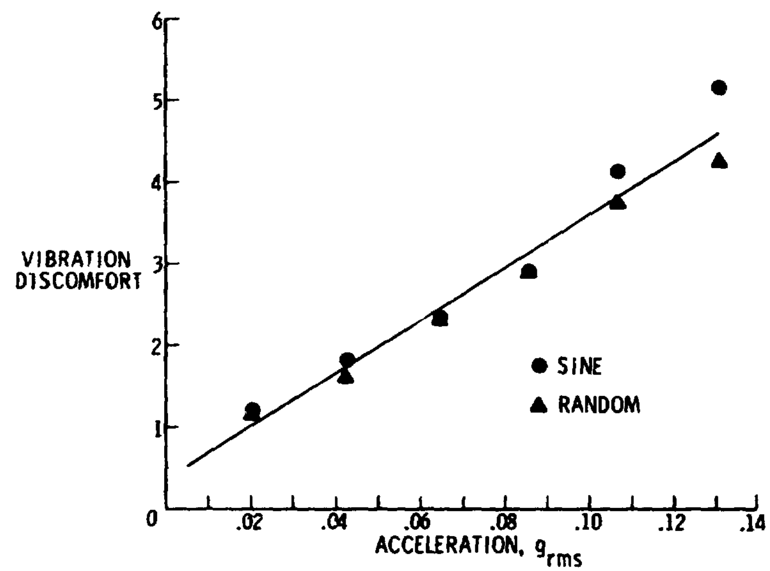


Figure 9.- Vibration discomfort as a function of vibration acceleration level.

## Noise-Vibration Criteria

This section addresses the fourth objective given in the introduction, to determine noise-vibration criteria for ride quality. Figure 10 displays a set of constant overall discomfort curves for the combined environment of noise and vibration. These curves were generated through combination of the information of the psychophysical functions for noise discomfort and vibration discomfort (figs. 8 and 9). The individual curves of figure 10 indicate the noise level (dB(A)) and vibration acceleration level ($g_{rms}$) required to produce constant amounts of overall discomfort for the noise and vibrations of the present study. This figure shows constant discomfort curves ranging from a value of one (DISC = 1), which is approximately the discomfort threshold, to values as high as DISC = 7 corresponding to seven times the discomfort threshold, or a very high level of discomfort. There are several important facts and implications that should be pointed out regarding these criteria curves. These facts include: (1) that the curves supply a single source of information for interpretation of the overall discomfort of a combined noise and vibration environment, (2) the benefits to ride quality are predictable from trade-off changes (either increases or decreases) between noise and vibration for this combined environment, (3) the threshold of noise discomfort in this combined environment is approximately 75 dB(A), and (4) beyond a noise level of approximately 95 dB(A), the vibration acceleration level covered in this investigation is of minor importance.

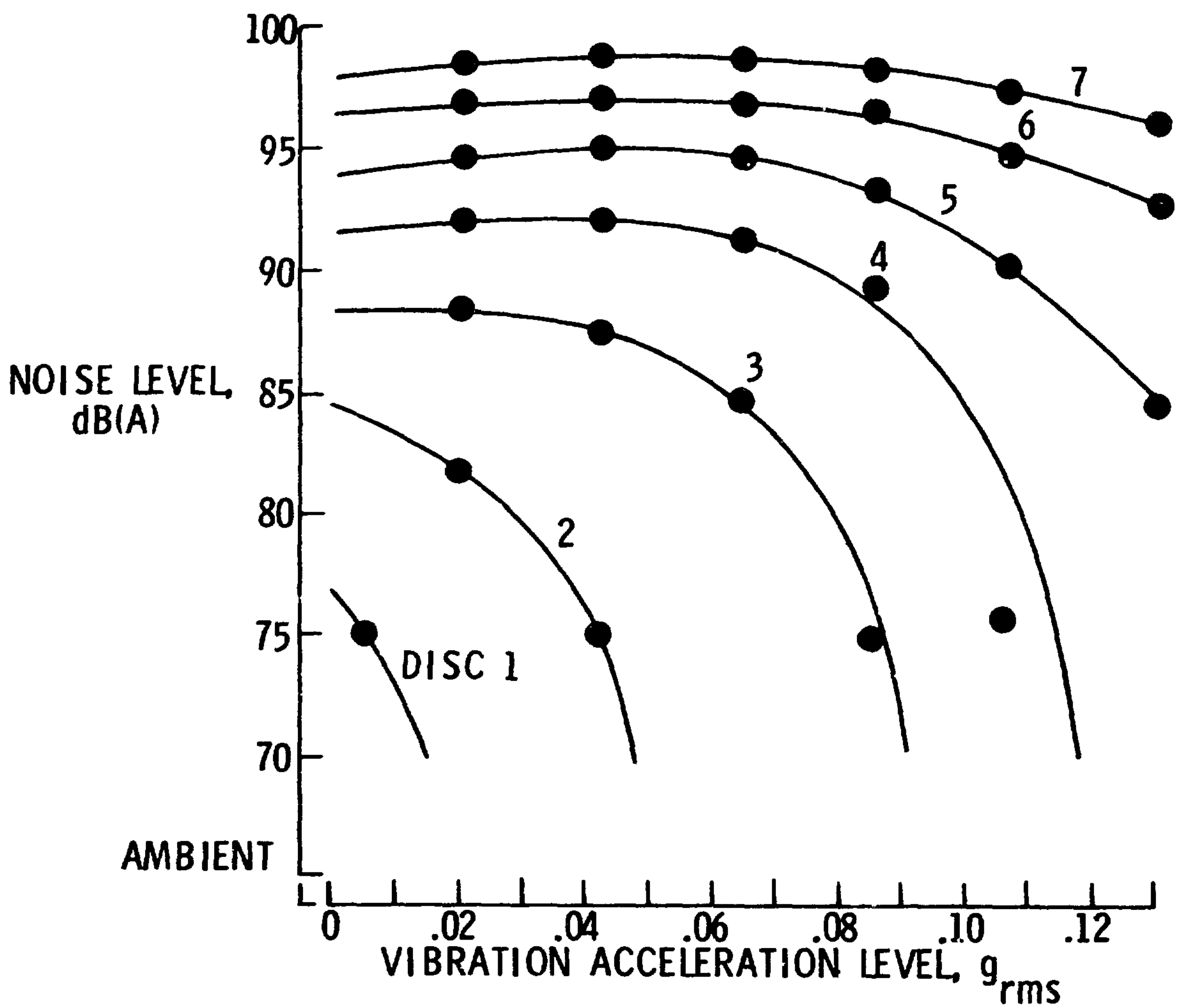


Figure 10.- Noise level (dB(A)) required to produce successive constant discomfort curves as a function of vibration acceleration level.

## CONCLUSIONS

Major conclusions derived from this investigation include: (1) the interactive effect of noise and vibration that results from analyses of overall discomfort responses is an artifact that disappears with the division of these global responses into noise discomfort and vibration discomfort, (2) through this division of overall discomfort, successive noise and vibration criteria rather than composite criteria appear appropriate for the prediction of ride quality, (3) through the division of the complex overall discomfort responses (which had no simple identifiable psychophysical functions) into components of noise discomfort and vibration discomfort, two different but simple psychophysical relationships were established to account for overall subjective reactions; the subjective responses of vibration discomfort increased linearly as a function of vibration acceleration (linear relationship) whereas the logarithmic values of subjective noise discomfort responses increased linearly with dB(A), (4) this latter power-type psychophysical function defines the noise correction for the ride quality model, (5) the noise correction values are similar if obtained from a random or sinusoidal vibration environment, and (6) a set of noise-vibration criteria curves were developed that supply a single source of information for interpretation of the overall discomfort associated with various combinations of noise and vibration.

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