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NASA TM X- 72623

COPY NO.

(NASA-TM-X-72623) A MODEL AND PREDICTIVE SCALE OF PASSENGER RIDE DISCOMFORT (NASA) 30 p HC $3.75 CSCL 05E

N75-13523

Unclas

G3/53 03646

A MODEL AND PREDICTIVE SCALE OF PASSENGER RIDE DISCOMFORT

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December 1974

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER, HAMPTON, VIRGINIA 23665

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM X-72623		
4. Title and Subtitle: A MODEL AND PREDICTIVE SCALE OF PASSENGER RIDE DISCOMFORT		5. Report Date: December 1974
		6. Performing Organization Code
7. Author(s): Thomas K. Dempsey		8. Performing Organization Report No.: TM X-72623
9. Performing Organization Name and Address: NASA-Langley Research Center, Hampton, VA 23665		10. Work Unit No.: 504-09-21-01
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address: National Aeronautics and Space Administration, Washington, DC 20546		13. Type of Report and Period Covered: Technical Memorandum
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

A model to define the interrelationship of the various factors (vibratory and nonvibratory) important to passenger comfort, in realistic transport vehicle vibration environments was developed as part of a ride quality program at NASA-Langley Research Center. The model, in addition to representing a mechanism for obtaining consistent information on the effects of vibratory and nonvibratory factors on passenger discomfort, represents: (1) a framework for the investigation of comfort within diverse transportation vehicles, (2) a mechanism for the development of a scale of comfort, (3) a mechanism through which design criteria can be obtained for improving the rideability of current and future transportation vehicles, and (4) a tool for obtaining information for the maximization of passenger ride quality, based upon sociological and psychological information.

The application of the model is based upon the computational steps necessary for derivation of the comfort scale. The emphasis within the scale is upon the summation of comfort units; the summation being obtained through the use of appropriately determined weighting factors, both within and between axes.

17. Key Words (Suggested by Author(s)) (STAR category underlined)	18. Distribution Statement
comfort, human comfort, passenger comfort, vibration, masking, human factors, human engineering — <u>05</u>	Unclassified Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	28	$3.75

*Available from The National Technical Information Service, Springfield, Virginia 22151; STIF/NASA Scientific and Technical Information Facility, P.O. Box 33, College Park, MD 20740

A MODEL AND PREDICTIVE SCALE OF PASSENGER RIDE DISCOMFORT

BY· THOMAS K. DEMPSEY

LANGLEY RESEARCH CENTER

ABSTRACT

A model to define the inter-relationship of the various factors (vibratory and non-vibratory) important to passenger comfort, in realistic transport vehicle vibration environments was developed as part of a ride quality program at NASA - Langley Research Center. The model, in addition to representing a mechanism for obtaining consistent information on the effects of vibratory and non-vibratory factors on passenger discomfort, represents: (1) a framework for the investigation of comfort within diverse transportation vehicles, (2) a mechanism for the development of a scale of comfort, (3) a mechanism through which design criteria can be obtained for improving the rideability of current and future transportation vehicles, and (4) a tool for obtaining information for the maximization of passenger ride quality, based upon sociological and psychological information.

The application of the model is based upon the computational steps necessary for derivation of the comfort scale. The emphasis within the scale is upon the summation of comfort units; the summation being obtained through the use of appropriately determined weighting factors, both within and between axes.

INTRODUCTION*

There have been numerous investigations (e.g., see refs. 1-7) of the effects of vibration on passenger comfort. However, there remains a lack of information on the empirical relationship (e.g., whether linear, logarithmic, etc.) between the total comfort response and the vibration as well as other interactive factors such as noise, temperature, ventilation, etc. The total comfort response refers to the subjective reaction obtained from the exposure of human subjects to random and multidimensional vibration inputs as well as the other environmental factors encountered in diverse transportation vehicles. The lack of such information can be conceptualized as arising from the absence of an integrative model of comfort. The model, the goal of which is comprehensive criteria specification, must account for both multifrequency and multiaxis vibration as well as nonvibratory factors.

In the past, criteria specifications were not based on an integrative model and as a consequence were quite incomplete. In general, these previous criteria utilized some form of equal comfort contour (e.g., see refs. 8-22). The most common comfort contour is the type recommended by ISO (see ref. 8), which is an acceleration-frequency contour based upon sinusoidal tests of subjects. The construction

*The author wishes to acknowledge the assistance, at various stages, of Walter Gunn, Jack Leatherwood, and David Stephens.

of equal comfort curve criteria has resulted in a multiplicity of comfort boundaries that vary considerably for different studies. The variation in these boundaries is possibly attributable to the use of different adjectives for boundary demarcation. These boundary type problems are futher complicated through an emphasis upon dichotomous zones (e.g., comfortable vs. uncomfortable), to the relative exclusion of the continuous nature of discomfort responses to increases in acceleration. More important, the construction of comprehensive criteria based on such boundaries is severely limiting because of: (1) the boundaries are derived for sinusoidal inputs and may not apply to multiple frequency inputs; and (2) there is a lack of such comfort boundaries or criteria for all axes of vibration.

In using equal comfort contours, the measured acceleration is usually expressed in the form of amplitude exceedance, power spectral density, absorbed power, 1/3-octave band level, etc., for evaluating the random vibration ride environment of vehicles. However, there are some assumptions and limitations associated with these approaches that prevent comprehensive criteria specification. The analysis of vibrations through the use of amplitude exceedances, for example, is based on percentages of time that a ride (or component) exceeds a preselected amplitude level, the exact level of which varies for different studies, and which may or may not be weighted for various frequencies. The studies that use this form of analysis thus assume the existence of valid criteria rather than representing investigations for criteria determination. More importantly, one implication of the use of the analysis is that amplitude variations below a preselected level are not important determiners of discomfort.

Another limitation of previous approaches to criteria specification has been a lack of methods for handling multiple frequency components. The mere algebraic summation of discomfort (units) associated with separately experienced frequency components, assume the nonexistence of masking of vibrations within an axis. The problem is magnified when one considers rides composed of vibrations in several axes. For the comfort analysis of these complex rides, there is an absence of empirical laws for the summation of discomfort (units or weights) that is associated with each axis. Analogously, the mere algebraic summation of the discomfort units of each axis, or the absence of between axis comfort summation laws, assumes the nonexistence of masking between axes. In addition to these limitations, none of the previous approaches provides for nonvibratory corrections. There is a lack in the final estimates (scales) of comfort for the influence of environmental, performance, temporal, personality, demographic, and biophysiological factors.

There are several reasons for the lack of integrative model of comfort. However, foremost among these reasons has been the inability to expose people to multiple-degree-of-freedom vibrations under controlled conditions. This problem has been partially overcome through the development and use of the Passenger Ride Quality Apparatus (PRQA), located at NASA-Langley Research Center, for simulation of ride vibration environments. A brief discussion of PRQA will be presented in the next section. Subsequent to this discussion, successive sections will address the model, its application, and the computational steps of the model.

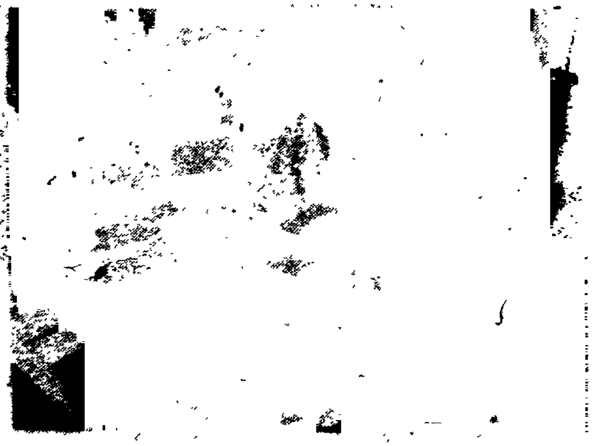
The purpose of the present paper is to describe an integrative comfort model. The proposed model has been constructed so as to remove both the limitations delineated in the previous paragraphs and to allow derivation of a comfort scale based on single and multiple axis effects, masking effects (within and between axes), and nonvibratory factor corrections. In addition to representing a mechanism for obtaining consistent information about the effects of vibration and other interactive factors such as noise on human discomfort, the resultant model will represent: (1) a framework for the investigation of comfort within diverse transportation vehicles, (2) a mechanism for the development of a scale of comfort rather than a scale of sensitivity, (3) a mechanism through which design criteria can be developed for improving the rideability of current and future transportation vehicles, and (4) a tool for obtaining information for the maximization of passenger ride quality based upon sociological and psychological information.

SIMULATOR

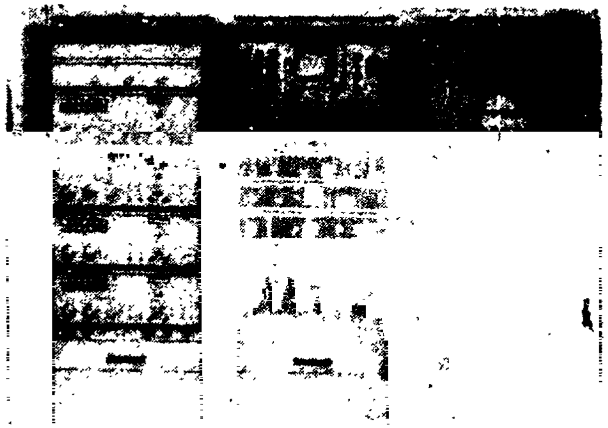
The photographs of the Passenger Ride Quality Apparatus (PRQA) and appropriate programming equipment are displayed in figure 1 on the next page. Included in the photographs are: the waiting room where subjects receive instructions, complete questionnaires, etc.; the simulator exterior, (the actual mechanisms that control the simulator are located beneath the pictured floor); the interior of the simulator with subjects seated in first-class type seats; and the control console which is located at the same level as the simulator and allows the console control operator to constantly monitor subjects within the simulator. Construction details and operating specifications of this system can be obtained from references 23 and 24.

(A) WAITING ROOM

(B) SIMULATOR EXTERIOR



(C) SIMULATOR INTERIOR



(D) CONTROL CONSOLE

FIGURE 1. PASSENGER RIDE QUALITY APPARATUS (PRQA)

STATEMENT OF MODEL

The comfort or ride quality of any particular ride is a function of several key factors as schematically represented in Table 1 on the next page. Comfort is a function of: (1) Stimulus Factors; inclusive of input vibrations, environmental factors, temporal factors, and performance factors, and (2) Psychological-Sociological Factors; inclusive of knowledge or capacity factors, personality factors, demographic factors, and biological-physiological factors. Some of the specific factors and/or potential determiners of ride quality are listed beneath these subdivisions. Through continued investigation, certain specified factors of the model will be omitted, and other factors added to the model as required.

Table

Statement of Ride Quality Comfort Model

Ride Quality = f
(comfort)

1. Stimulus factors
   - 1.1 Input vibrations (linear & rotational)
     - 1.1.1 Frequency
     - 1.1.2 Amplitude
     - 1.1.3 Masking (within & between)
     - 1.1.4 Onset
     - 1.1.5 Offset
     - 1.1.6 Impulse
     - 1.1.7 Multiple axes
   - 1.2 Environmental factors
     - 1.2.1 Noise
     - 1.2.2 Ventilation (O_2, temperature, smoke)
     - 1.2.3 Seat characteristics (size, type, adjustment, etc.)
     - 1.2.4 Illumination
     - 1.2.5 Seat location
     - 1.2.6 Pressure
   - 1.3 Temporal factors
     - 1.3.1 Time of day
     - 1.3.2 Day of week
     - 1.3.3 Season
     - 1.3.4 Length of session
   - 1.4 Performance factors
     - 1.4.1 Task/function
     - 1.4.2 Time-sharing load
     - 1.4.3 Stress-load

2. Psychological-Sociological
   - 2.1 Capacity
     - 2.1.1 Intelligence
     - 2.1.2 Aviation information
   - 2.2 Personality
     - 2.2.1 Traits
     - 2.2.2 Style
     - 2.2.3 Needs
     - 2.2.4 Self concept
     - 2.2.5 Values
   - 2.3 Demographic
     - 2.3.1 Age
     - 2.3.2 Sex
     - 2.3.4 Income
     - 2.3.5 Education
     - 2.3.6 Race
     - 2.3.7 Class
   - 2.4 Biological-Physiological
     - 2.4.1 Anthropometric
     - 2.4.2 Vestibular sensitivity
     - 2.4.3 Kinesthetic sensitivity
     - 2.4.4 Circadian rhythm disruption
     - 2.4.5 Sleep disruption

MODEL APPLICATION

The way in which the model is applied to the ride quality problem is presented in figure 2, on the following page. The application is addressed at establishing the comfort response that occurs as a result of exposure to various stimulus factors (vibratory or non-vibratory). The resultant of the application is a comfort scale (extreme right), the value of which is a function of various vibration factors (extreme left), and various non-vibration factors (factors vertically represented at the right).

Starting at the left hand side, the components of vibration represent the ride spectra. Further to the right, the abbridged comfort scale, analogous to the phon scale (eq. see refs. 27-28) will reflect comfort differences as a function of: (1) axis effects; or ride spectra for each axis, (2) masking effects; within and between axes, and (3) correction effects; of duration, onset, offset, and impulse within each axis. The abbridged comfort scale is then corrected for various non-vibratory factors (for example, environmental, performance, etc. factors). The composite of these corrections then result in a final comfort scale.

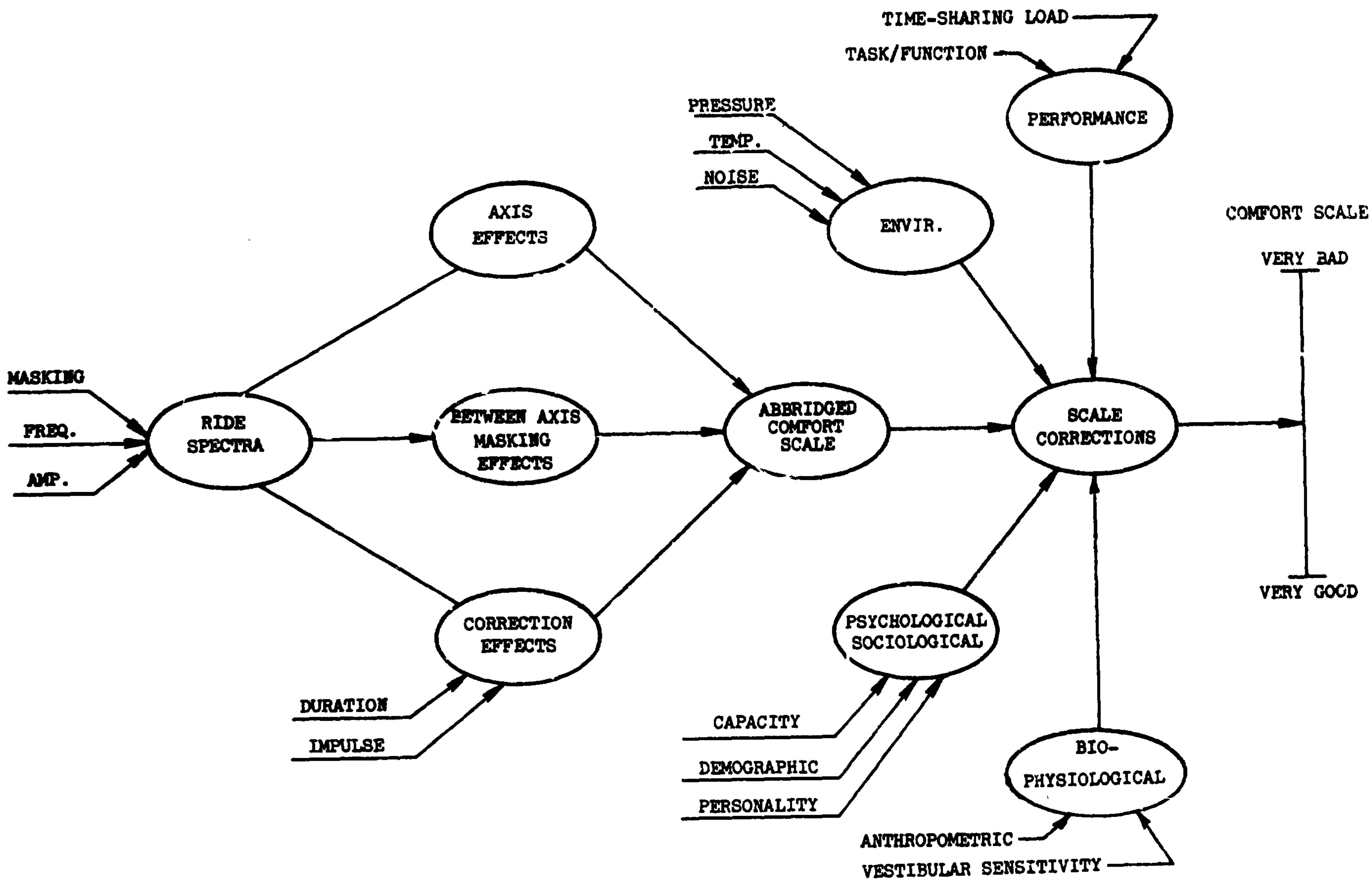


Figure 2.- Comfort Model Application.

COMFORT MODEL COMPUTATIONS

The comfort model can be viewed as composed of the nine computational steps necessary for derivation of the comfort scale. The first eight steps involve computations related to vibratory stimuli, whereas the last step involves non-vibratory stimuli corrections. These steps involved in derivation of the comfort scale are discussed in turn.

Discomfort Units (Steps 1-4)

The computational Steps 1 through 4 are displayed in figure 3, on the next page. The initial scale problem addressed by these computations is a determination of the discomfort units associated with components of a ride. The components selected for these assessments were 1 Hz bandwidths as displayed in Step 4.

Through an investigation, "equal comfort curves" are established, as displayed in Step 1. These curves can be obtained through either: (1) intensity matching; the equal discomfort intensity matches are between the acceleration levels that would be required of successive frequency, and the acceleration level of standard frequency, or (2) magnitude estimates; estimates of the discomfort of various acceleration levels, of successive frequencies (see ref. 25 for a comparison of these methods).

Through Step 2, which represents a rearrangement of Step 1 data, the discomfort (DISC) associated with increasing acceleration of each frequency is determined. Step 3 represents a tabular presentation of the data obtained within Step 2. Finally, the data of Step 3 can be used to determine the discomfort units of each component of the PSD displayed in Step 4.

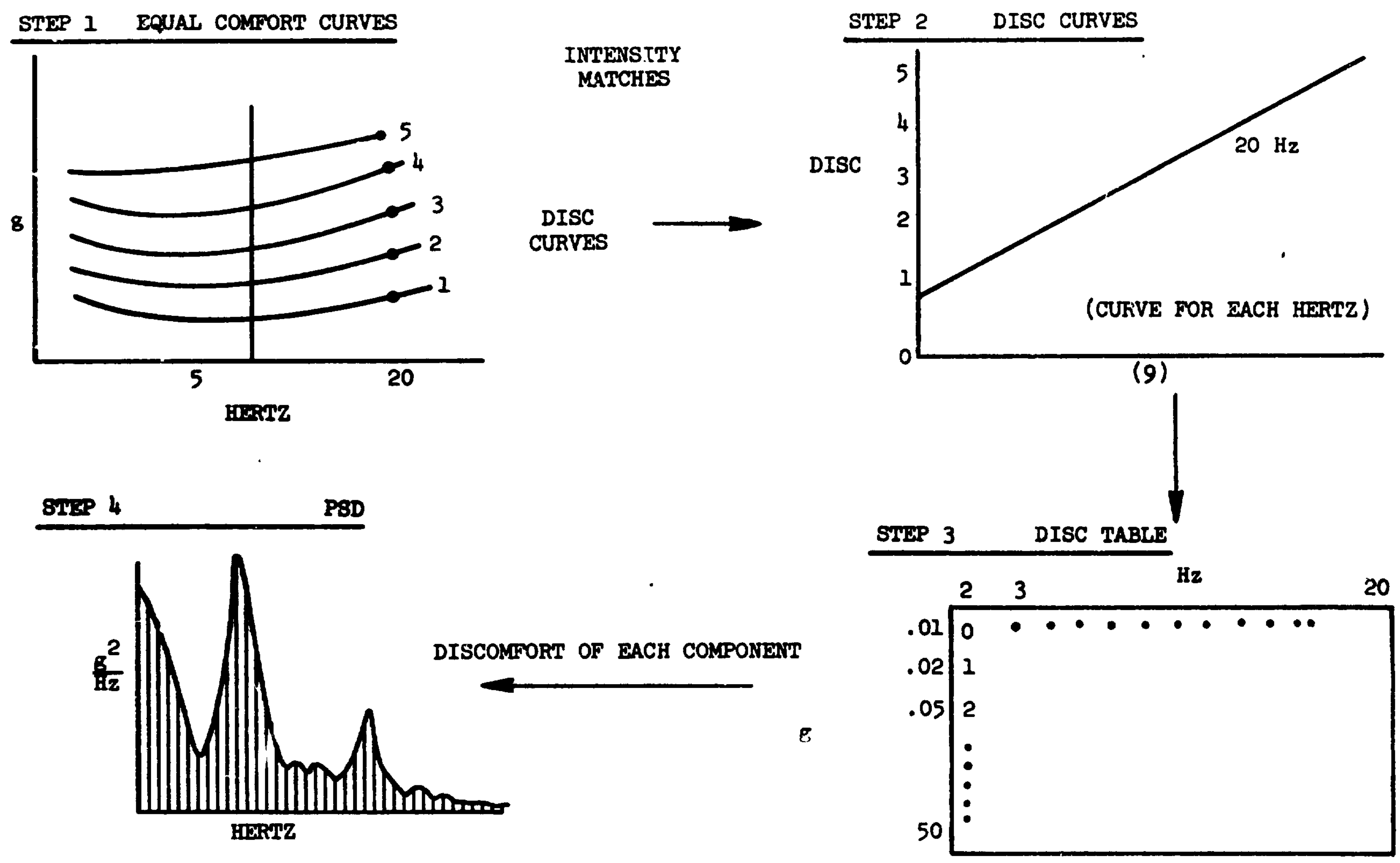


Figure 3.- Discomfort Units of a Ride (Steps 1-4).

Masking (Step 5)

The computations of this step are directed at obtaining empirical information for the weighting of components ($g^2 \times Hz$) in combination. The masking studies address the question of how the discomfort of a ride varies when different frequency components are combined. The composite weights of a typical ride are thus based upon the discomfort of several components in combination rather than an arbitrary algebraic summation of the discomfort units of these components that had been separately experienced.

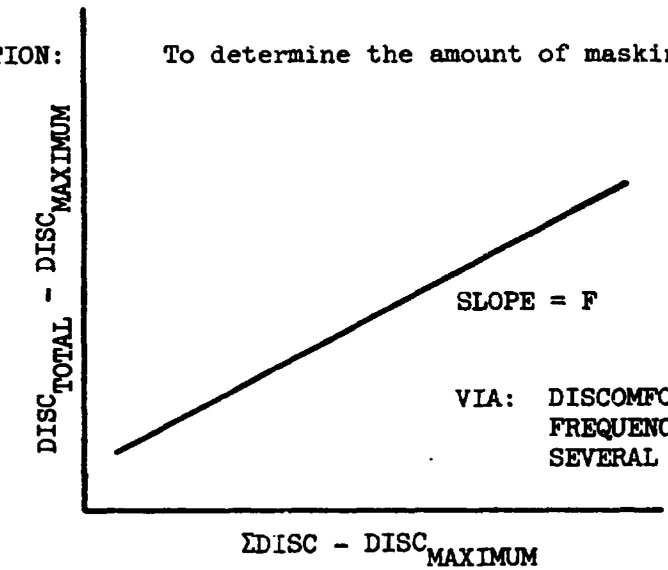
The computations of Step 5, including formulas 1 and 2, are displayed in figure 4, on the following page. Formulas 1 and 2 used in these computations, are based upon previous work in psychoacoustics (eq. see refs. 26-33) and vibration sensitivity (eq. see refs. 34-40). Formula 1 states that the Total Discomfort ($DISC_{Total}$) of a ride, is a function of the maximum discomfort ($DISC_{Maximum}$) component, plus, F (the summation of discomfort units ($\Sigma DISC$) associated with all components of the PSD, minus the discomfort of the maximum component ($DISC_{Maximum}$)). The first four steps provide the necessary components for computation of the formula, except for F, the masking factor, which represents the basis of the problem of this step. Formula 2 supplies the exact value of F. The $DISC_{TOTAL}$ in this latter case, is the discomfort of the frequency combination under investigation, measured in terms of the discomfort of the standard frequency. Thus, a study for determination of F, would require subjects to adjust a ride (composed only of the standard frequency and of specifiable DISC) equal to various rides (each composed of several frequencies). As displayed in figure 4, the slope resulting from these comparisons determines the value of F. Thus, when F has been determined, the $DISC_{TOTAL}$ of a ride can be determined.

FORMULA(1) = $DISC_{(TOTAL)} = DISC_{(MAXIMUM)} + F(\Sigma DISC\text{-}DISC_{MAXIMUM})$

FORMULA(2) = $F = (DISC_{TOTAL} - DISC_{MAXIMUM}) / (\Sigma DISC\text{-}DISC)_{MAXIMUM}$

PROBLEM: How is the discomfort as obtained from discrete frequency tests altered by the presence of other frequencies?

SOLUTION: To determine the amount of masking or (F)*



VIA: DISCOMFORT MATCHING OF THE STANDARD FREQUENCY RIDE TO RIDES COMPOSED OF SEVERAL FREQUENCIES.

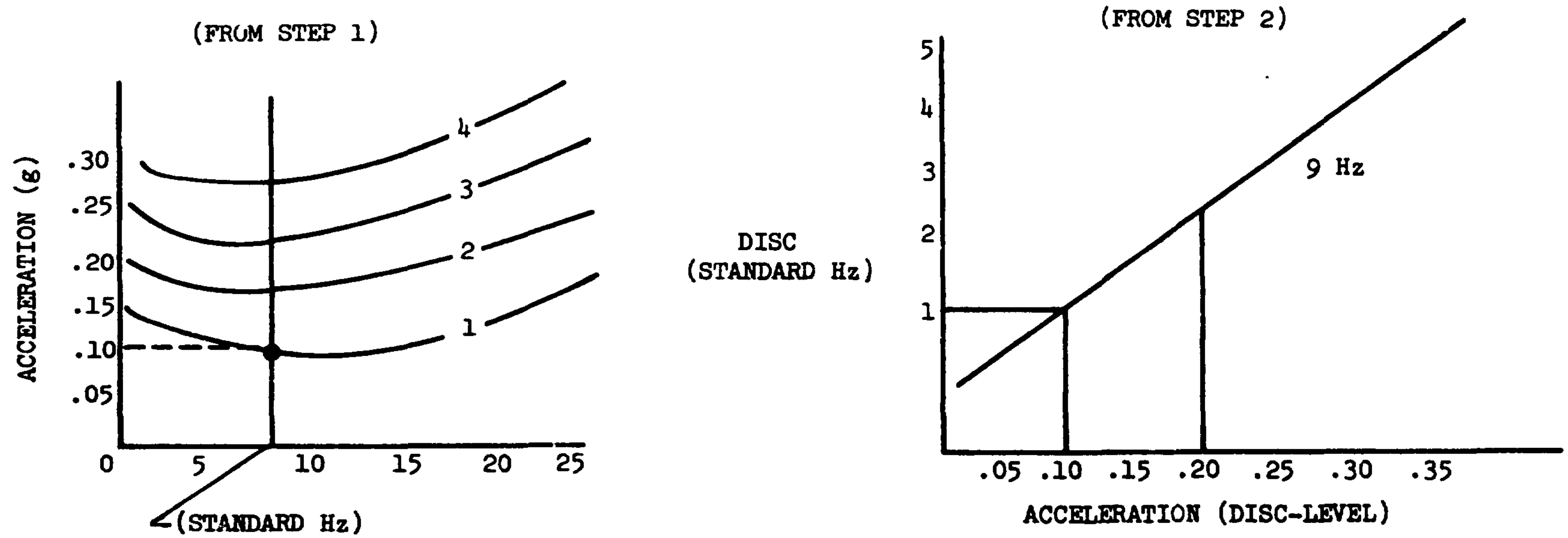
*Not corrected for onset, offset, duration, or impulse.

Figure 4.- Masking (Step 5).

Discomfort Scale (Step 6)

The computations of Step 6 for the conversion of DISC values (discomfort units) of a ride, to DISC LEVEL (discomfort scale) are presented in figure 5, on the following page. The DISC units, as previously mentioned, are numbers assigned to frequencies, of different acceleration levels, that produced the same discomfort. (See for example, the first portion of figure 5.) Therefore, DISC units could be used to represent discomfort independent of specific frequency. DISC-LEVEL, on the other hand, is the acceleration level (g) of the standard frequency. The empirical relationship between DISC units (of the standard frequency) and DISC-LEVEL (of the standard frequency) displays the amount of discomfort associated with increases of acceleration of the standard frequency. (See the second portion of figure 5.) This means the acceleration level of the standard frequency (DISC-LEVEL) provides a convenient way to represent the discomfort of any ride, regardless of frequency composition. However, it will be necessary to remember the DISC units corresponding to gradations of the DISC-LEVEL scale until a familiarity is developed with the scale. The DISC-LEVEL scale and associated computations for conversion of DISC units to DISC-LEVEL may not be needed in the model. The typification of a ride in DISC units will suffice if the relation between DISC units and acceleration (discomfort and vibration) is simply linear. However, if the relationship between these two is logarithmic, power, etc.; the DISC-LEVEL scale will be necessary.

The actual conversion of DISC units to DISC-LEVEL has already been accomplished in Step 2. The analyses of Step 2 for the standard frequency provides the empirical relation between DISC and DISC-LEVEL, as displayed in the second portion of figure 5.



DISC (UNITS) = THE DISCOMFORT (UNITS) TO A PASSENGER OF A VIBRATION. 1 DISC HAS ARBITRARILY BEEN ASSIGNED TO THE DISCOMFORT OF A 9 HZ VIBRATION, AT .10 PEAK ACCELERATION

DISC-LEVEL (DISCOMFORT SCALE) = IS THE PHYSICALLY MEASURED ACCELERATION LEVEL OF THE STANDARD FREQUENCY (9 Hz), THAT HAS BEEN RELATED TO THE DISC UNITS. (The conversion may not be needed as stated in the text)

Figure 5.- Discomfort Scale (Step 5).

Effective DISC-LEVEL (Step 7)

The composition (Formula 3) and computations of Effective DISC-LEVEL (EDL), Step 7, are displayed in figure 6 on the following page. Formula 3 indicates that EDL represents the DISC-LEVEL of the ride, plus corrections in DISC-LEVEL due to temporal variations of ride spectra characteristics (eq. duration, onset, offset, and impulse). Because of the similarity of procedures involved in each correction, only the method for duration correction will be discussed.

The duration correction would involve determining the influence upon discomfort, of increases in the duration of the standard frequency (e.g., 9 Hz, @ .10g, 10 seconds; assuming duration does not interact with frequency nor the acceleration of different frequencies). The study required for this correction would involve magnitude estimates of the discomfort of standard frequency rides for increasing durations. Through additional computations ΔDISC-LEVEL would be determined as the basis for the duration correction. ΔDISC-LEVEL is the difference between the DISC-LEVEL of the standard frequency ride at 10 seconds, and the DISC-LEVEL of successive but separate durations of the same ride. As displayed in figure 6, the study would result in a scale correction (ΔDISC-LEVEL) for increasing ride durations.

$$\text{FORMULA(3)} = \text{EDL} = \text{DISC-LEVEL} + \Delta\text{DISC-LEVEL}_{(\text{DURATION})} + \Delta\text{DISC-LEVEL}_{(\text{ONSET})}$$

$$+ \Delta\text{DISC-LEVEL}_{(\text{OFFSET})} + \Delta\text{DISC-LEVEL}_{(\text{IMPULSE})}$$

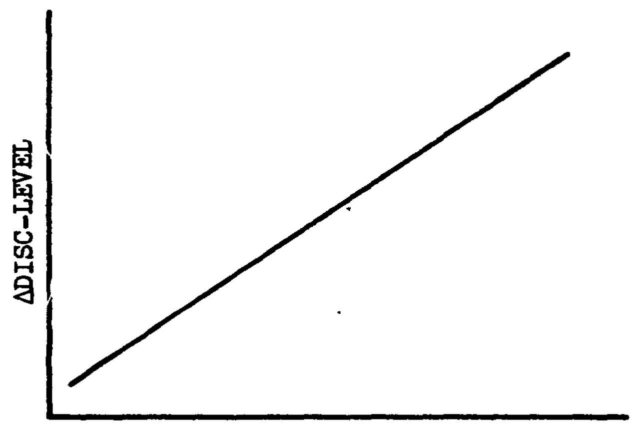


Figure 6.- Effective DISC-LEVEL (Step 7).

Composite DISC-LEVEL (Step 8)

The components of the Composite DISC-LEVEL (CDL), of a ride are displayed in Formula 4.

$$\text{Formula(4) } CDL = EDL_{(\text{Vertical})} + EDL_{(\text{Fore \& Aft})} + EDL_{(\text{Side} \times \text{Side})} \ldots.$$

The CDL represents a combination of the EDL's for each axis, expressed in a single discomfort value. Formula 4 indicates the CDL of each axis receives an equal weighting regardless of the axis. However, Formula 4 would be adequate only if it was assumed that: (1) an equal amount and type of masking occurred in each axis, and (2) there was no masking between axes. There are two solutions that remove the necessity of making these assumptions.

The first solution would involve a factor analysis of the energy components of a ride. The major measures from this factor analysis, representative of each factor, would then serve as the bases of a multiple correction. The multiple correlation would be between comfort ratings and the major energy measures. The first solution, and these analyses, would result in Formula 5.

$$\text{Formula(5) } CDL = \beta EDL_{(\text{Vertical})} + \beta EDL_{(\text{Fore \& Aft})} + \beta EDL_{(\text{Side} \times \text{Side})}$$

The Beta weights of Formula 5 would provide the relative discomfort contribution of each axis, to the total discomfort of a ride. The end result would thus be a method for the summation of the proportional discomfort contribution of each axis to the total discomfort of a ride.

The second solution to the problems presented by Formula 4, would be a re-application of Step 5 analyses, but between instead of within axes. The application of Step 5 analyses to more than one axis simultaneously would represent a determination of between axis masking effects. The analyses would provide a differential weighting of the discomfort contribution of each axis to the total discomfort of a ride, rather than on equal weighting of axes. Thus, the CDL could be represented in Formula 6 as:

$$CDL = DISC_{(Total\text{-}Maximum)} + F(\Sigma DISC_{(Totals)} - DISC_{(Total\text{-}Maximum)})$$

Instead of the addition of DISC units applicable to components of a PSD, Formula 6 provides for addition of $DISC_{(Total)}$ units of each axis. The $DISC_{(Total\text{-}Maximum)}$ represents the axis that provides the greatest DISC total, and $\Sigma DISC_{(Total)}$ represents the total DISC values of each axis summed. The F value is directly analogous to that of Step 5, but is obtained between instead of within axes.

In summary, the first solution is both less costly than the second, and more applicable to operational studies. The second solution, on the other hand, is extremely systematic, and more applicable to laboratory investigation. The present line of investigation, within the present model, provides for the use of both solutions.

Total DISC-LEVEL (Step 9)

The composition (Formula 7) and computations for the Total DISC-LEVEL (TDL), Step 9, are presented in figure 7, on the following page. Formula 7 for TDL, as a final estimate of the total discomfort of a ride, provides corrections for non-vibratory factors. Formula 7 indicates TDL is a function of CDL, plus DISC-LEVEL corrections for environmental, temporal, performance, capacity, personality, demographic, and bio-physiological factors. These corrections for TDL are analogous to those for EDL of Step 6. Therefore, only a brief discussion of these corrections is presented.

The noise level during a ride, an environmental factor, is an example of these corrections. The correction would involve determining the influence upon discomfort of increases in the noise level for standard frequency rides (e.g., 9 Hz, @ .10g, 10 seconds; assuming noise level does not interact with frequency nor the acceleration level of different frequency vibrations). The study required for this correction would involve magnitude estimates of the discomfort of standard frequency rides that have increasing noise levels. Through additional computations, ΔDISC-LEVEL would be determined as the basis for the noise level correction. ΔDISC-LEVEL (for this correction) is the difference between the DISC-LEVEL for the standard frequency ride during ambient noise and that for similar rides of increasing noise level. Thus, figure 7 displays the amount of ΔDISC-LEVEL correction, for rides containing increasing levels of noise.

Formula (7)

$$TDL = EDL + \text{DISC-LEVEL}_{(Environmental)} + \text{DISC-LEVEL}_{(Performance)} + \text{DISC-LEVEL}_{(Temporary)} + \text{DISC-LEVEL}_{(Capacity)}$$
$$+ \text{DISC-LEVEL}_{(Personality)} + \text{DISC-LEVEL}_{(Demographic)} + \text{DISC-LEVEL}_{(Bio\text{-}Physiological)}$$

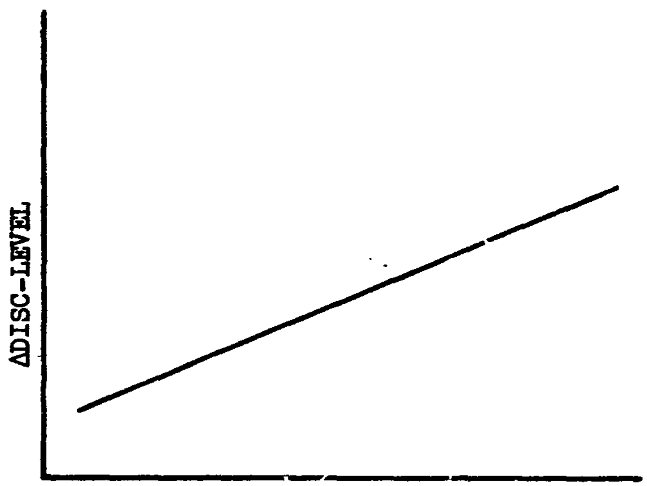


Figure 7.- Total DISC-LEVEL (Step 9).

CONCLUDING REMARKS

The proposed comprehensive model contains several major concepts. These concepts are:

1. The establishment of equal comfort curves for all axes.
2. The establishment of discomfort units as a function of frequency and amplitude within an axis.
3. A determination of the empirical laws for summation of discomfort within an axis based on masking within an axis.
4. A determination of the empirical laws for summation of discomfort units between axes based on between axis masking.
5. The derivation of a scale of discomfort (comfort).
6. The correction of the comfort scale for temporal variations in ride spectra characteristics.
7. The correction of the comfort scale for nonvibratory factors.

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