A TRADE-OFF ANALYSIS DESIGN TOOL -- AIRCRAFT INTERIOR NOISE-MOTION/PASSENGER SATISFACTION MODEL

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LIST OF SYMBOLS

$\bar{a}_q$	rms. Value of generic motion variable q

Subscript of $\bar{a}$:

L	Longitudinal acceleration (g)
P	Pitch velocity (°/sec)
R	Roll velocity (°/sec)
T	Transverse acceleration (g)
V	Vertical acceleration (g)
Y	Yaw velocity (°/sec)
Z	Normal acceleration to cabin floor (g)

A_p	Passenger satisfaction
b	# of blades in a propeller
coi	A unit on a i level comfort scale (co7 - unit on a 7 point comfort scale)
C_p	Passenger comfort
C_s	Subject comfort

Subscript of C_s:

env	Due to environment
$\dot{h}$	Due to change in altitude
i	For segment i
man	Due to maneuver
M	Due to motion
$MN_{p/s/a}$	Due to motion and noise level ($PNdB/SIL_1/dB_A$)
MSN(A)/MSN(c)	Due to motion and noise source for aircraft A/Commercial data
N	Due to noise
o	Overall
$\dot{p}$	Due to pressure change
seat	Due to seat
T	Due to temperature

C_{SN_i}	Mean SN_i contribution to subject comfort
d_c	Conversation difficulty
dB	20 log (p/p_{ref}) (See Appendix E)

Subscript of dB:

A/D	A/D weighted OSPL (Appendix E)
i	1/3 octave band i
ij	for ith source, jth 1/3 oct. band

Superscript of dB:

o	Octave band

E_i	Environmental variables for segment i
f	Frequency (Hz)/or generic function symbol

Subscript of f(Hz):

$an_{i/max}$	Aerodynamic noise for band i/maximum among all bands
bp	Blade passage
er	Engine rotation
pr	propeller rpm

f_n	Source noise function
G	Gear ratio
h	Harmonic number (integer)
$\dot{h}$	Rate of altitude change
H	Hypotesis
K	Comfort Coefficient

Subscript of K:

o	Constant
V	Vertical accl.
T	Transverse accl.
N_i	Source noise levels, SN_i

ℓ	leg room (cm)
ℓ_d	band dB, corrected for weighting function (Appendix E)
L_{eq}	Energy averaged noise level (Appendix E)

Subscript of L_{eq}:

A	A weighted noise level
(8)	Eight hour averaged A level

L_{dn}	Day-night corrected L_{eq} (Ref. 47)
m_i	# of bands in noise source i
m_s	# of segments in flight
n/N	Sample/population size
OSPL	Overall sound pressure level (dB - Appendix E)
p	Roll rate (only Table 1.2)/or acoustic pressure level
p_{ref}	0.0002 μbar pressure
PNdB	perceived noise level (Appendix E)
q	a generic variable
r	Propeller rpm
R	Reciprocating propeller aircraft
s_q	Generic symbol for square root of sample variance of variable q
S_i	Subject # i (Appendix B)
SN_i	Noise level for source i (Noy)

Subscript i =

1	Engine noise
2	Aerodynamic noise
3	Radio noise

SIL_1/SIL_2	Speech interference level--weighting type 1/type 2 (Appendix E)
t	Wing thickness
TP	Turbo-prop aircraft
V	Velocity (MPH)

w	Seat width (cm)
w(i)/W(i)	Unnormalized/normalized weight for segment i
X	A generic variable
$\bar{X}_n$	Average X based on set of size n
α	Probability of Type I error (confidence level)
γ	Gamma correlation/or flight path angle (only Table 1.2)
δ_q	A generic symbol for permissible error in q/or Kroneker δ based on some function of q (only Table 1.2)
$\Delta\ell_A/\Delta\ell_D$	Weighting correction factors for band dB (Appendix E)
ϵ	Error in prediction
θ	Pitch angle
μ_q	Mean of generic variable q
ρ	Density
ρ_p	Pearson's correlation
σ_q	Standard deviation of generic variable q
ϕ	Roll angle

Superscripts

- $-$ Average
- $'$ Predicted value

ABSTRACT

A design tool has been developed to enhance aircraft passenger satisfaction. It can be used by systems designers for conducting tradeoff analyses of future aircraft interior environments and for evaluating existing aircraft. The effect of aircraft interior motion and noise on passenger comfort and satisfaction has been modelled. The effects of individual aircraft noise sources have been accounted for. Further, the impact of noise on passenger activities and noise levels to safeguard passenger hearing have been investigated. The motion-noise effect models not only provide a means for tradeoff analyses between noise and motion variables, but they also provide a framework for optimizing noise reduction among noise sources. The data for the models have been collected on-board commercial aircraft flights and specially scheduled (flight and ground) tests.

CHAPTER I

INTRODUCTION

The aim of this study is to develop a design tool for systems designers to evaluate existing aircraft passenger satisfaction and to conduct tradeoff analyses of future aircraft interior environments for passenger satisfaction. The major objective is to obtain a quantitative relationship (model) between the interior environment of an aircraft and passenger satisfaction.

1.1 Background

The classes of aircraft chosen for this study are those used in the current commuter air transportation system. These aircraft have many interior environment problems (1-4). Both passengers and crew feel that much can be done to improve their satisfaction with the ride quality, which is an important mode-choice-factor.

In addition to the users (passengers and flight crew) and the operators (management and ground personnel), non-users (viz. the surrounding community), manufacturers and the government are affected by the commuter air transportation system. Figure 1.1 illustrates the components in the commuter air transportation system acceptance problem. This study will be restricted to investigating user satisfaction, or more specifically, passenger satisfaction.

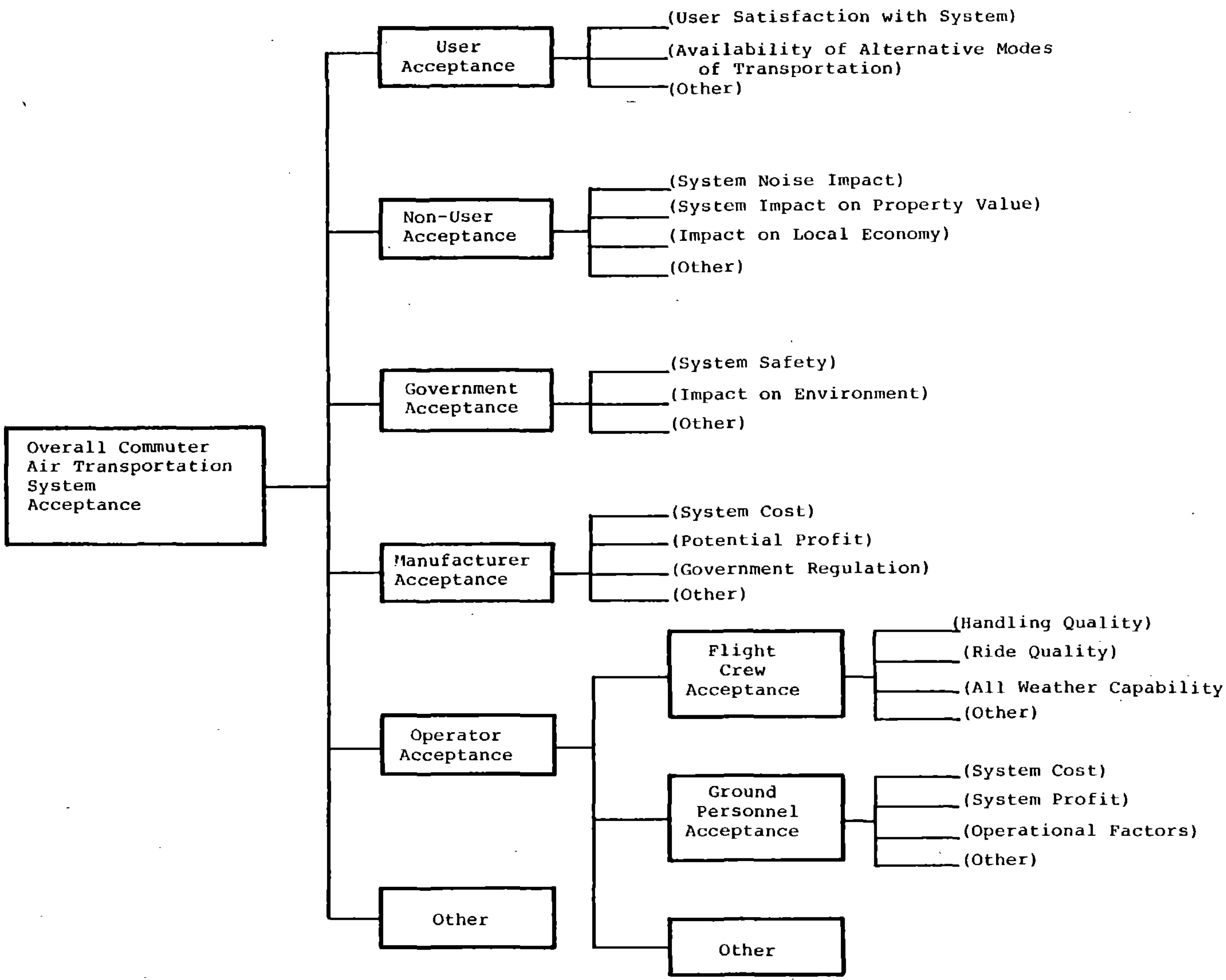

Figure 1.1 Objectives Tree for Overall System Acceptance

1.2 Passenger Satisfaction Factors

A number of factors contribute to passenger satisfaction.* Some of the important components of satisfaction (5-8) are given in Figure 1.2. The relationships between satisfaction and these underlying variables are given in a number of articles (6-15), and so will not be repeated here.

As Figure 1.3 (16) illustrates, safety and reliability are judged to be the most important variables, time savings, convenience and comfort are "very important", and the rest of the factors "somewhat important". In order to ensure passenger satisfaction, both safety and reliability have to be guaranteed. Once these are satisfied, time savings, convenience and comfort become the factors determining passenger satisfaction. Comfort has been chosen for study here for the following reasons:

(a) Among the satisfaction factor groups (Table 1.1), the hardware systems designer has more control over vehicle inputs, which affect comfort and ability to work. Since comfort and ability to work are strongly interrelated (5), comfort was chosen.

(b) In order to remain a viable alternative in the face of future competition, passenger comfort has to be improved.

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*Passenger satisfaction is assessed by the percentage of passengers who are willing to ride on the system again. This is discussed in more detail subsequently.

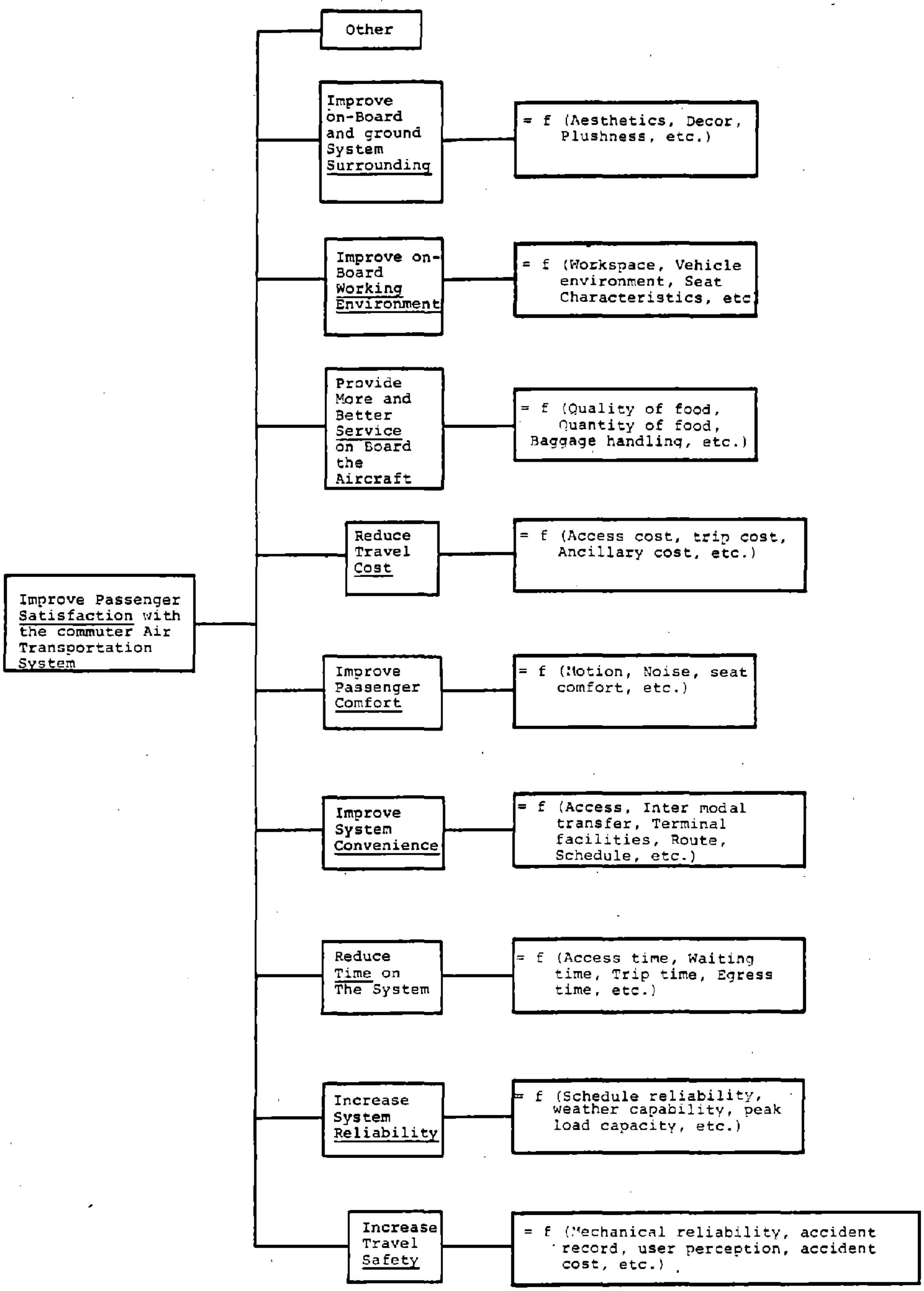

Figure 1.2 Relationship Between Passenger Satisfaction and its Underlying Factors.

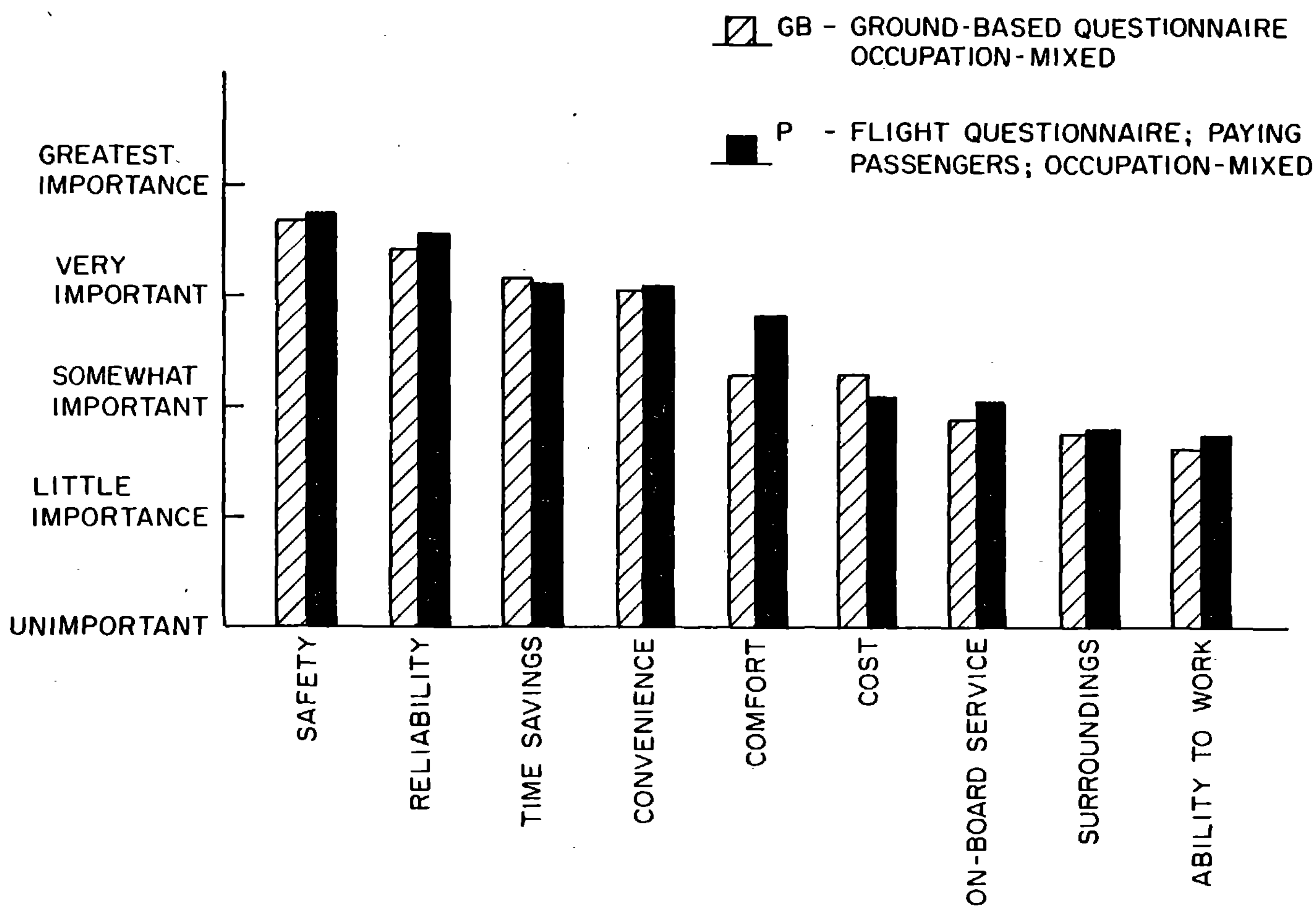

FIGURE 1.3 Importance of Air Travel Satisfaction Factors (Ref. 16)

a. Effects of Inputs during Travel in Vehicle:

Comfort (ride and cabin environment)

Ability to work (read, write, etc.)

b. System Characteristics Effects:

Safety	Reliability
Time on the System	Convenience
Travel Cost	Service
Aesthetics (surroundings)	etc.

c. Passenger Related Inputs:

Demographic features,

Motivation,

Socio-economic features,

System impressions,

Value system, etc.

TABLE 1.1

RELATIONSHIP BETWEEN PASSENGER SATISFACTION FACTORS AND UNDERLYING VARIABLES (8,9)

The relationship between passenger comfort[†] and passenger satisfaction, as formulated in previous studies, is illustrated in Figure 1.4 (5).

1.3 Passenger Comfort

There are many factors which affect passenger comfort. The functional relationships between passenger comfort and some of its important factors (5,8,10-14) are given in Figure 1.5. McFarland (17) has summarized the relationship between comfort and environmental factors based upon findings available through 1953 (see Figure 1.6). His results are not useful for this study since he assumes independence among the variables. The chart does not provide a means for combining the effects due to the simultaneous presence of many variables. Further the data base, on which his results are based, is inadequate. The criteria given in Figure 1.6 should be used only as qualitative guidelines.

Jacobson (13) has summarized the work through 1972. Most of the references in the literature deal with optimum levels of the variables for comfort (e.g. 8,13,14,18-25). Relatively few publications describe quantitative relationships between comfort and the underlying factors. A summary of the literature is presented in Table 1.2[†]. In the table, comfort models for motion, noise, temperature, pressure change and seat factors are also described. These

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[†]For the comfort responses used in this study - low numbers represent the comfortable end of the scale, and high numbers the uncomfortable end. See Table 2.2 for the seven point scale used.

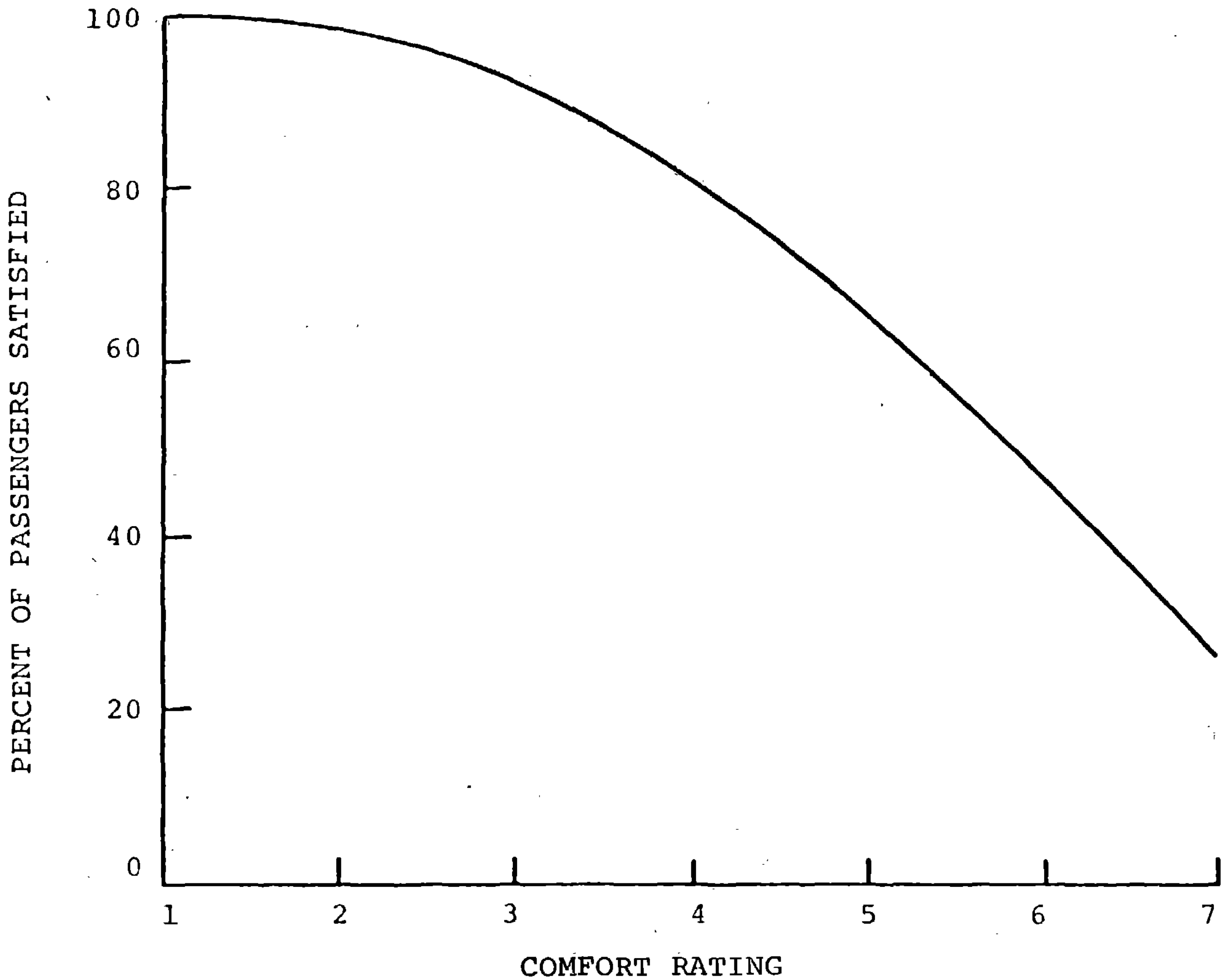

Figure 1.4 Willingness to Fly Again (Passenger Satisfaction) by Passenger Comfort Level.

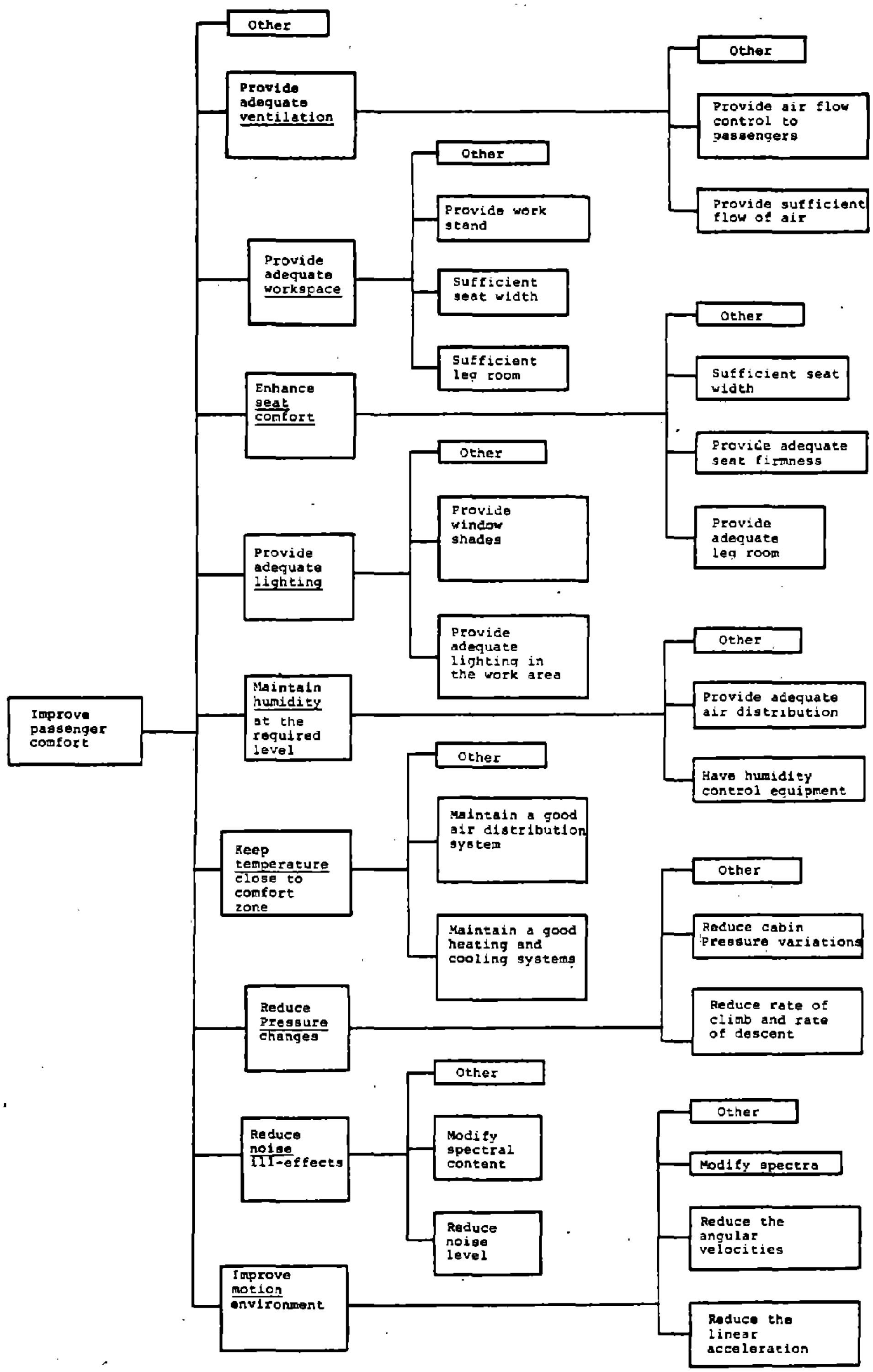

Figure 1.5 Components of Passenger Comforts.

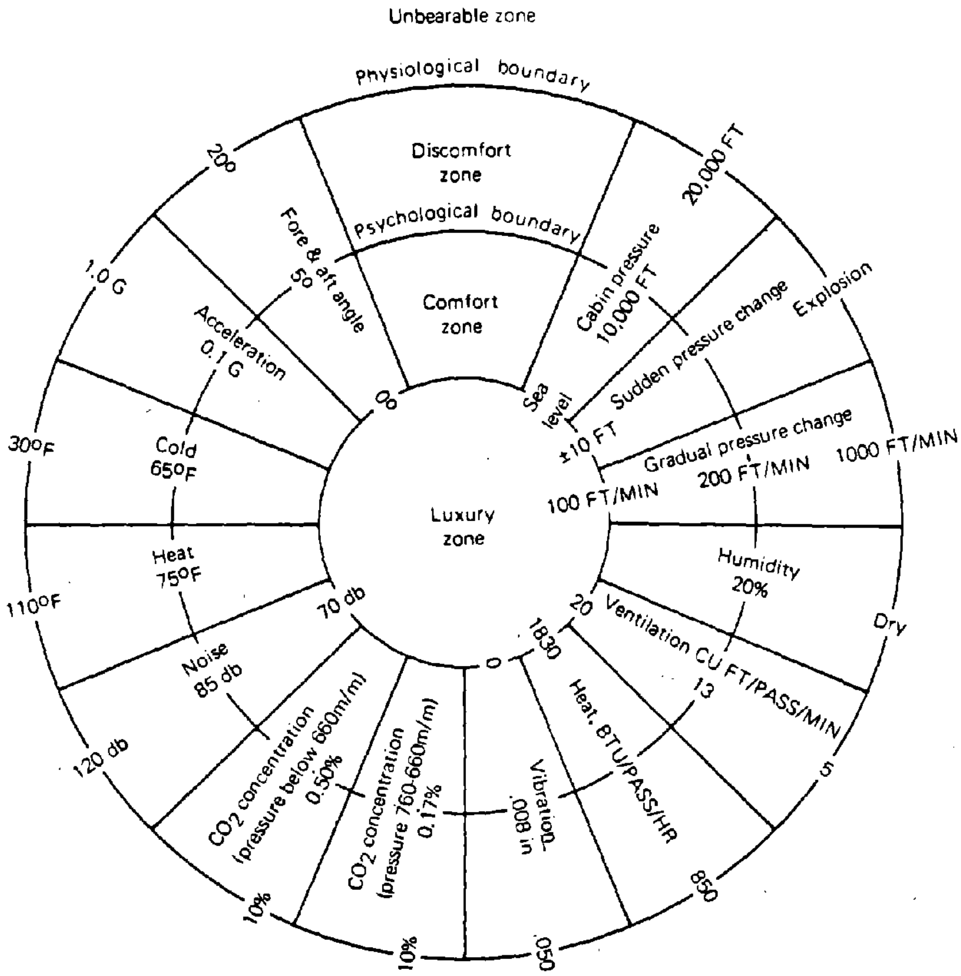

FIGURE 1.6 Some Environmental Variables Affecting Passenger Comfort during Flight (Ref. 17).

COMFORT FACTOR (Components effecting human responses)	Type of Effect	Recommended Limits	Models Relating Comfort* and the Factors	Comments	References
MOTION (Level, frequency, direction, duration)	(a) G-loads (b) Vibration (c) Maneuver		(b) $C_{s_M}^{\dagger} = \begin{cases} 17.85\,\bar{a}_V + 11.4\,\bar{a}_T; & \bar{a}_V \geq 1.6\,\bar{a}_T \\ 1.5\,\bar{a}_V + 37.5\,\bar{a}_T; & \bar{a}_V < 1.6\,\bar{a}_T \end{cases}$ (1.1) (c) $C_{s_{man}} = f\left[\phi_{max}, P_{max}, a_z, \bar{a}_V, \bar{a}_T, \bar{a}_L, \theta_{max}, \gamma_{max}, V_{max}, \dot{h}\ rms, C_{s_V}, C_{s_{\dot{p}}}, C_{s_T}\right]$ Ref. (21, 46)	(a) Effect Not relevant (b) Good model - based on extensive data (23) (c) Only during terminal area maneuvers	8, 13, 16, 18-24, 46
NOISE (Level, frequency, time history, spectral complexity)	Psychological reactions		$C_{s_N}^{\dagger} = 0.171\,(dB_A - 78)\,\delta_N$ (1.2)	Preliminary version - few data (16)	13, 16, 26-31, 42, 47
PRESSURE (Level, magnitude and sign of change)	(a) Static (b) Rapid Change (c) Gradual Change	a) < 3000 meters alt. c) Rate of descent < 90 m/min Rate of climb < 150 m/min (13) Rate of change < 60 m/min (17)	(a) —— (b) —— (c) $\bar{C}_{s_{\dot{p}}} = 0.005\,(\dot{h} - 90)\,\delta_{\dot{h}}$ (1.3)	(a) Effect not relevent (b) ,, (c) Model independent of sign-preliminary version (21)	13, 14, 17-21
THERMAL COMFORT (Temperature, humidity, ventilation, clothing, activity, sunshine, pressure)	(a) Temperature (b) Humidity (c) Airflow	b) 20 to 80% ; rate < 20%/hr. (13) c) 3 to 14 m/min (13) 0.36 to 0.56 m^3/min (17)	(a) $C_{s_T} = 0.054\,(T - 20.5)\,\delta_T$ (1.4)	(a) Unimodal - preliminary model (21) (b) combined model not available (c) -- ,, --	13, 14, 18-21
LIGHTING (luminance, glare, contrast, color information, etc.)	Illuminance	70 - 150 ft. candles (18)	——	Model not available	18-20
SEAT COMFORT AND WORKSPACE (Seat characteristics and seat dimensions)	Seat comfort		$C_{s_{seat}} = 1 + \left[0.0077(63 - w)^2 + 0.16(30 - \ell)^2\right]^{1/2}$ (1.5)	Good Model - includes seat dimensions	18, 20, 21, 25, 48

KEY

C_s - Subject Comfort responses

Subscript for C_s (due to:)

- M - Motion
- N - Noise
- $\dot{p}$ - Pressure Change
- T - Temperature
- seat - Seat
- man - Maneuver

$\bar{a}$ - rms accelerations (g)

Subscript for $\bar{a}$

- V - Vertical
- T - Transverse
- L - Longitudinal

a_z - Normal acceleration

$$\delta_N = \begin{cases} 1 & \text{for } dB_A > 78 \\ 0 & \text{for } dB_A \leq 78 \end{cases}$$

$$\delta_{\dot{h}} = \begin{cases} 1 & \text{for } \dot{h} > 90 \text{ m/min} \\ 0 & \text{for } \dot{h} \leq 90 \text{ m/min} \end{cases}$$

$$\delta_T = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \text{ for } 1 + C_{s_m} + C_{s_N} + C_{s_{\dot{h}}} \begin{bmatrix} > 3.4 \\ \leq 3.4 \end{bmatrix}$$

- ϕ - roll angle
- p - roll rate
- θ - pitch angle
- γ - flight path angle
- V - airspeed

- $\dot{h}$ - rate of altitude change, m/min
- dB_A - noise level (dB_A)
- T - Temperature, °C
- w - Seat width, cm
- ℓ - Seat legroom, cm

*Comfort rating on a seven point scale

† These models were obtained in a five point scale, but the results are presented in an equivalent seven point scale (by linear transformation)

TABLE 1.2 RELATIONSHIP BETWEEN COMFORT RESPONSES AND ITS FACTORS models can be combined to yield the cumulative comfort C_s, formulated as (21),

$$C_s = \text{Max}\ (C_{s_{env}}, C_{s_{man}}, C_{s_{seat}}) \tag{1.6}$$

where

$$C_{s_{env}} = 1 + C_{s_M} + C_{s_N} + C_{s_{\dot{P}}} + C_{s_T} \tag{1.7}$$

$C_{s_{man}}$, $C_{s_{seat}}$ - subject comfort response due to seat/maneuver

The formulation assumes that comfort due to the three factors, viz., environment, maneuvers and seating are independently assessed and that the maximum is the perceived comfort.

Among the comfort models, the effects of motion and seat comfort are known with a great deal of confidence (23,25). The influence of other environmental factors is only partially known.

References (1,5,8,16,21-24) indicating passenger perceptions of environmental variables affecting comfort revealed that noise is one of the most important factors (Figure 1.7) (16), and that over 65% of the passengers find commuter aircraft interior noise uncomfortable (Figure 1.8) (16). In addition opinions of pilots operating general aviation aircraft, indicated their number one concern

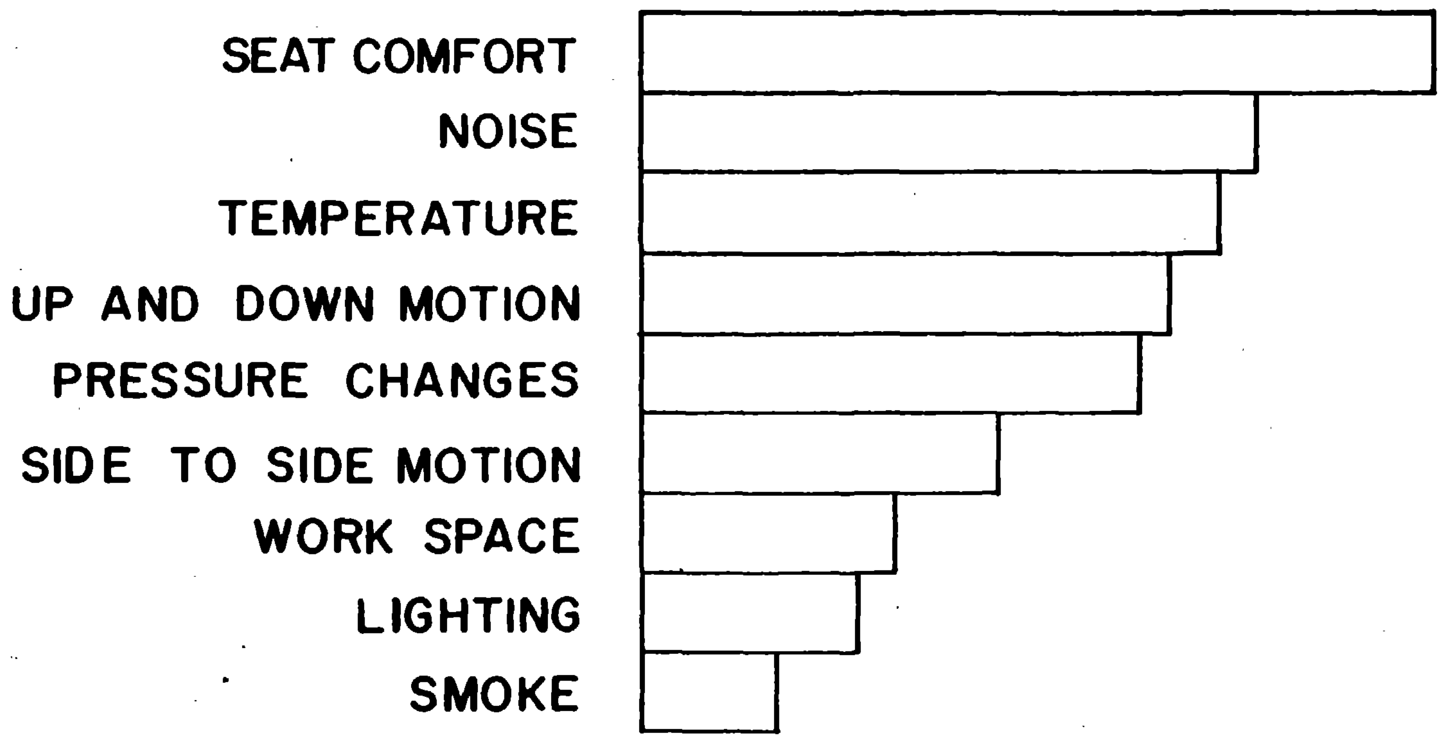

FIGURE 1.7 Relative Importance of Environmental Variables Affecting Comfort.

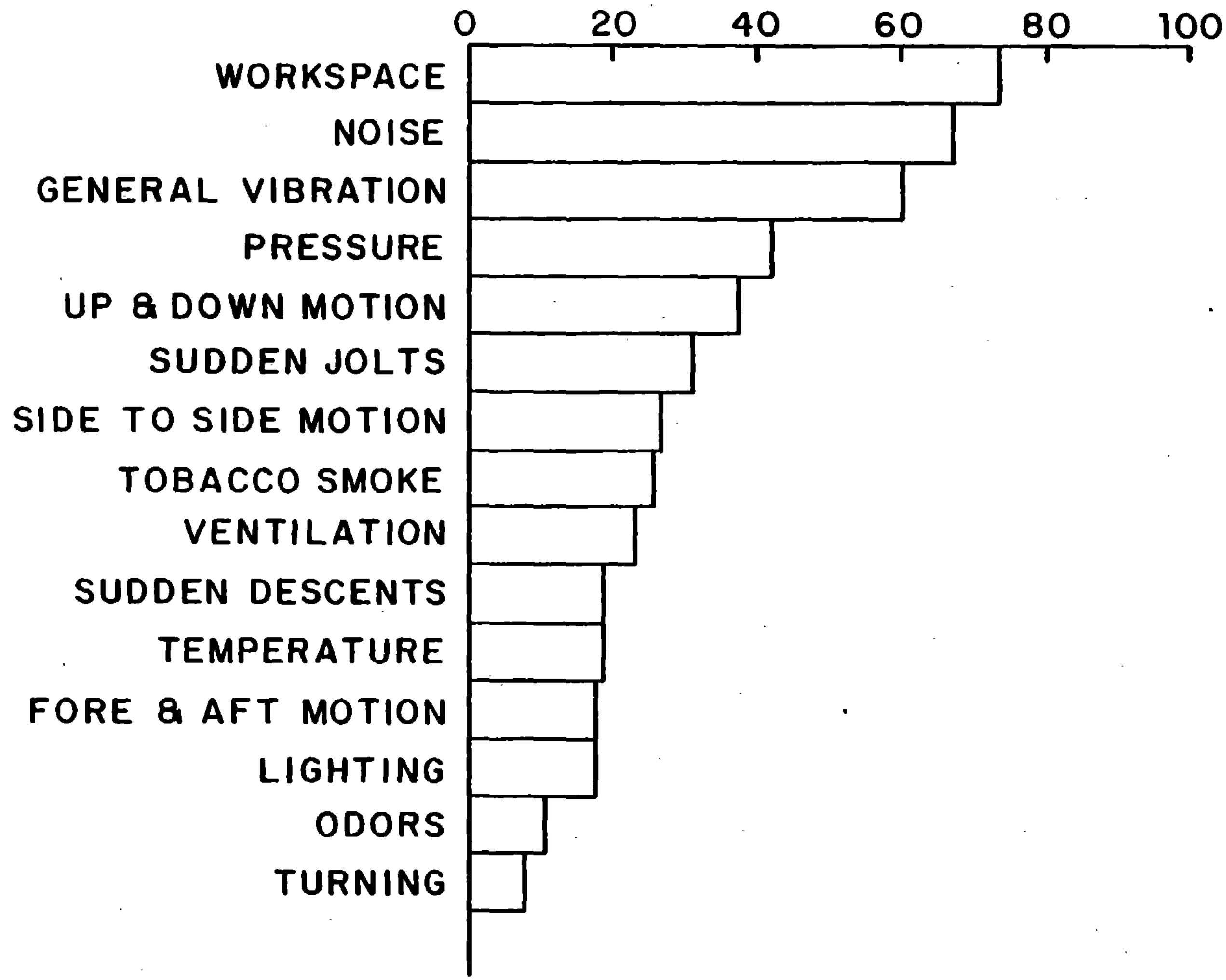

FIGURE 1.8 Percentage of Passengers Finding Environmental Variables Very or Somewhat Uncomfortable.

to be the noise environment, with 84% feeling more research was needed to provide a quieter interior. Further, passenger feelings revealed cabin noise and vibration as the items requiring most improvement (1).

These observations, then, point out the importance of assessing the effect of noise on passenger comfort and satisfaction.

1.4 Aircraft Interior Noise

Most of the literature dealing with the effect of noise on people is related to the impact of exterior noise on community acceptance rather than that of interior noise on passengers (13,26-31). Because of differences in motivation, psychological factors and duration of exposure, community noise results are not applicable here.

Although interior cabin noise was investigated as early as 1951 (32), little is known about the relationship of noise to passenger acceptance. Most articles deal primarily with documenting interior noise data but do not relate these data to comfort, annoyance or acceptance. Most notable of these have been Gasaway (33) for military aircraft and Lane (34) for medium-to-large commercial jet aircraft. A summary of interior noise data for many types of transportation systems can be found in references (2,35).

The impact of cabin interior noise on the flight crew has been the subject of a few investigations [e.g. (33,36-38)].

Although passengers and flight crew experience approximately the same levels of noise (2), the crew response differs due to motivation, task and experience differences (39).

A detailed description of noise effects is presented in Appendix F and a summary is given in Table 1.3. In addition, in Table 1.3, the relevance of the noise effects for this study is also noted, based on expected exposure levels of 70 to 105 dB_A* (34,40,41).

Among the noise responses in Table 1.3, little is known about the impact of aircraft interior noise on in-flight passenger psychological responses and performance decrements. Although considerable literature exists on noise induced hearing damage (e.g. 26-28, 42), safe noise levels within transportation vehicles have not been agreed upon (43-45).

1.5 Problem Statement

In summary, the goal of this study is to provide systems designers with a design tool for conducting tradeoff analysis of aircraft interior environments for passenger satisfaction. Major emphasis is placed on obtaining a model relating interior noise to passenger psychological responses, and task interference. This has many elements to it, viz., to:

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*See Appendix E, for definition of noise indicies.

Type* of Response	Effects	Noise Characteristics: Levels, Frequencies, etc.	Relavence to the Study
Threshold	-	Threshold curve: 30 Hz - 16 KHz (26,29).	-
Psychological	Annoyance, discomfort, etc.	> 40 dB_A† 50 Hz - 10 KHz (26).	Relavent
Performance Decrement	(a) Auditory (speech)	> 65 dB_A, 350 Hz-5.6 KHz (27,36,37)	Ralavent
	(b) Non-auditory (e.g. read, write)	> 50 dB_A, 50 Hz-10 KHz (26,27,49-51)	Relavent
Hearing Loss	Temporary and Permanent threshold shifts	350 Hz - 5.6 KHz L_{eq} > 70dB_A (26-28, 42-45)	Relavent
Physiological Levels	Body functions, Respiration, EEG responses etc.	(a) 70 - 115 dB_A(?)	(a) No long term effects (19,27)- Not Relavent
		(b) > 115 dB_A(?)	(b) Harmful effects (19)
		long durations	Not relavent

*Reference (19 - Vol II, Ch. 9) classifies noise responses into physiological and phychological responses. However, each group includes a very broad set of responses. In this study, a five way break has been chosen for convenience.

†All dB measurements are referenced to 0.0002 μbar.

TABLE 1.3 PASSENGER RESPONSES TO NOISE

(a) assess the impact of aircraft interior noise on passenger psychological reactions as a function of the sources causing the noise,

(b) assess the impact of noise on passenger tasks,

(c) establish an operational safe noise exposure criterion to protect passenger hearing, and

(d) select a psychological descriptor which is strongly related to both the environmental variables and passenger satisfaction.

The study will enable:

(a) the system designer to perform cost/benefit analyses on improvements in interior noise and motion environments,

(b) the assessment of ill-effects due to noise on passengers and the establishment of goals for interior noise reduction, and

(c) the application of this methodology to other modes of transportation.

CHAPTER II

EXPERIMENTAL DESIGN

In this chapter, the test design, questionnaire development and procedure for separation of noise effects will be described. An objectives tree for this study is shown in Figure 2.1. Noise hearing threshold (Box 121) and physiological responses were not investigated.

2.1 Test Phases

Since the aim of this study is to model passenger reactions, commercial flight tests were conducted. On these flights, passenger psychological factors (such as motivation, attitudes, flight feelings, etc.) that may affect their responses to the flight exist. However, passenger reactions were obtained only once during each of these flights, reflecting their overall flight feelings, thus restricting the available data for modelling. Further, since the flight environment cannot be modified on these flights, the confidence and range of applicability of the empirical models (relating passenger reactions to the flight environment) are also limited [because of lack of spread of data - Ref. (22,52)]. In order to resolve these problems, special flights, both semicontrolled and controlled, were conducted. The controlled flights involved flight environment modification (resulting in wider range of application

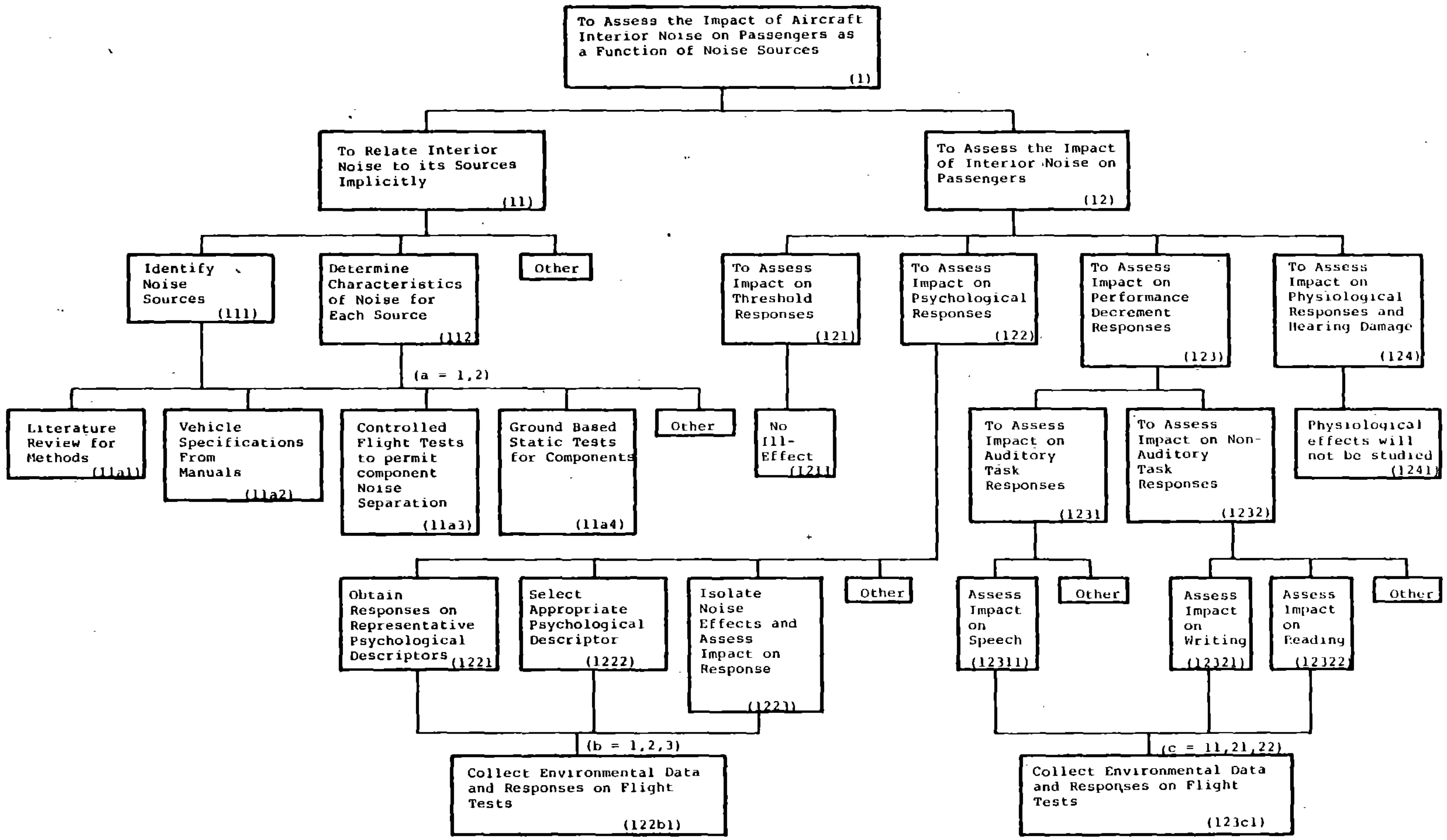

FIGURE 2.1 Components of the Aircraft Interior Noise Study.

of models), and collection of subject* responses for many segments in each flight (larger data base). However, to increase realism, semicontrolled flights were conducted, which established a link between the controlled and commercial flights. During these flights, subject responses to the flight (as in the controlled flights) were obtained, for flight environments which resembled the commercial flights.

Further, a few environmental tests (flight and ground tests) were conducted to survey interior noise at various locations within the aircraft and to obtain noise source characteristics. These tests were necessitated due to the difficulty of conducting detailed surveys with passengers on board.

In all, data were collected in the following test phases:

Commercial Flights

Semicontrolled Flights } Special Flights

Controlled Flights }

Environmental Tests:

- Flight Tests
- Ground Tests

A schematic description of the test phases is shown in Figure 2.2. These tests enabled an increase in confidence and increase in range of application of the satisfaction models.

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*Subjects are trained personnel, whose purpose in flying on-board these flights, is to evaluate the flight in more detail.

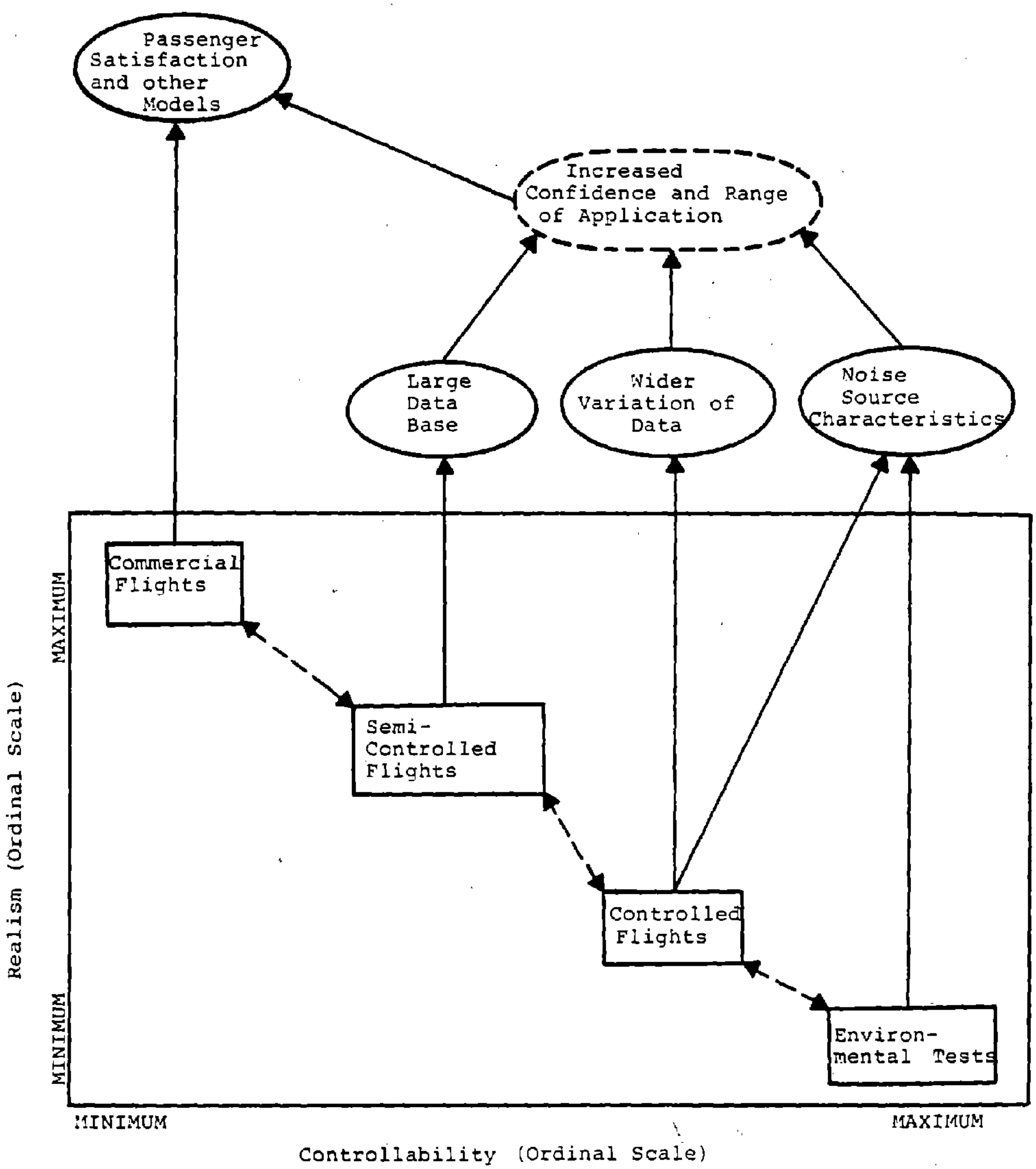

FIGURE 2.2 Test Phases Purpose -- Schematic.

2.1.1 Test Phase Data

Three types of data were collected, viz., aircraft information, environmental data, and subjective responses (see Figure 2.3). Not all data were collected for all test phases (see Table 2.1). Aircraft information included a description of the power plant characteristics, aircraft performance characteristics, aircraft interior information, etc. (see Appendix A).

2.1.1.1 Environmental Data

All the factors that significantly affect subjective comfort were measured. The environmental variables included motion, noise (both level and spectra), temperature and pressure change. Further general flight information such as cruise altitude, cruise velocity, etc., were recorded (see Appendix C). Other environmental variables such as lighting, were not included since they were judged to be not important (see Figure 1.8). Further, since passenger reaction to seating is an independent judgement (21), it was not included.

Each flight test was divided into a number of segments (typically 6-11 segments, each lasting for about one minute). Environmental data and subject responses were obtained for each segment. Noise and motion data were continuously recorded throughout the flight allowing both overall and spectral data. In addition, temperature, and noise level

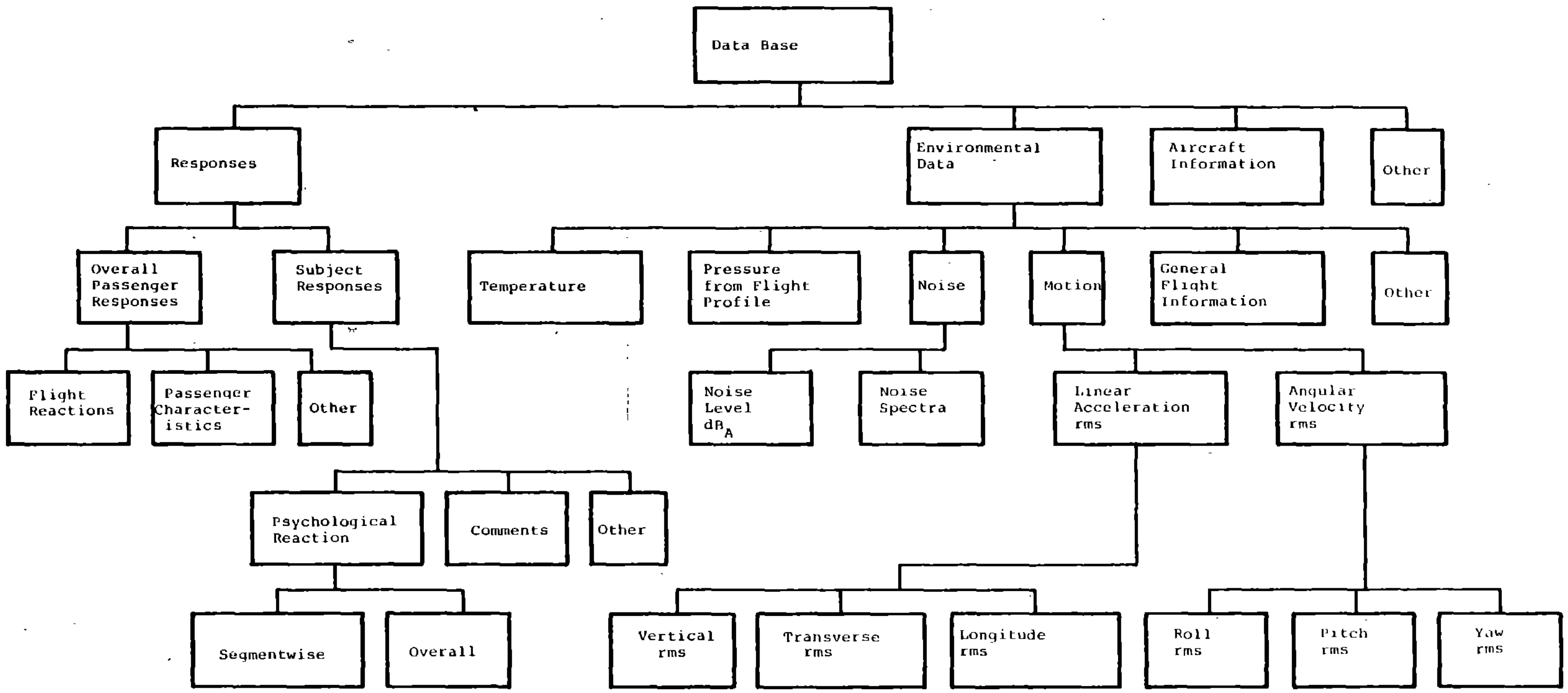

FIGURE 2.3 Data for Test Phases.

Test Phases	Aircraft Type	Environmental Measurements	Responses*
Commercial Flights	Reci-prop. Turboprop.	Motion, Noise, Temp., Pressure	Passenger (questionnaire), Subject (segment and overall)
Semicontrolled Flights	Reci-prop. Turboprop.	Motion, Noise, Temp., Pressure	Subject (segment and questionnaire)
Controlled Flights	Reci-prop.	Motion, Noise, Temp., Pressure	Subject (segment and questionnaire)
Environmental Flight Tests	Reci-prop.	Motion, Noise, Temp., Pressure	---
Environmental Ground Tests	Reci-prop.	Noise	---

*Types of responses will be described later.

TABLE 2.1

DATA BY TEST PHASES

in dB_A were recorded for each segment of the flight. Pressure information was obtained from the general flight data.

2.1.1.2 Responses

Subjective responses to the flight environment were obtained on all but the environmental tests. Passenger questionnaire data were obtained only on commercial flights. Questions on demographic factors, attitudes, motivation, responses to the flight, on-board activities, etc. were asked. Passengers were requested to fill in the questionnaire towards the end of each flight. Their responses to the flight reflected their overall feelings for the flight. Comfort was rated on a 7 point scale shown in Table 2.2.

Since passenger responses for all segments of a flight could not be obtained for logistical reasons, subject comfort response, based on the seven point comfort scale (Table 2.2) was obtained for every segment of each commercial flight. In addition, at the end of the flight, subject comfort responses, reflecting their overall comfort responses, were obtained. These subject comfort responses were obtained on all tests, except the environmental tests. Subjects also answered questionnaires on the semicontrolled and the controlled flights.

1 - Very Comfortable

2 - Comfortable

3 - Somewhat Comfortable

4 - Neutral

5 - Somewhat Uncomfortable

6 - Uncomfortable

7 - Very Uncomfortable

TABLE 2.2

COMFORT SCALE

2.1.2 Test Phase Description

A summary of the test phases is presented in Table 2.3. A brief description of each phase is given below.

2.1.2.1 Commercial Flights

Tests were conducted on regularly scheduled commercial airlines. Subject responses (Table 2.1) from two subjects and environmental data were recorded for all segments. Passenger questionnaire data and subject overall comfort responses were also collected.

2.1.2.2 Semicontrolled Flights

Semicontrolled flight profiles were based on the flight profiles observed on commercial flights. A schematic of the eight segment flight profiles is shown in Figure 2.4. The parameters varied in the semicontrolled flights are tabulated in Table 2.4. Each of the flights shown in the table, involved collection of general flight information, environmental data and subject responses (to the segments and the questionnaire).

2.1.2.3 Controlled Flights

Controlled flight tests were conducted in order to obtain responses to a wider variation of interior noise, as a function of both noise level and noise sources. In order to vary noise level and spectra, a number of factors were controlled and modified during flight. These factors are listed in Table 2.5. The relationship between these

TABLE 2.3

TEST PLAN

(On all tests environmental measurements were made)

I Commercial Flights	II Special Flights	III Environmental Survey Tests*
S&P,R/TP,F,SL,U,NP	S,R/TP,F,SL,OS/U,C/PC	N,R,G/F,A,OS,C
	Semi-Controlled: R/TP,U,PC	Ground: OS (possible on Ground)
Purpose: To obtain S & P responses under commercial flight conditions	Controlled: R,OS,C	Flight: OS (possible only flying)
	Purpose: To obtain relationship between Subj. responses and noise sources, with higher confidence.	Purpose: To obtain direct relationship between interior noise, and noise sources and location.

KEY

(a) Type of Responses
- N - None
- S - Subjects
- P - Passengers

(b) Type of Aircraft
- R - Reciprocating Prop.
- TP - Turboprop

(c) Type of Test
- G - Ground
- F - Flight

(d) Locations
- SL - Representative Locations (2-3)
- A - Several Locations

(e) Variation of Source Noise
- OS - One at a Time when possible
- U - Uncontrolled

(f) Flight Profile
- NP - Normal Profile
- PC - Partially Controlled Profile
- C - Controlled Profile

*Only noise data were collected on these tests.

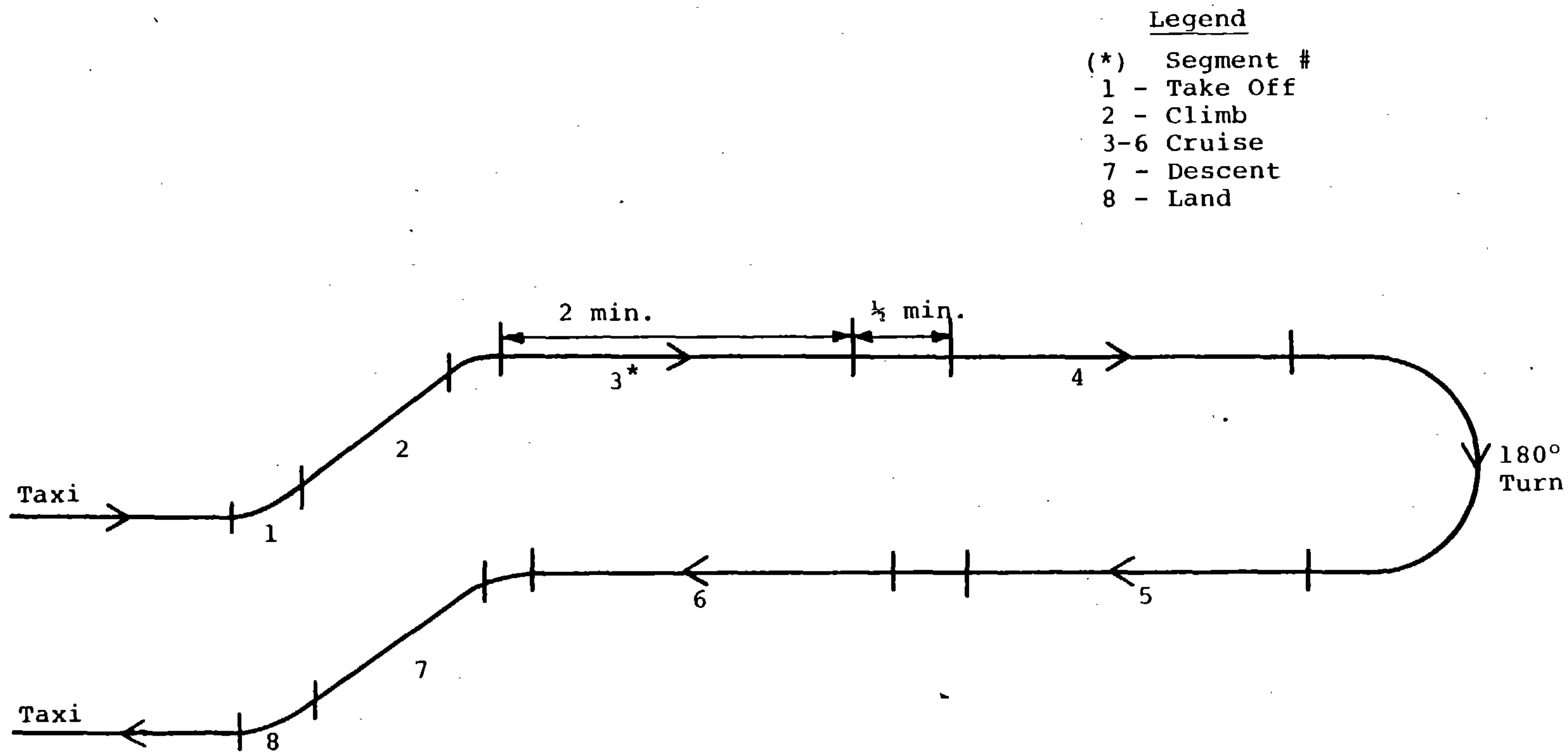

FIGURE 2.4 Schematic Diagram of the Semi-controlled Flight Profiles.

TABLE 2.4

SEMICONTROLLED FLIGHT PROFILE PARAMETERS

Aircraft	Subject Group #	Flight #	CLIMB (Seg* #2) Rate of climb (ft/min)	CRUISE (Seg #3 - 6) Cruise altitude (ft.)	Cruise Velo. (MPH)	DESCENT (Seg. #7) Rate of descent (ft/min)	Pressurization
Reciprocating Propeller Type, Aircraft A							
A	I	1	500	4000	180	500	NO
	I	2	800	5000	180	500	NO
	II	1	500	4000	180	500	NO
	II	2	800	5000	180	500	NO
Turboprop Type, Aircraft E							
E	III	1	700	5000	180	700	NO
	III	2	1400	10000	220	1500	YES
	IV	1	700	5000	180	700	NO
	IV	2	1400	10000	220	1500	YES

*Segment #'s are as shown in Figure 2.4.

TABLE 2.5

NOISE - SOURCE CONTROLLABLE FACTORS

Altitude

Engine Power

Velocity

Radio (on/off)

Vent (open/closed)

Location

Flight Phase (e.g. take-off, cruise, climb/descent, or landing) factors and the interior noise sources (Appendix H) are shown in Table 2.6. The interior noise modification procedure used on these tests is illustrated in Figure 2.5.

Aircraft A (see Appendix A for description), was used on the controlled flights. The seating arrangement in the aircraft is shown in Figure 2.6.

As part of the controlled flight tests, two flight profiles were selected. In the flights, subjects were exposed to variations in all noise source factors shown in Table 2.5, except location. The flight profiles for the two flights are described in Tables 2.7 and 2.8. Each profile has 11 segments and each segment represents a variation of one noise source factor from the standard conditions, defined in the tables.

2.1.2.4 Environmental Tests

The purpose of the environmental tests was to survey the interior noise at various locations in the aircraft used on the controlled flight tests, both in flight and on the ground. In both tests, only interior noise (level and spectra) was recorded. Measurements were made at four locations 1R, 2L, 3R and 4L, shown in Figure 2.6, for all cases.

The environmental flight tests were conducted for conditions identical to those in the controlled flights. The interior noise survey was not feasible on the controlled

TABLE 2.6

RELATIONSHIP BETWEEN THE CONTROLLABLE NOISE VARIABLES AND THE UNDERLYING NOISE SOURCES‡

UNDERLYING NOISE SOURCES (Appendix H)	FACTORS CONTROLLING NOISE LEVEL†	FACTORS CONTROLLING FREQUENCY
1. ENGINE	A, B, C*(B), E, F, G*(B)	(ENGINE RPM)
2. AERODYNAMIC NOISE	A, C, F, G*(C)	C, (AIRCRAFT PARAMETERS)
3. RADIO	A, D, F	(FUNCTION OF RADIO)
4. VENT	A, B, C, E	(NOZZLE PARAMETER)
5. AUXILIARY UNITS	(?)	(UNKNOWN)

KEY: CONTROLLABLE NOISE VARIABLES

A. ALTITUDE

B. ENGINE POWER

C. VELOCITY

D. RADIO

E. VENT

F. LOCATION

G. FLIGHT PHASE

---

†See Key for Explanation.

*Already Accounted for Through ( ).

‡See Appendix H.

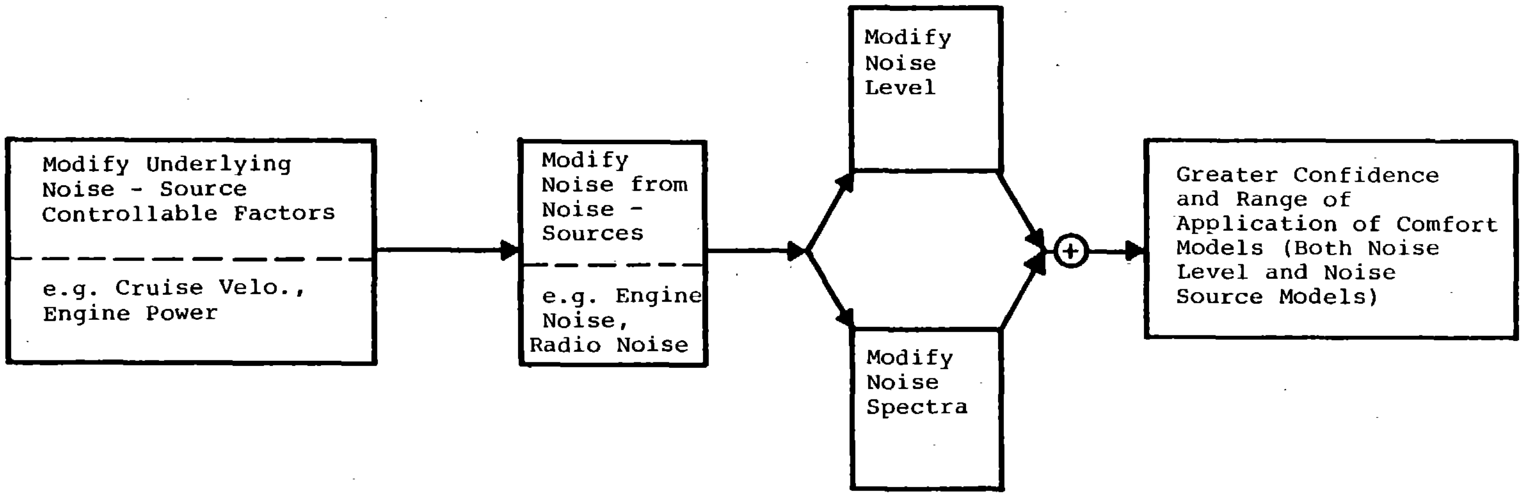

FIGURE 2.5 Noise Modification Process on Special Flights.

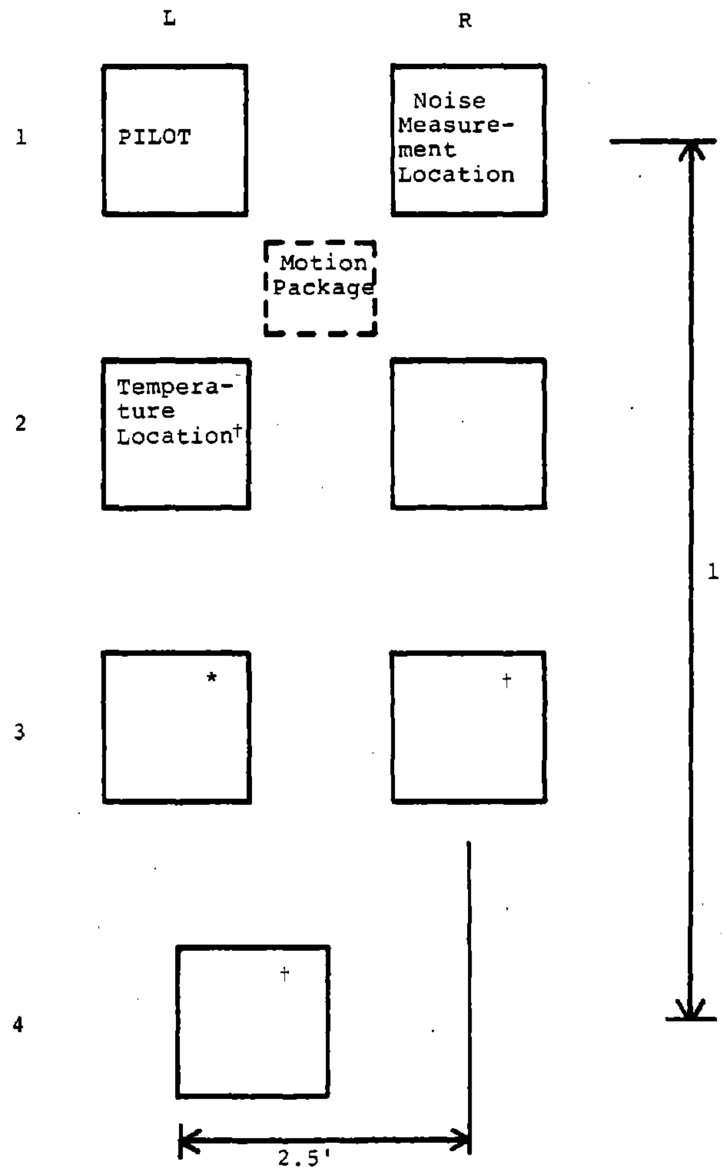

FIGURE 2.6 Seating Arrangement in Aircraft A.

* During one Segment of the Controlled Flight, noise is also measured here.
† During Environmental Tests, noise is measured at these locations as well, for all segments.

TABLE 2.7

PROFILE FOR CONTROLLED FLIGHT #1

Segments*:

1. Climb to 3000 ft. (rate of climb = 500'/min.)
2. Cruise at 3000 ft., 25" manifold pressure, indicated airspeed __________mph, vent open (heat on as required), no conversation
3. Climb to 5000 ft. (rate of climb = 500'/min.)

Std.**

4. At 5000 ft., 25" manifold pressure, trim for 0 rate of climb, (std. indicated velocity _________mph)
5. Climb to 7000 ft. (rate of climb = 500'/min.)

(Standard Turn)

6. At 7000 ft., 25" manifold pressure, trim for 0 rate of climb, (indicated velocity _________mph)
7. At 7000 ft., 25" manifold pressure, standard velocity _________mph (rate of descent _______'/min.)
8. Climb to 9000 ft. (rate of climb = 300'/min.)
9. At 9000 ft., 25" manifold pressure, trim for 0 rate of climb, (indicated velocity _______mph)
10. Descent (rate of descent = 800'/min.)
11. Land

---

*Subjects record their comfort responses at the end of each segment and fill out questionnaire upon landing.

**Standard Condition.

TABLE 2.8

PROFILE FOR CONTROLLED FLIGHT #2

Segments*:

1. Climb to 5000 ft., (rate of climb = 500'/min.)

Std.** 2. Cruise at 5000 ft., 25" manifold pressure, std. indicated velocity ______________ mph.

3. At 5000 ft., 25" manifold pressure, standard air-speed +25 mph______________(by descending, rate of descent = ________'/min.)

(Return to 5000 ft.)

4. At 5000 ft., 25" manifold pressure, standard air-speed -25 mph______________ (by climbing, rate of climb = _______________'/min.)

(Return to 5000 ft.)

5. 21" Manifold pressure, at standard indicated air-speed ____________mph, (by descending, rate of descent = ______________'/min.)

(Return to 5000 ft. and standard turn)

6. 23" manifold pressure, at standard indicated air-speed ______________mph, (by descending, rate of descent = _____________'/min.)

7. At 5000 ft., 25" manifold pressure, with radio on.

8. At 5000 ft., 25" manifold pressure, environmental measurements taken at 3-L location in aircraft.

9. At 5000 ft., 25" manifold pressure, vent closed (heat off).

10. Descent (rate of descent = __________'/min.)

11. Land

---

*See Footnote Table 2.7.

**Standard Condition.

flights, due to the presence of the subjects. In the ground tests, noise measurements were recorded at the four locations for conditions shown in Table 2.9.

2.2 Questionnaire Development

In order to relate passenger responses to the environment, commercial passenger data was obtained. This was collected during the flight using a questionnaire.

A number of questionnaires have been developed and used as part of the previously reported ride quality program (5,25). Since those questionnaires have proven useful in field studies (5,25,53), the questionnaires for this study have been modeled after them.

The questionnaire (Figure 2.7) included questions on general information, and reactions and activities. The purpose of the former questions is to investigate appropriate data stratifications in analyzing the effect of environment on reactions and activities. Passenger responses to the second set of questions were used to determine the effect of the flight environment on passengers and to select the best psychological descriptor of the environment.

A review of literature (13,26) indicated that a number of category scales are used to judge the effect of noise. In the questionnaire used, a small number of these subjective scales were incorporated. Based on an investigation of the appropriateness of the psychological descriptors, with respect to its relationship to environmental variables and satisfaction,

TABLE 2.9

TEST CONDITIONS FOR GROUND TEST

No.	
1	All systems off (Background)
2	Only Radio on
3	Only Gyro on
4	Engine Power Setting - 19" Manifold Pressure
5	Engine Power Setting - 21" Manifold Pressure
6	Engine Power Setting - 23" Manifold Pressure

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This questionnaire is part of an effort by this Airline, the National Aeronautics and Space Administration, and the University of Virginia to obtain from you, the flying public, information to be used in the improvement of transportation systems. The goal of the program is to identify the needs and desires of airlines passengers, so that future systems may increase passenger satisfaction.

Your cooperation in completing this form will be most appreciated and can only be of benefit to you, the air traveler. Thank you, and enjoy your flight.

You need not answer any question that offends you.

1. Age .... 2. Sex: ☐ M ☐ F

3. What is the primary purpose of this trip? (check one)
   ☐ Company business ☐ Personal business ☐ Pleasure

4. Please indicate your overall reaction to this flight:
   - ☐ Very comfortable
   - ☐ Comfortable
   - ☐ Somewhat comfortable
   - ☐ Neutral
   - ☐ Somewhat uncomfortable
   - ☐ Uncomfortable
   - ☐ Very uncomfortable

5. About how many times have you traveled by air?
   - ☐ 0 (this is my first time)
   - ☐ 1 - 3
   - ☐ 4 or more

6. Do you fly because you have to (for the purpose of this trip)?
   ☐ Yes ☐ No

7. Please check the box which completes the following statement:
   "The noise you experienced during this flight is
   ☐ more than ☐ the same as ☐ less than
   the noise level you experience at your place of work."

8. Please indicate how pleasant you found this flight:
   - ☐ Very unpleasant
   - ☐ Unpleasant
   - ☐ Somewhat unpleasant
   - ☐ Neutral
   - ☐ Somewhat pleasant
   - ☐ Pleasant
   - ☐ Very pleasant

9. How do you feel about traveling by air?
   - ☐ I like it.
   - ☐ I have no strong feelings.
   - ☐ I dislike it

10. Indicate the importance of the following factors in your choice of travel mode for this flight:

	Not Important	Moderately Important	Very Important
Time savings	☐	☐	☐
Cost	☐	☐	☐
Comfort	☐	☐	☐
Ability to converse	☐	☐	☐
Ability to read and write	☐	☐	☐

11. Specify your seat location: (check all of the following that apply)
    - ☐ Ahead of the wing ☐ Window seat
    - ☐ Over or under the wing ☐ Center seat
    - ☐ Behind the wing ☐ Aisle seat

12. Please indicate how difficult it is to perform each of the following activities during this flight:

	Not Difficult	Somewhat Difficult	Very Difficult
Reading	☐	☐	☐
Writing	☐	☐	☐
Conversation	☐	☐	☐
Dozing	☐	☐	☐
Looking out the window	☐	☐	☐

13. Check the box which indicates how much time during this trip you spent on each of the following activities:

	Little or None	Some	Considerable
Looking out the window	☐	☐	☐
Dozing	☐	☐	☐
Reading	☐	☐	☐
Writing	☐	☐	☐
Conversation	☐	☐	☐

14. Please check the box which indicates the extent to which each of the following items contributes to your feelings about this flight

	Not at all	Somewhat	Very much
Noise	☐	☐	☐
Seat comfort	☐	☐	☐
Temperature	☐	☐	☐
Pressure change	☐	☐	☐
Up and down motion	☐	☐	☐
Side to side motion	☐	☐	☐

15. Indicate your reaction to each of the following statements:

	Agree	Disagree	Strongly Disagree
This seat has enough leg room	☐	☐	☐
The firmness of the seat is satisfactory	☐	☐	☐
The shape of the seat is satisfactory	☐	☐	☐
The seat can be adjusted to your satisfaction	☐	☐	☐

16. Please indicate your feelings about the noise and motion of this flight:

	Noise (check one)	Motion (check one)
Not noticeable	☐	☐
Noticeable, but not annoying	☐	☐
Somewhat annoying	☐	☐
Annoying	☐	☐
Very annoying	☐	☐

17. Have you taken airsickness medication for this flight?
    ☐ Yes ☐ No

    If yes, how long before the flight did you take the medication?
    .... Hours

    Did you experience any symptoms of airsickness on this flight?
    ☐ Yes ☐ No

18. After experiencing this flight, I would: (Check one)
    - ☐ Be eager to take another flight
    - ☐ Take another flight without hesitation
    - ☐ Take another flight, but with some hesitation
    - ☐ Prefer not to take another flight
    - ☐ Not take another flight

19. Comments: ....

THANK YOU FOR YOUR ASSISTANCE

FIGURE 2.7 Questionnaire

comfort, pleasantness and annoyance were selected. Passengers and subjects were asked to rate flights on seven point comfort and pleasantness scales, and then motion annoyance and noise annoyance on five point annoyance scales. The comfort scale was presented in Table 2.2. The pleasantness and annoyance scales are given in Tables 2.10 and 2.11.

A summary of the questionnaire data is displayed in Table 2.12.

2.3 Noise Effect Separation

Passenger response in an aircraft environment is affected not only by interior noise, but also by motion, temperature, pressure change, etc. Hence, to ascertain the noise effects alone, they must be separated from other effects.

The following two procedures were used to separate the noise effects:

(a) If exogenous variable models were available, then their effects were eliminated by analytic techniques, and

(b) If exogenous variable models were not available, then the data set selected for analysis were restricted to those cases in which the influence of spurious variables on comfort responses was minimal.

TABLE 2.10

PLEASANTNESS SCALE

1. Very Unpleasant
2. Unpleasant
3. Somewhat Unpleasant
4. Neutral
5. Somewhat Pleasant
6. Pleasant
7. Very Pleasant

TABLE 2.11

MOTION AND NOISE ANNOYANCE SCALES

1. Not Noticeable
2. Noticeable, but not Annoying
3. Somewhat Annoying
4. Annoying
5. Very Annoying

TABLE 2.12

QUESTIONNAIRE DATA SUMMARY

Respondee Specific Data	Reactions and Activities		Miscellaneous
	Reactions	Activities	
Age	Comfort	Importance of, Activities and Factors	Air Sickness Medication
Sex	Pleasantness		
# of Times Flown	Annoyance (Motion, Noise)	Difficulty in performing	Comments
Noise Exposure	Environmental Variable Reaction	Time Spent on Activities	
Purpose of Trip	Seat Reaction		
Captive/Choice Traveller	Feelings about taking Another Flight		
Air Travel Feelings			
Location			

In the case of motion, since the relationship between motion and comfort is known (Chapter I), motion effects were eliminated by relating noise to the comfort response not accounted for by motion. Since comfort models for temperature and pressure have not been fully developed (Chapter I), the latter procedure was used to isolate noise effects.

CHAPTER III

DATA ACQUISITION

3.1 Equipment

The equipment needed to measure, record and reduce the data are described in Appendix G and summarized in Table 3.1. As shown in the table, flight noise and motion recordings were subsequently reduced to yield rms motion, and 1/3 octave band noise levels respectively. Except for the ground data reduction equipment (a PDP-11 computer, General Radio realtime analyser Model #1921, etc.) all other equipment shown in Table 3.1 are portable and are used to measure and/or record flight data.

The equipment used to measure and record motion, noise and temperature data is shown in Figure 3.1.

3.2 Sample Size for Test Phases

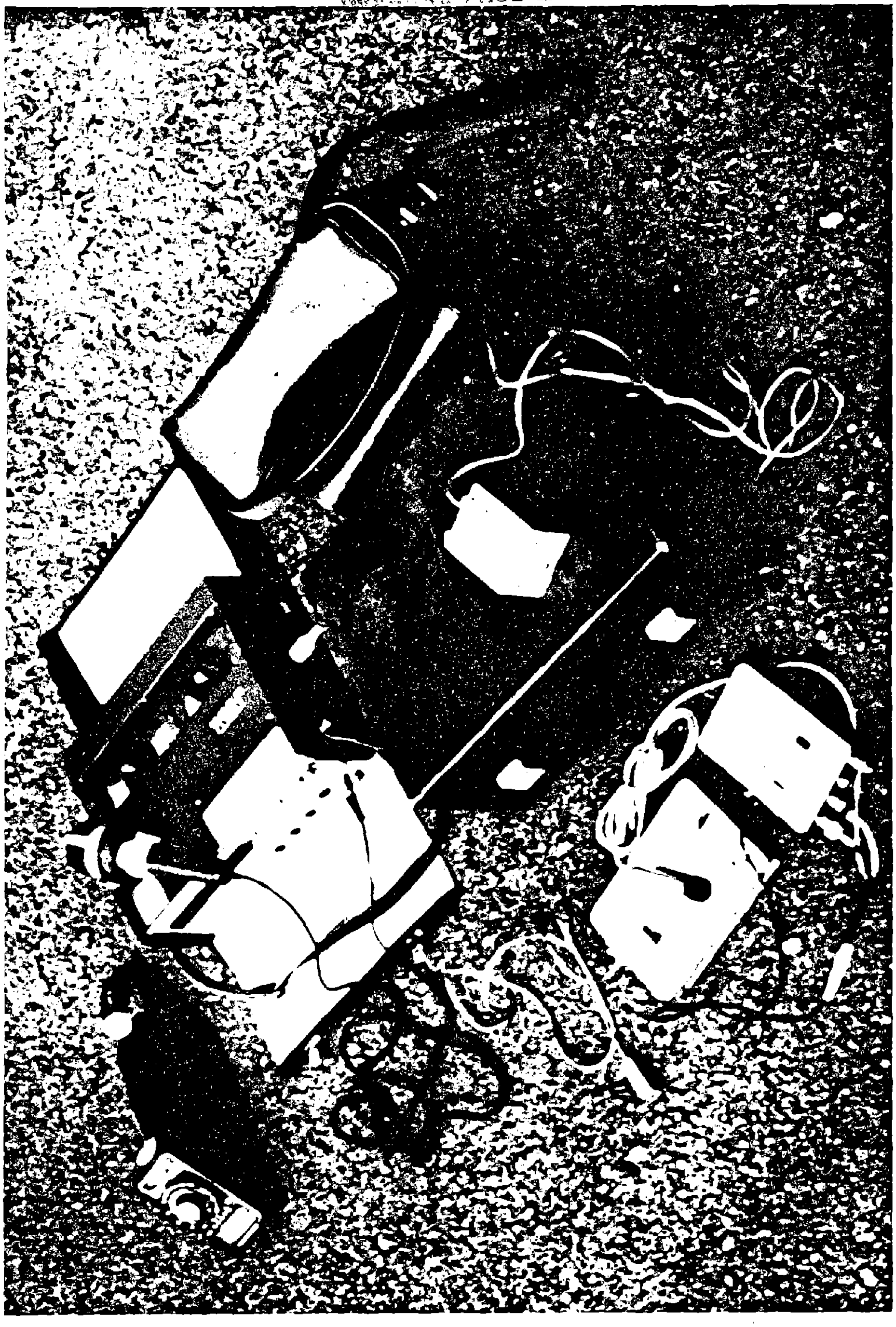
Sample size estimates were made for each test phase, in order to ensure that the data base used for this study would be adequate to obtain significant results. The estimation procedure is described in Appendix D. The confidence level chosen for this study is 90% ($\alpha = 0.1$). The permitted error for passenger comfort responses (δ_{c_p}) and subject comfort responses (δ_{c_s}) chosen for this study were respectively,

TABLE 3.1

EQUIPMENT USED FOR DATA COLLECTION

Data Variables	Type of Data	Equipment/Recording Medium	Miscellaneous Frequency of Measurement, (Respondents)
MOTION	FM-Multiplexed 6 deg. of freedom motion recordings	UVA Motion Package and UHER-4400 Stereo tape recorder	Continuous
	rms. linear acceleration, and angular velocities	UVA Motion Reduction Equipment (includes PDP-11 Computer)	Each Segment
NOISE	dB_A	Scott Sound Level Meter Type 451	Each Segment
	Noise Recordings	B & K Mic. Sys., NAGRA SN-Tape Recorder	Continuous
	1/3 Oct. Spectra, OSPL etc.	GR - Real Time Analyser #1921	Each Segment
TEMPERATURE	°F	Thermometer/Log Sheets	Each Segment
PRESSURE	Cruise Cabin Pressure, Rate of Pressure Change etc.	Log Sheets	Each Flight
GENERAL FLIGHT INFORMATION	Flight Profile, Cruise Conditions, etc.	Log Sheets	Each Flight
RESPONSE	Questionnaire Responses	Questionnaire Sheets	Each Flight (Pass. or Subj.)
	Comfort Responses	Log Sheets	Each Segment and Flight (Subject)

FIGURE 3.1 Portable Instrument Package and Recording Equipment (see next page).



$\delta_{c_p} = 0.5$ co7*, and

$\delta_{c_s} = 0.5$ co7.

It was estimated from the data available from previous studies that the square root of the variance, s, of the passenger and subject comfort responses, c_p and c_s respectively, are

$s_{c_p} = 0.76$ co7, and

$s_{c_s} = 0.3$ co7.

Using these values, sample sizes required for the tests were determined (Table 3.2).

3.3 Data Summary

The data collection for this study involved four test phases, four airlines, five models of aircraft, viz. aircraft, A through E (Appendix A), both reciprocating propeller and turbo-prop types of aircraft, fifty three flights and one ground test, 152 passengers, and 178 subject** flight cases. These data are sufficient for the sample size estimations given in Table 3.2.

A summary of the available data is presented in Table 3.3. [See Appendix C for the types of data collected].

---

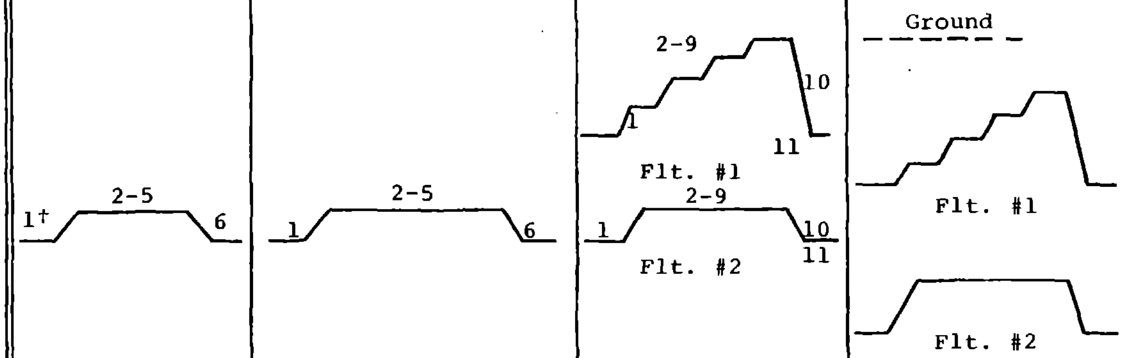
*co7 is a unit in a seven point comfort scale (see Chapter V for more details).

**See Appendix B for subject profiles.

TABLE 3.2

SAMPLE SIZE ESTIMATES FOR TEST PHASES

Sample Size (90% Confidence)	I Commercial Flight	II Special Flights		III Environmental Tests
Type		Semi-Controlled Flights	Controlled Flights	
Type of aircraft	R/TP*	R/TP*	R*	R
# of flights/aircraft type	3 - 4	3 - 4	3 - 4	3 (1 Each)
# of passengers/aircraft type	24	-	-	-
# of subjects/flight	2	3	3	-
Total # of subjects	3 - 4	4	4	-
# of segments/flight	5 - 6	5 - 6	As required	As required
Flight profile schematic (time vs. Altitude)				



†Segment #

*R - Reciprocating Propeller a/c

TP - Turbo-prop. a/c

TABLE 3.3

DATA SUMMARY

Test Phase/Subgroup		Descriptor	Aircraft Type*	Aircraft	# of Tests	# of Subject-Tests	# of Passengers	# of Noise Data Tests	# of Motion Data Tests	# of Subject/ # of Passenger Response Tests	# of Other Data (T,P† etc) Tests
Environmental Tests (E)	Tests	Ground	R	A	1	2	--	1	--	--	--
		Flight	R	A	2	4	--	2	2	--	2
Controlled Flights	Pro-file	#1	R	A	6	31	--	4	6	6	6
		#2	R	A	5	27	--	4	5	5	5
Semi-controlled Flights	Air-Craft	R	R	A	4	24	--	4	4	4	4
		TP	TP	E	4	32	--	4	--	4	4
Commerical Flights	Airline	A	R	B	9	18	22	9	6	9	9
		B	TP	C	13	26	30	13	--	13	13
		C	TP	D	6	12	64	5	6	6	6
		D	TP	C	4	8	34	4	4	4	4

*Aircraft Type: R - Reciprocating Propeller, TP - Turbo-prop.

†T: Temperature, P: Pressure Data.

This table is a cross tabulation of the number of test cases vs. test phase. Table 3.4 shows the breakdown of the data by aircraft. In Table 3.5, the range of stimuli, to which passengers and subjects were exposed, is presented.

The data gathered in this study is cataloged in much more detail in reference (54).

TABLE 3.4

NUMBER OF FLIGHTS VS. AIRCRAFT

AIRCRAFT	# OF FLIGHTS	MOTION	NOISE METER dB(A)	NOISE SPECTRA	TEMP	PRESSURE	TEST SUBJECT RESPONSES	PASSENGER RESPONSES
A	17	17	17	14	17	17	15	0
B	9	6	9	9	9	9	9	9
C	17	4	17	17	17	17	17	11
D	6	6	6	5	6	6	6	6
E	4	0	4	4	4	4	4	0

TABLE 3.5

RANGE OF STIMULI EXPERIENCED BY PASSENGERS AND SUBJECTS

Motion	
rms Angular Velocities	$< 4.0°$/sec.
rms Longitudinal Acceleration	< 0.1 g
rms Transverse Acceleration	< 0.09 g
rms Vertical Acceleration	< 0.2 g
Noise Level	79 to 100 dB_A
Temperature	12 to 39°C
Pressure	1 to 0.7 atm.
Altitude	0 to 3000 meters
Cruise Velocity	240 to 355 Km/hr.
Rate of Climb/Descent	$<$ 460 meters/min.
Rate of Pressure Change	$<$ 0.033 atm/min.
Flight Duration	15 to 70 min.

CHAPTER IV

DATA ANALYSIS METHODOLOGY

The procedures used to generate satisfaction and task effect models are outlined below. In addition to these models, data analysis involved investigation of the questionnaire data and hearing noise effects. These are described in detail in Chapter VI and Appendix J, respectively.

4.1 Satisfaction Models

The relationship between the flight environment and satisfaction with the system is taken as a two part process, viz., to relate the flight environment to passenger comfort* and then to relate passenger comfort to satisfaction with the system. This is illustrated in Figure 4.1. Since passenger comfort responses (overall), were obtained only once towards the end of each flight, and environmental data throughout the flights, subject responses have been used as the intermediate variables relating the two.

The satisfaction modelling process, then has four steps, viz., to relate:

(a) flight segment environments to subject segment responses

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*In keeping with past work (8,16,22,23), comfort was adopted as the descriptor relating passenger feelings to the flight environment.

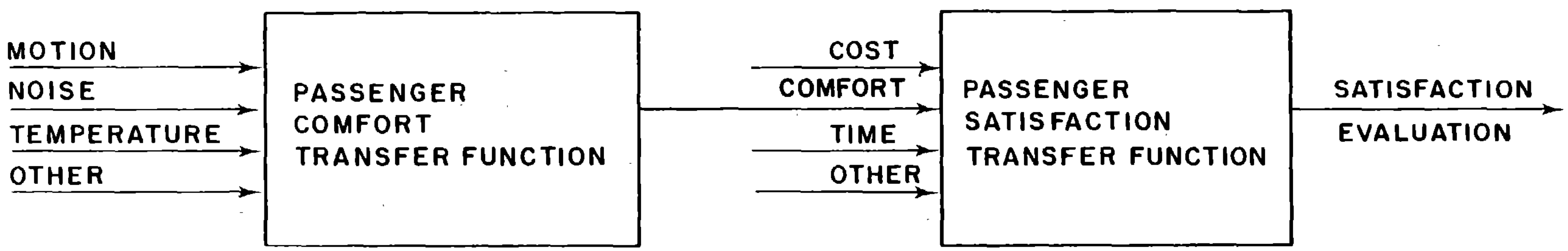

FIGURE 4.1 Block Diagram of Passenger Reaction to Transportation System.

(b) subject segment response to subject overall responses,

(c) subject overall responses to passenger overall responses, and

(d) passenger overall comfort response to passenger satisfaction.

These steps are functionally represented as,

$$C_{s_i} = f\ (E_i) \tag{4.1}$$

$$C_{s_o} = f\ (C_{s_i},\ \text{all } i) \tag{4.2}$$

$$C_p = f\ (C_{s_o}),\ \text{and} \tag{4.3}$$

$$A_p = f\ (C_p,\ \text{other system variables}) \tag{4.4}$$

where

Subscript i/o - segment number/overall

C_s - subject comfort response

C_p - passenger comfort response

E - environmental data

A_p - passenger satisfaction

The modelling process is illustrated in Figure 4.2. Test phase data that were used to develop the models in each of the four steps are illustrated in Figure 4.3.

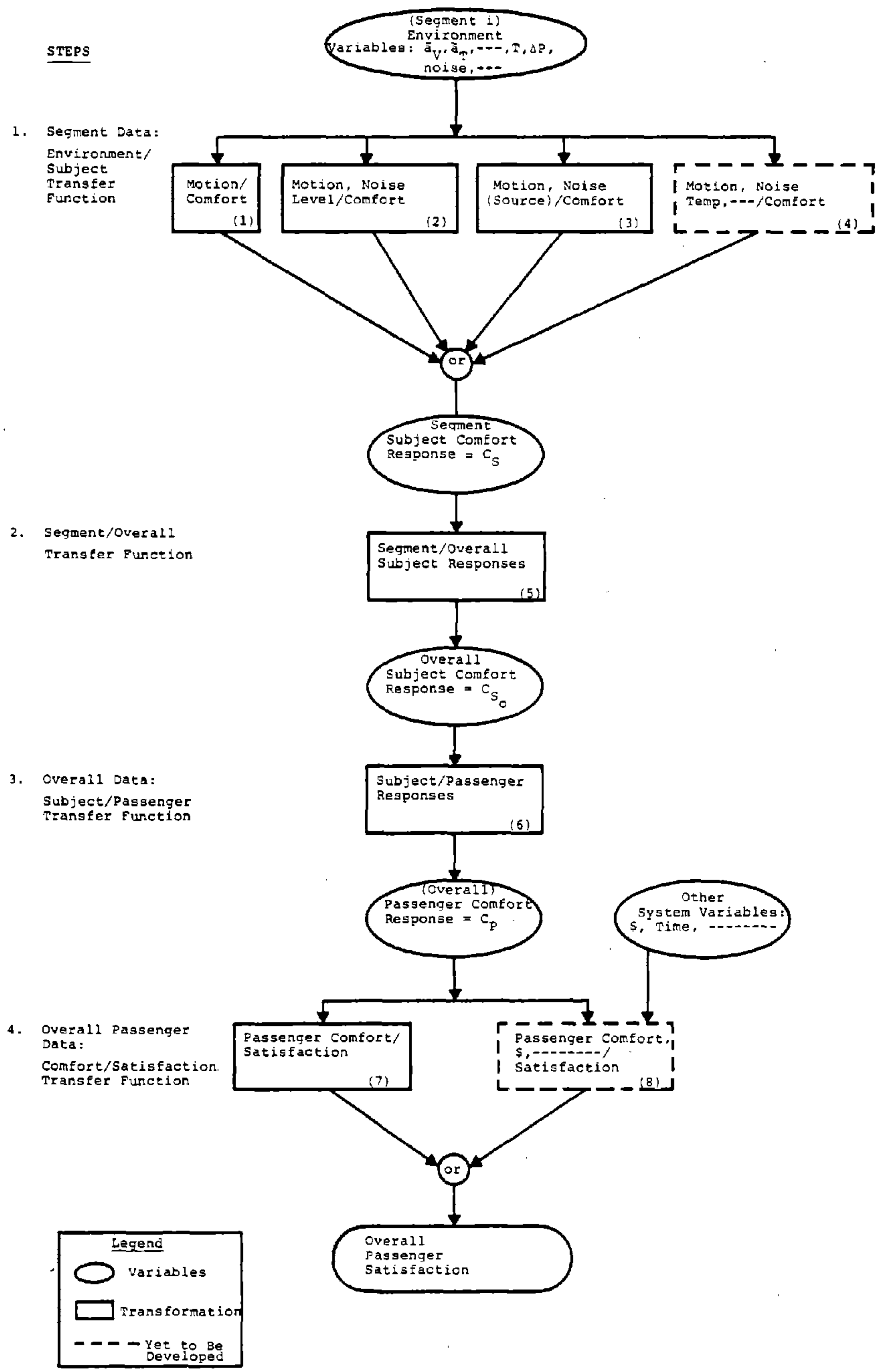

FIGURE 4.2 Block Diagram of Passenger Satisfaction Modeling Process.

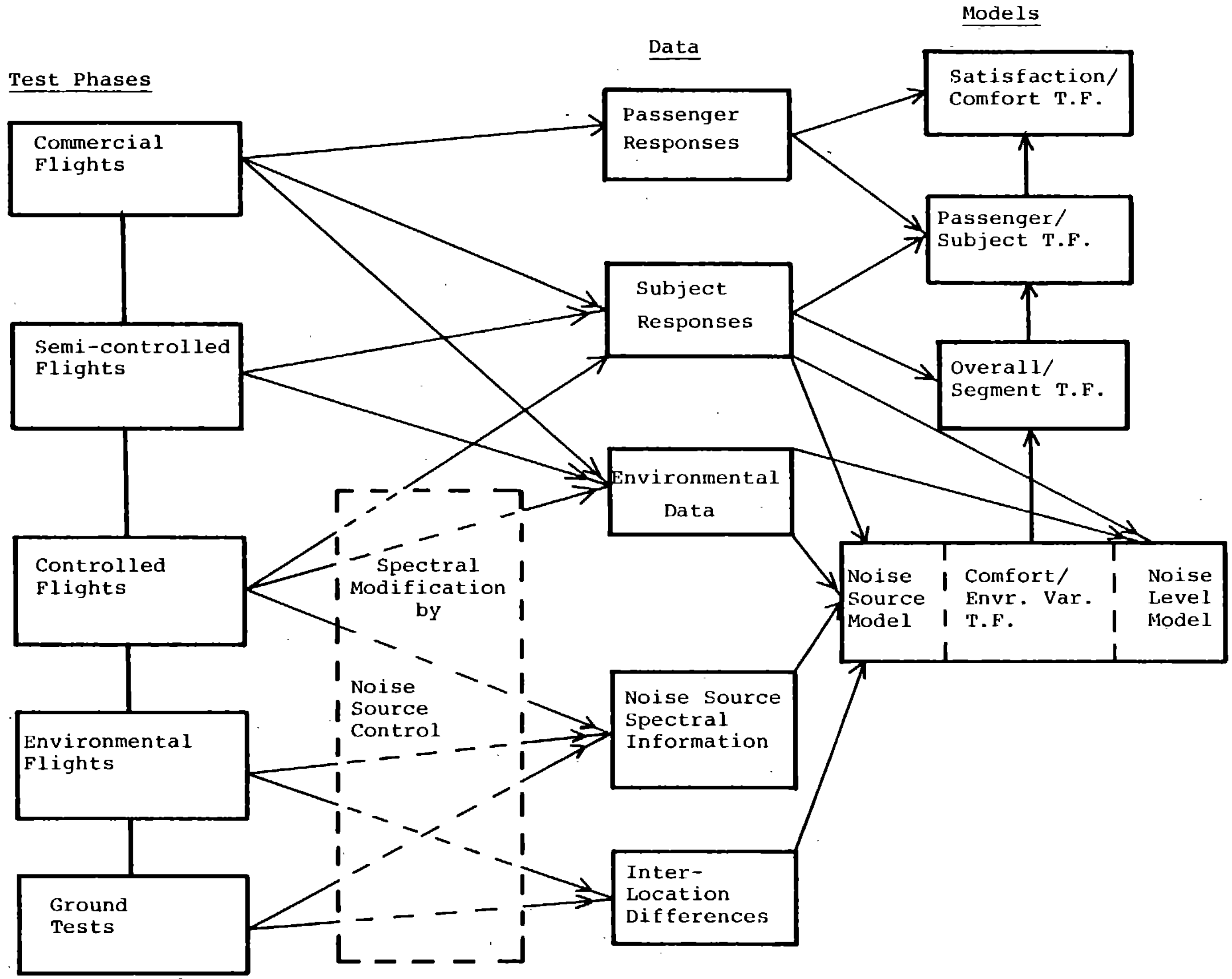

FIGURE 4.3 Relationship Between Test Phases, Data and Satisfaction Models.

Boxes 1 through 4 (Figure 4.2) represent segment environment/subject response transfer function of increasing complexity, and blocks 7 and 8, those of satisfaction models. The model shown in box 1 and a preliminary version of the model in box 2, have been developed in previous studies (Chapter I, 16,23). The box 1 model was used as a basis for the present effort (boxes 2 and 3). The models represented by boxes 5, 6 and 7 were formulated in past studies (5,16,39,53), and their applicability was also investigated in this study. Future studies should allow expansions to transfer functions in boxes 4 and 7.

4.2 Task Effect Models

The procedure used to model the effect of noise on activities difficulty* is outlined in Figure 4.4. Among the activities, only conversation effect was modelled, since since the other noise effects were not significant.

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*"Activities difficulty", as used in the text, does not necessarily imply delitarious effect. Responses are on a three-point scale, viz., 1-Not difficult, 2-Somewhat difficult, and 3-Very difficult.

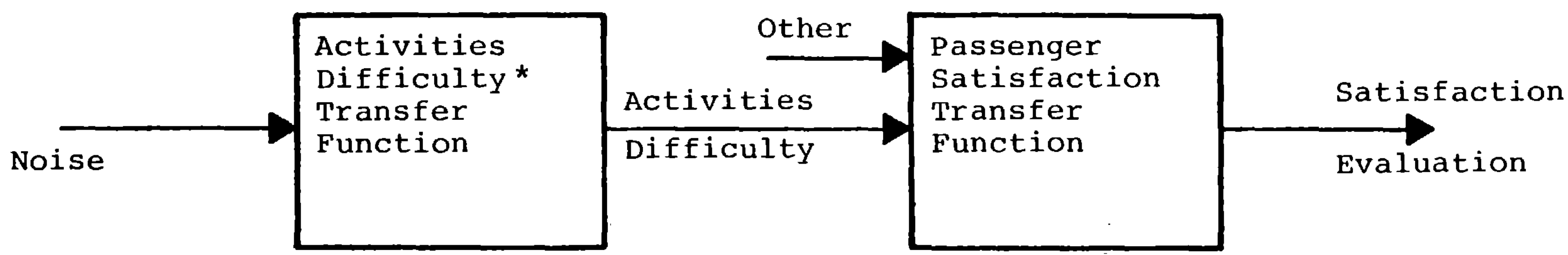

FIGURE 4.4 Block Diagram of the Effect of Noise on Activities.

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*See footnote p. 62.

CHAPTER V

DATA ANALYSIS - PART I: SATISFACTION MODELS

In this chapter, the effect of noise on passenger comfort and satisfaction are discussed. Models relating satisfaction to motion and noise are developed. Noise as a function of both overall measures and frequency measures related to sources are examined. The process follows the four step methodology described in Chapter IV (Figure 4.2).

5.1 Comfort/Noise Level Relationship

5.1.1 Controlled and Environmental Flight Data

The effects of varying noise source factors (Table 2.5) on interior noise level (dB_A) and subject comfort response (co7* units) are illustrated in Figure 5.1. The noise level changes associated with variations in location (35), altitude - velocity (35,41,57-60), vent, radio, engine power and flight phase are as expected. The associated changes in comfort responses indicate that, except for climb/descent, vent and location (1R) variations, noise level and comfort responses are correlated positively (sensitivity $\sim$ 0.14 co7/dB_A) indicating a relationship between the two. The noise effect is however, masked in the climb/descent test by pressure effects (19), in the vent test by airflow

*Assuming an interval scale (55,56), a general comfort unit will be defined as a coi unit, where i is the number of levels in the scale. Thus co7 represents one comfort unit on a 7 point scale.

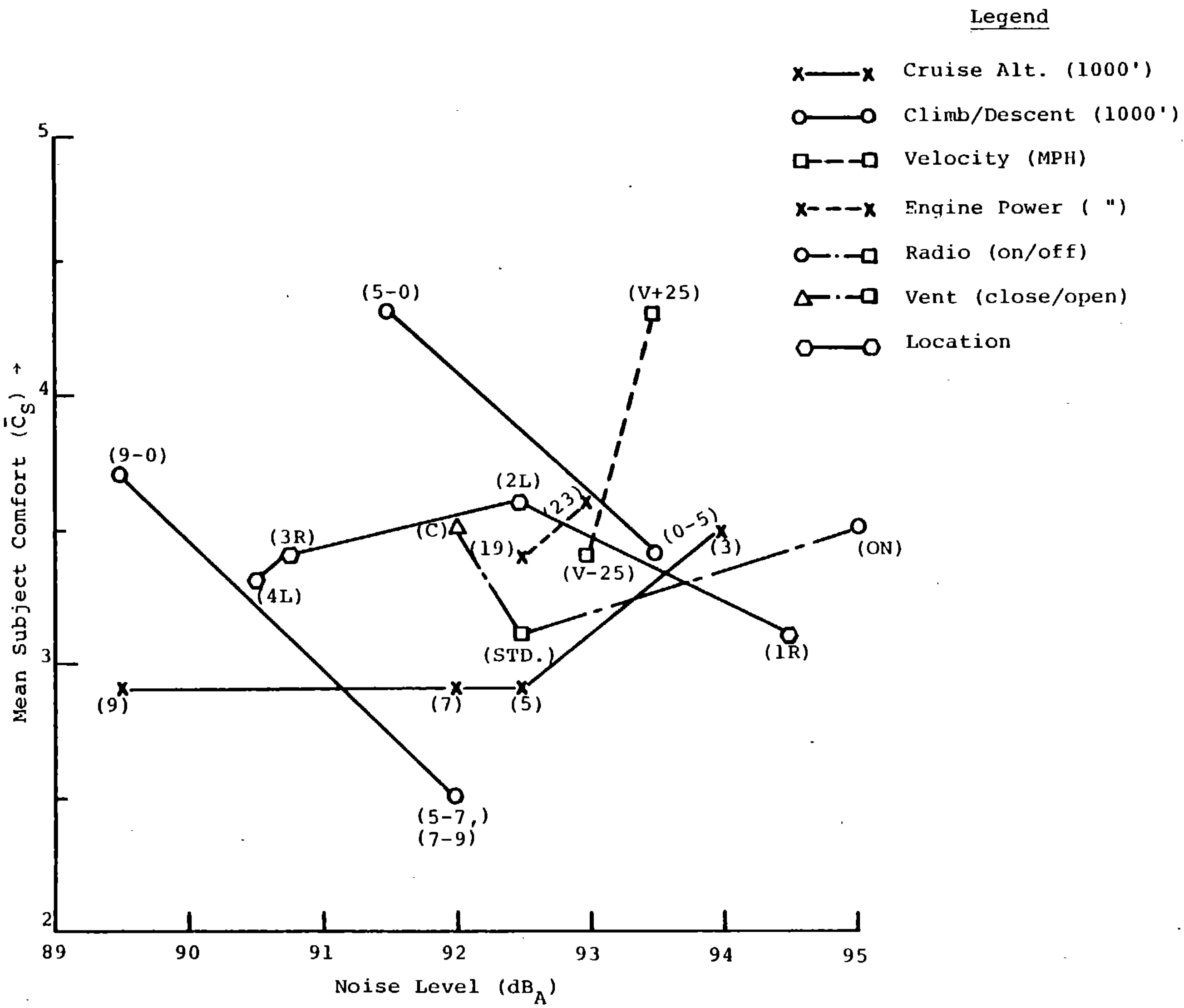

FIGURE 5.1 Effect of Variation of Noise-Source Factors on Subject Comfort and Noise Level (dB_A).

effects (17,19,20), and at location 1R by subject preoccupation with tasks, which results in a negative correlation between noise level and comfort response for these cases.

5.1.2 Comfort/Noise Level-Motion Model

Standard regression analysis programs (56) were used to obtain models relating noise level and motion to subject comfort.

Noise effects were separated (see § 2.3) from the rest of the environment by restricting data to the cases with minimal influence of spurious variables (e.g. temperature, pressure change). Further, motion effects were accounted for by using models from previous studies (16,23), after verifying the applicability of these models.

The contribution of motion to subject comfort (23) on a seven point scale, is given by,

$$C'_{s_M} = \begin{cases} 2.5 + 17.85\ \bar{a}_V + 11.4\ \bar{a}_T, & \text{if } \bar{a}_V \geq 1.6\ \bar{a}_T \\ 2.5 + 1.5\ \bar{a}_V + 37.5\ \bar{a}_T, & \text{if } \bar{a}_V < 1.6\ \bar{a}_T \end{cases} \qquad (5.1)$$

where

C'_{s_M} - predicted subject comfort due to motion, co7 .

$\bar{a}_V/\bar{a}_T$ - average rms vertical/transverse acceleration in "g's".

In order to examine the applicability of this model (equation 5.1), to the present study, a linear regression model was generated between the subject comfort response and the motion variables, $(\bar{a}_V, \bar{a}_T)$. The Pearson's correlation* (ρ_p) for this model was 0.65, whereas that for Eqn. (5.1) was 0.649. Since the difference was insignificant, and since Eqn. (5.1) was based on a much larger data base (∿ 3000 cases (25) vs. 443 cases), it is used as the comfort/motion model.

This comfort model was extended to include the effect of noise level as a function of PNdB, dB_D, dB_A, SIL_1 and SIL_2 (see Appendix E and References 26 and 47 for definitions).

The part of the subject comfort response that is not explained by motion alone

$$\Delta C_M = C_s - C'_{s_M}, \qquad (5.2)$$

where

C_s - segment subject comfort response and

ΔC_M - error between actual comfort response and motion predicted comfort response

has three contributions to it, viz., that due to other environmental variables (e.g. noise, temperature), subject

*The terms "Pearson's correlation", "correlation" and "ρ_p" are used interchangeably in the text. See Ref. (61) for definition.

differences, and random error. The correlation between ΔC_M and the noise levels is shown in Table 5.1.

Table 5.1 indicates that the correlation coefficients between the noise measures and ΔC_M are of the order of 0.3, but those among the noise measures are quite high (> 0.7). Hence one noise measure is sufficient to define noise effects.

Using regression analysis with 443 cases, the relationship between noise level (PNdB, dB_A and SIL_1) and ΔC_M were obtained. These were reformulated into comfort equations as,

$$C'_{s_{MN_p}} = \begin{cases} 1 + 17.85\,\bar{a}_V + 11.4\,\bar{a}_T + 0.076\,\{PNdB - 85\} & \text{for } \bar{a}_V \geq 1.6\,\bar{a}_T \\ 1 + 1.5\,\bar{a}_V + 37.5\,\bar{a}_T + 0.076\,\{PNdB - 85\} & \text{for } \bar{a}_V < 1.6\,\bar{a}_T \end{cases} \quad (\sigma_{error} = 0.73) \tag{5.3}$$

$$C'_{s_{MN_a}} = \begin{cases} 1 + 17.85\,\bar{a}_V + 11.4\,\bar{a}_T + 0.065\,\{SIL_1 - 56\} & \text{for } \bar{a}_V \geq 1.6\,\bar{a}_T \\ 1 + 1.5\,\bar{a}_V + 37.5\,\bar{a}_T + 0.065\,\{SIL_1 - 56\} & \text{for } \bar{a}_V < 1.6\,\bar{a}_T \end{cases} \quad (\sigma_{error} = 0.72) \tag{5.4}$$

TABLE 5.1

CORRELATION MATRIX OF THE NOISE MEASURES AND THE SUBJECT COMFORT NOT EXPLAINED BY MOTION (ΔC_M)

	dB_A	dB_D	PNdB	SIL_1	SIL_2	ΔC_M
dB_A	1.0					
dB_D	0.95	1.0				
PNdB	0.95	0.99	1.0			
SIL_1	0.81	0.7	0.76	1.0		
SIL_2	0.81	0.7	0.78	0.99	1.0	
ΔC_M	0.33	0.28	0.31	0.35	0.35	1.0

$$C'_{s_{MN_a}} = \begin{cases} 1 + 17.85\,\bar{a}_V + 11.4\,\bar{a}_T + 0.105\,\{dB_A - 75\} & \text{for } \bar{a}_V \geq 1.6\,\bar{a}_T \\ 1 + 1.5\,\bar{a}_V + 37.5\,\bar{a}_T + 0.105\,\{dB_A - 75\} & \text{for } \bar{a}_V \leq 1.6\,\bar{a}_T \end{cases}$$

(σ error - 0.73)

(5.5)

where

$C'_{s_{MN_p}}/C'_{s_{MN_s}}/C'_{s_{MN_a}}$ - predicted comfort due to

PNdB/SIL_1/dB_A, and the bracketed quantities

$$\{q\} = \begin{bmatrix} q & \text{if } q > 0 \\ 0 & \text{if } q \leq 0 \end{bmatrix}$$

These models were significant at a probability of better than 99.9%. The Pearson's correlation ρ_p, improved from 0.65 to 0.7 (i.e. variance explained 42% to 49%), with the inclusion of noise level (dB_A). Likewise, Spearman's rank order correlation* improved from 0.65 to 0.72. Hence noise inclusion in the comfort models gave a significant improvement.

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*Spearman's rank order correlation [see Ref. (56) for definition], is a nonparametric statistic, whereas Pearson's correlation (ρ_p) is a parametric statistic. Nonparametric statistics require only qualitative properties for the variables, viz., nominal or ordinal levels of measurement [as in the Stevens (55) hierarchical levels of measurements: - nominal (lowest), ordinal, interval, and ratio

In the present formulation, the noise level is assumed to affect comfort only if it exceeds the threshold values of 85 PNdB, 56 SIL_1 and 75 dB_A. [Note that all the noise measurements of 79 to 100 dB_A (Table 3.5) exceed these threshold values]. The dB_A - comfort model compares favourably with past studies (16) where the threshold is given as 78 dB_A, and the sensitivity as 0.171 co7/dB_A.

Table 5.2 summarizes the model properties. The dB_D and SIL_2 model properties were obtained by

$$dB_D = PNdB - 7.9, \text{ and} \quad (5.6)$$

$$SIL_2 = SIL_1 - 1.2, \quad (5.7)$$

which were derived from the present data. Noise level scattergrams (13,26) indicated that the noise level threshold values agreed very well with each other. Since the present models were based on a larger data base than previous models (16), greater confidence can be placed on them.

——————— (footnote continued from previous page)

* (highest)]. However, parametric statistics not only require quantitative properties for the variables, viz., interval or ratio scale, but also assume distribution properties (usually normal distribution) for data (56). Although comfort responses were obtained only at the ordinal scale level, it is implicitly assumed to be at the interval level of measurement (as required in the regression analysis). Hence parametric statistics can be used. [See Ref. (56) for justification]. However, since the assumption is unverified, nonparametric statistics were also needed. Hence both Pearson's correlation (assumes interval scale) and Spearman's rank order correlation (abbr. Spearman's correlation; assumes ordinal scale) were obtained.

TABLE 5.2

EFFECT OF NOISE LEVELS ON COMFORT--SUMMARY OF PARAMETERS

Noise Level	Threshold	Sensitivity co7/Unit noise Level
dB_A	75	0.105
PNdB	85	0.076
dB_D [Using Eqn. (5.6)]	77	0.076
SIL_1	56	0.065
SIL_2 [Using Eqn. (5.7)]	55	0.065

Since dB_A is correlated very well (>0.8) with other noise measures (Table 5.1) and since it is widely used, iso-comfort contours for the comfort/dB_A-motion model (Eqn.(5.5)] were obtained (Figure 5.2). This figure can be used for tradeoff analyses between motion and noise level for a preselected comfort level. Similar iso-comfort contours can be obtained for PNdB, dB_D, SIL_1 and SIL_2 noise measures. Equations (5.3) through (5.5) represent the models in box 2 in Figure 4.2.

5.2 Comfort/Noise-Source Relationship

The relationship between comfort response and noise as a function of its sources (box 3, Figure 4.2) can provide a more detailed insight into the problem. The relationship was developed separately for aircraft A alone, and the remaining four aircraft together, because of differences in noise sources (radio noise existed only on aircraft A) and data base (larger on aircraft A). The modelling process utilized to develop the comfort/motion-noise source model is outlined in Figure 5.3.

5.2.1 Noise Sources and Their Characteristics

The noise sources that contribute to interior noise (40,62), were classified for this study as shown in Table 5.3. A description of each of these sources is given in Appendix H. The description includes the frequency characteristics of each source for the five aircraft used

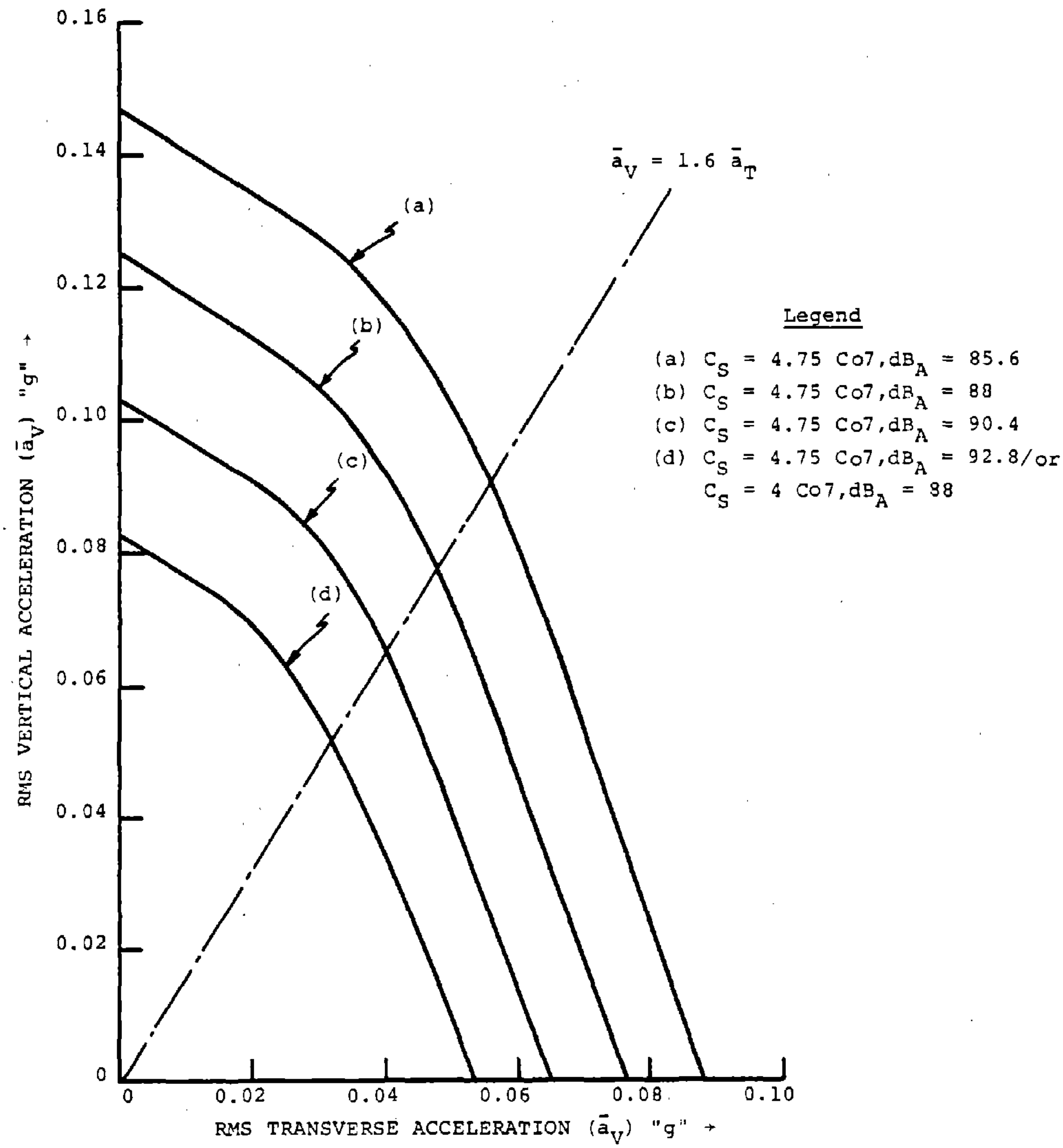

FIGURE 5.2 Iso-Comfort Contours in the Motion and Noise Level Dimensions.

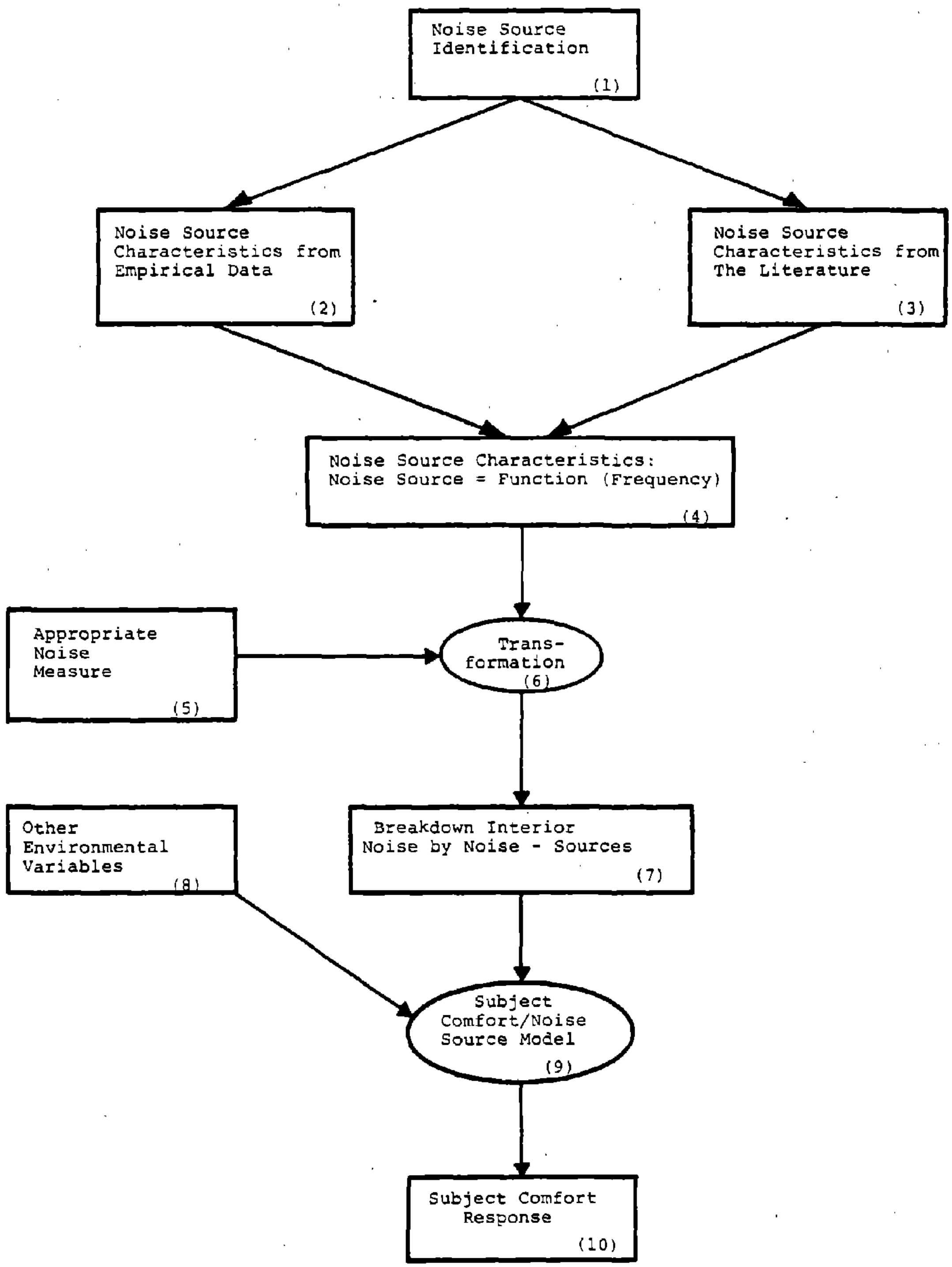

FIGURE 5.3 Subject - Comfort/Noise - Source Modeling Process.

TABLE 5.3

AIRCRAFT INTERIOR NOISE SOURCES

Engine* (Propeller, Airborne and Structurally borne, etc.)

Aerodynamic Noise

Radio

Vent

Miscellaneous (All the rest)

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*Engine noise refers to the noise originating in the entire propulsion system.

in the present test program. In brief, engine noise is characterized by narrow band peaks at low frequencies, radio by broad band noise in the speech frequency range and aerodynamic and vent noise by broad band noise in the mid to high frequency range.

5.2.1.1 Aircraft A Empirical Data

Controlled and environmental tests on aircraft A were analyzed to observe the effect of variation of noise source factors (Table 2.5) on interior noise spectra and subject comfort responses. These tests also provided empirical data on noise source frequency characteristics.

Cruise noise spectra for aircraft A (Figure 5.4) exhibits peaks at 40, 62 and 125 Hz, which coincide with the engine noise frequencies given in Appendix H (Table H.3). 62 Hz corresponds to a sub-harmonic of the blade passage frequency (125 Hz). Further, because of the aerodynamic noise contribution (Table H.4, Appendix H), flight spectra are broader than ground spectra, (Figures I.1 and I.2, Appendix I). The effect of noise source factors on noise spectra and comfort response is summarized in Table 5.4. (See Appendix I for more details). The table also indicates the dominant frequencies associated with the noise sources.

5.2.1.2 Noise Source Separation

The noise sources are characterized by the frequencies over which they dominate (box 4, Figure 5.3). Further,

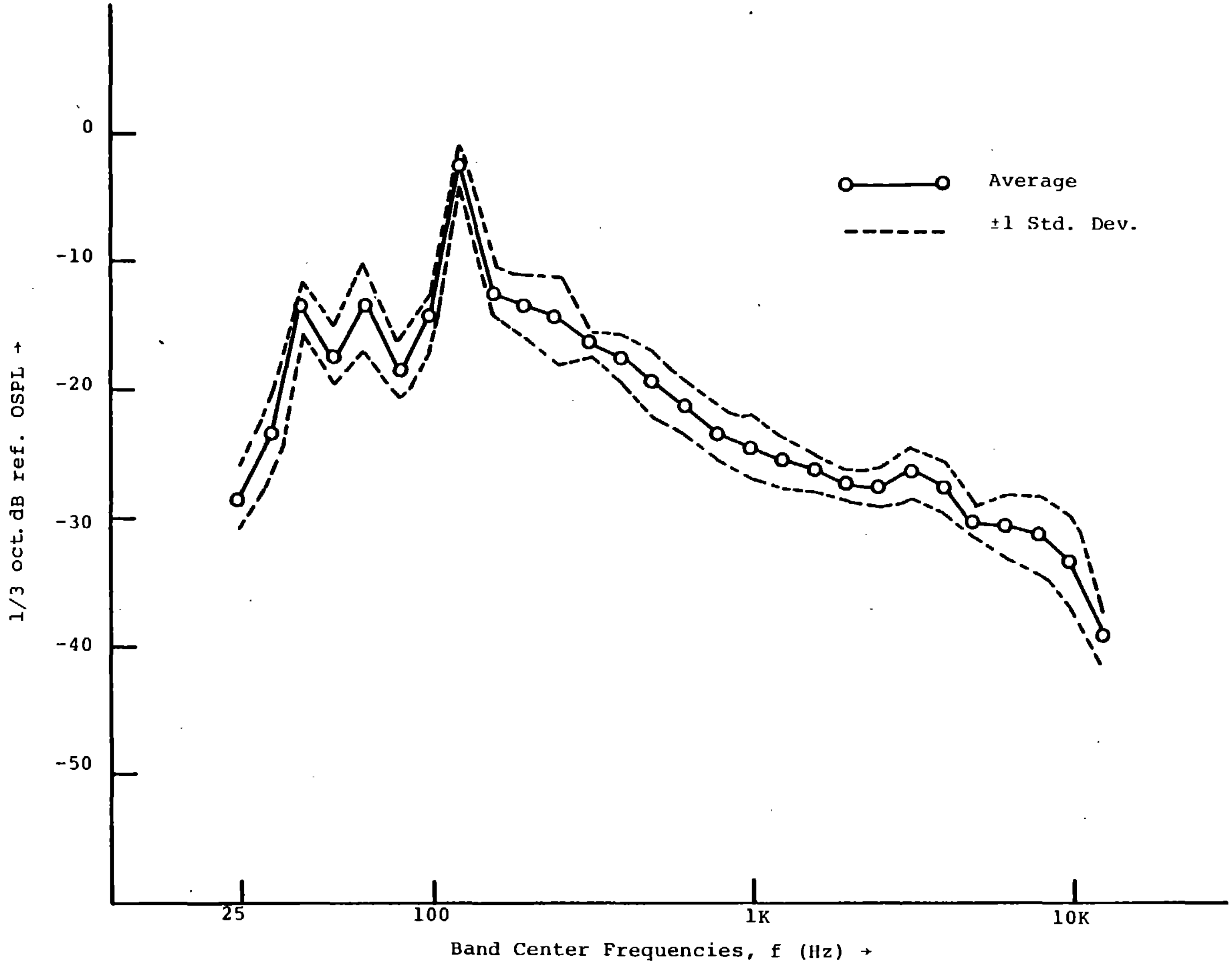

FIGURE 5.4 Average Normalized Spectra -- Aircraft A Cruise.

TABLE 5.4

SPECTRAL COMPARISON SUMMARY

Type of Comparison	ΔdB_A/ ΔOSPL	Dominant Characteristic Frequencies (Hz)	Peaks/ Valleys (P/V)	Subject Comfort Change	Comments: Sources	Comments: Explanation of Effect
1. Altitude a. Cruise (5000'-9000')	1.3/0.7	315-1.25K 40,62,125,250	P V	O	Aero. Engine	Mainly noise
b. Climb [(0-3000')-(7000'-9000')]	3/2	315-12.5K 62	P V	1.1	Aero. Engine	Mainly aero-dynamic noise
2. Flight Phase [climb(0-5000')-Descent(5000'-0)]	9.5/5	31 125-12.5K	V P	-0.9	Engine(?) Engine+Aero	Pressure Change
3. Velocity (Low-High)	-0.6/0.5	40,62,250 315-12.5K	P V	-0.9	Engine Aero-	Mid.-and High-Frequency Noise
4. Radio (on-off)	3.5/1.5	1.25K-2.5K	P	0.4	Radio	Mainly Noise
5. Vent (closed-open)	-0.8/-0.9	63,250-500 5K-12.5K	V P	0.4	Engine,Vent ?	Mainly Fresh Air
6. Engine Power (Hi-Lo)	1.25/1.25	200, 1.6K	P	0.2	Engine Harmonics(?)	Mainly Noise
7. Location(4locs.) Inter-location Comparison (Front-Rear)	0-2/ 0-3	62 400-1K	P P	-- --	Engine Aero.	-- --

it is assumed that each frequency band is associated with only one noise source. This is not strictly correct but is a reasonable assumption for this study.

The cruise noise spectra for aircraft B through E are presented in Figures 5.5a through 5.5d. The noise spectra for the other flight phases are given in Ref. (54). Comparing the noise spectra with the discussions given before and the noise source descriptions (Appendix H), noise source characteristics were obtained, as given in Table 5.5. The upper limit for the engine noise was selected at 250 Hz, because no propeller noise peak approached the OSPL within 15dB above 250 Hz (for any flight phase). Further for aircraft A, the ground tests (Appendix I) indicated that engine noise has little contribution above 250 Hz. Here engine noise (25-250 Hz), which is the most dominant source, accounts for the engine peaks (Table H.3), engine noise broad band (63) and frequency variations during takeoff and landing. Radio noise for aircraft A, was based on Table 5.4. Aerodynamic noise is effective only beyond 315 Hz, since it is dominated by engine at low frequencies. [Due to the low speed characteristics of these aircraft, both the noise level and the center frequency of the aerodynamic noise are lower (64-67)]. The overall effect of vent noise is only of the order of 1dB and since it's

C-2

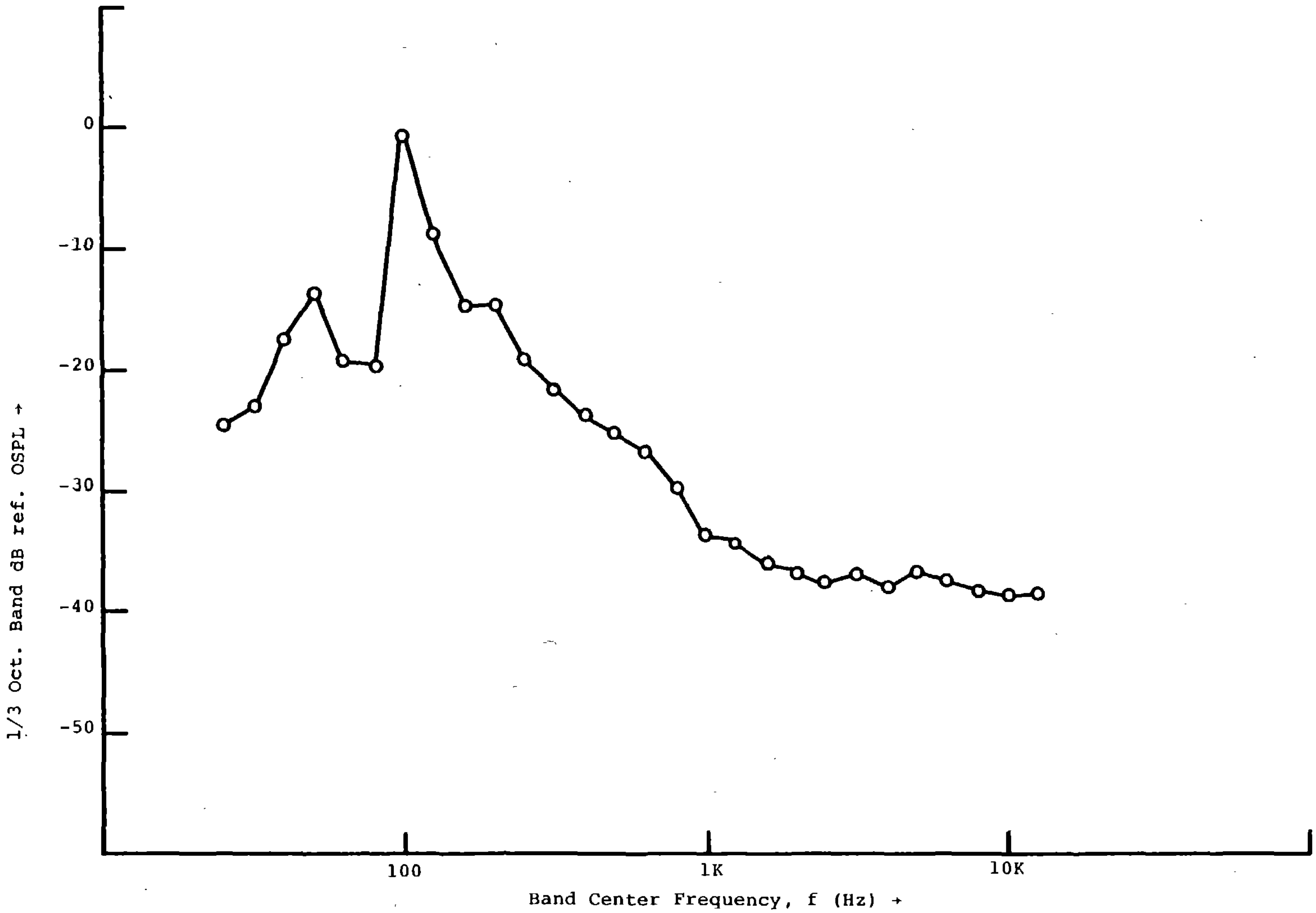

FIGURE 5.5a Cruise-Average Normalized Spectra -- Aircraft B.

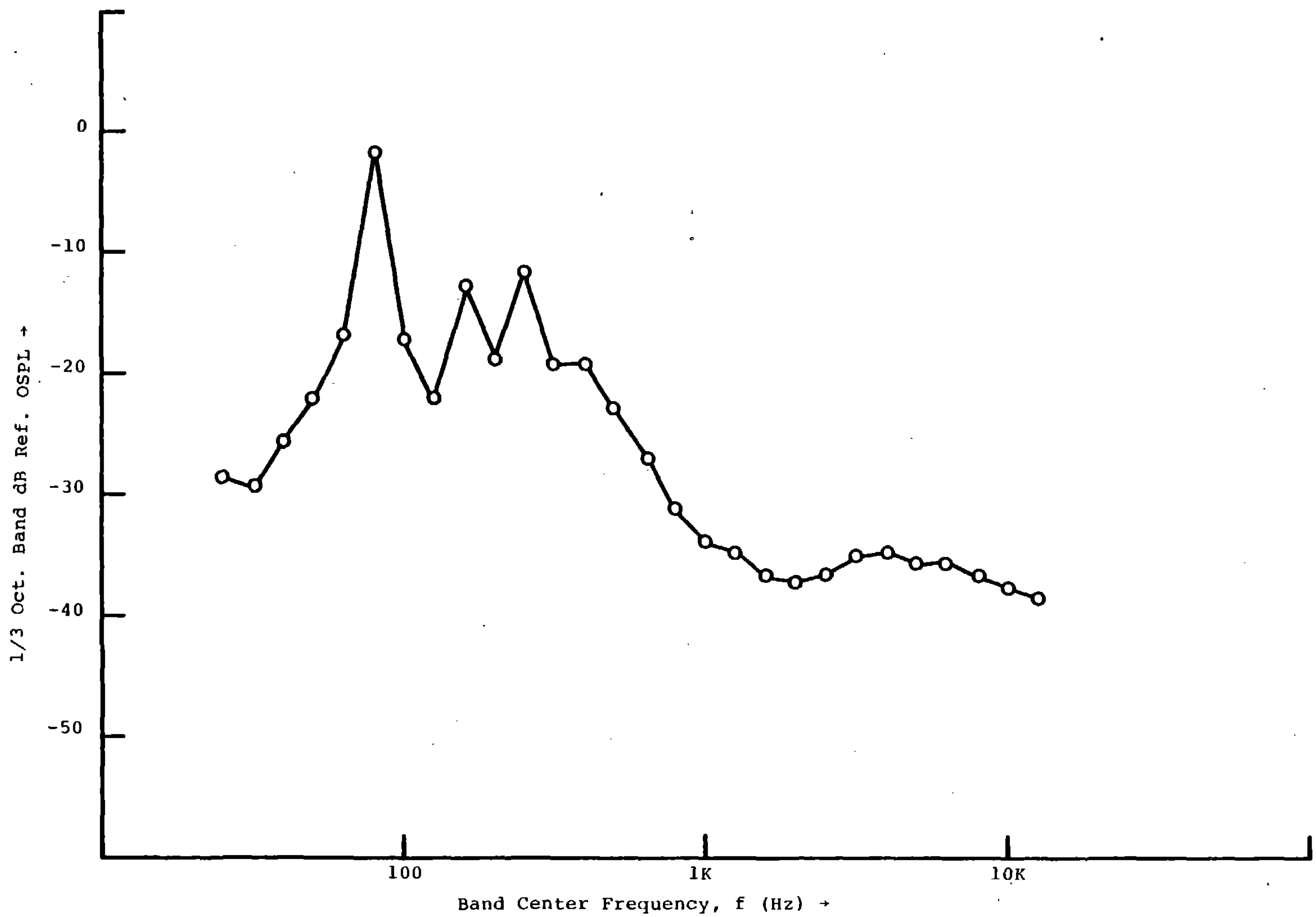

FIGURE 5.5b Cruise-Average Normalized Spectra -- Aircraft C.

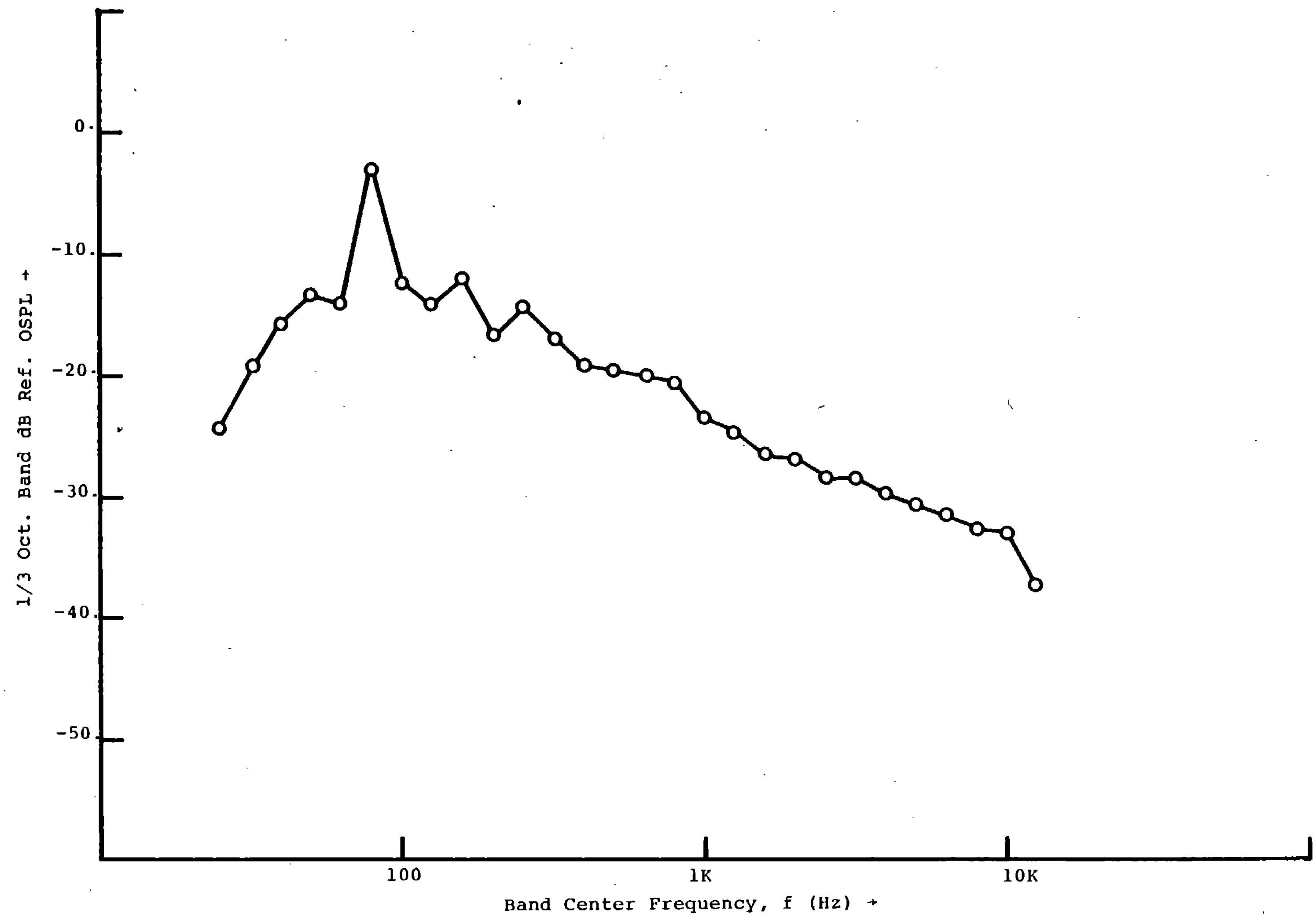

FIGURE 5.5c Cruise-Average Normalized Spectra -- Aircraft D.

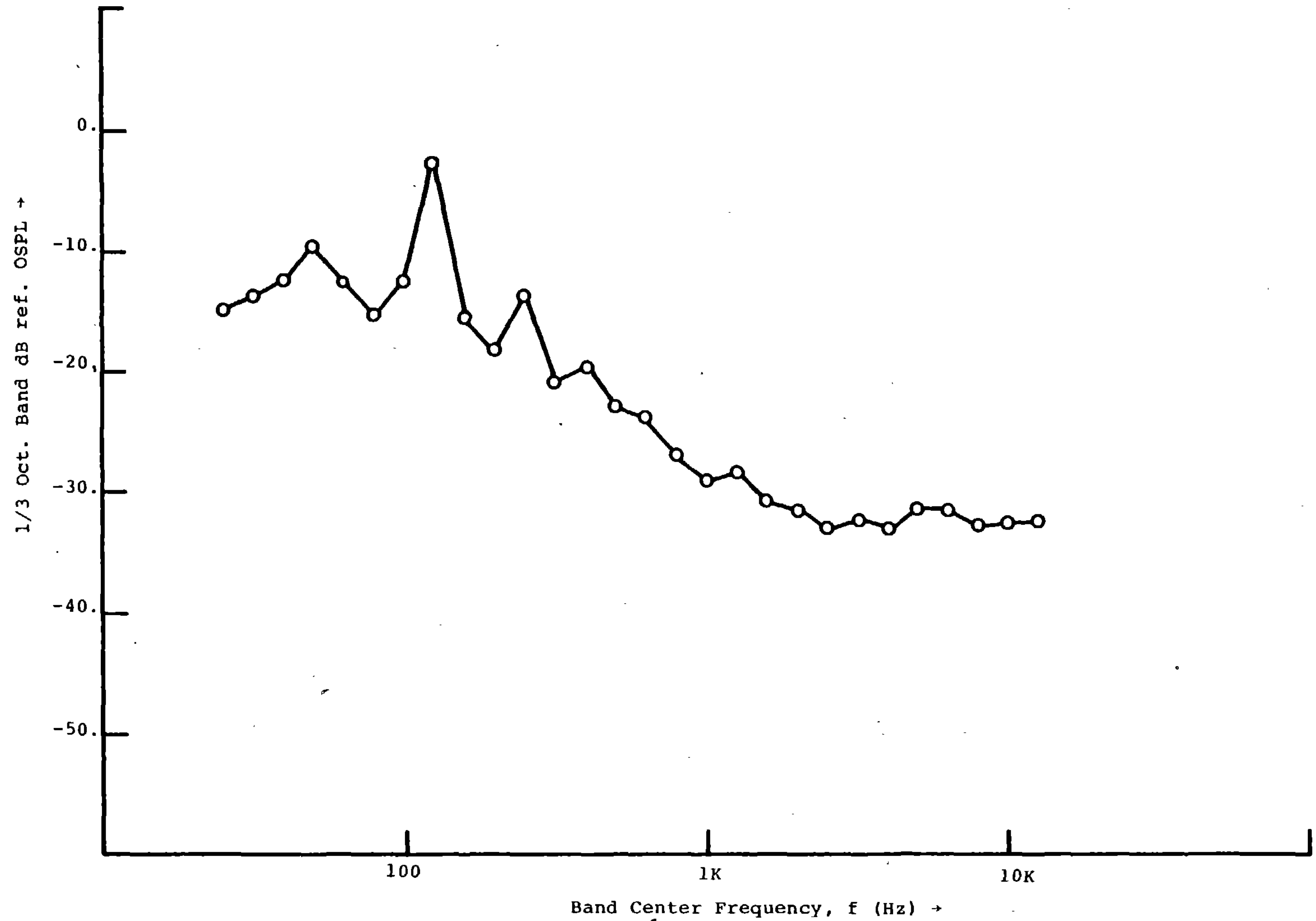

FIGURE 5.5d Cruise-Average Normalized Spectra -- Aircraft E.

TABLE 5.5

FREQUENCY DISTRIBUTION OF NOISE SOURCES--ALL AIRCRAFT

Aircraft	Noise Sources - Band Frequencies (Hz)			
	Engine*	Aerodynamic*	Radio	Misc.‡
A Version I†	25-250	315-1K	1.25K-2.5K	3.15K-12.5K
A Version II	25-250	315-1K, 3.15K-12.5K	1.25K-2.5K	--
B	25-250	315-12.5K	--	--
C	25-250	315-12.5K	--	--
D	25-250	315-12.5K	--	--
E	25-250	315-12.5K	--	--

* These sources will be refered to as "engine"/"aerodynamic" although vent contributes to it.

† Since Version I did not prove to be fruitful for aircraft A, only one version was examined for aircraft B through E, with misc. frequencies part of aerodynamic noise.

‡ Misc. noise source does not refer to the auxiliary equipment, whose effect is not formulated in this study.

corresponding frequencies (62, 250-500 Hz: - Table 5.4) are dominated by other sources, it was merged with them.

5.2.1.3 Source Noise Values

The next step in the modelling process (Figure 5.3) is to obtain source noise values (noise contribution from sources), which are defined as

$$SN_i = \sum_{j=1}^{m_i} f_n \ (dB_{ij}) \tag{5.8}$$

where dB_{ij} - jth 1/3 octave band (dB) for source i

m_i - # of 1/3 octave bands in source i

f_n - appropriate noise function

The functions selected for evaluation were Noy*, Sone*, dB and energy values [see Appendix E and Ref. (26,47) for definition], whose properties are summarized in Table 5.6. These functions were evaluated on the basis of summation properties, subjectiveness, the data range. Noy and Sone satisfied these criteria. However Noy was selected because it represents subjective noisyness as opposed to loudness and because people judge aircraft noise to be more noisy

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*Both are computed with masking effect. See Reference (26,47). This is the definition used throughout the text except where mentioned.

TABLE 5.6

SUMMARY OF NOISE MEASURES

$f_n(dB_{ij})$	RELATIONSHIP TO ACOUSTIC PRESSURE (p)	COMMENT
NOY*	$\sim p^{0.6}$	SUBJECTIVE NOISINESS, RESTRICTED SUMMATION†
SONE	$\sim p^{0.6}$	SUBJECTIVE LOUDNESS, RESTRICTED SUMMATION.
dB	α 10 LOG p^2	NOT SUBJECTIVE, NOT SUMMABLE.
ENERGY	α p^2	SUBJECTIVE (?), RANGE TOO WIDE, SUMMABLE.

*Chosen for this study.

†Noy(/Sone) can be summed within restrictions, since the Noy(/Sone) of the sum of two noises, without frequency overlap, is equal to the sum of Noy(/Sone) of those two noises.

than loud (68). Noy, Eqn. (5.8), and SN_i then represent boxes 5,6 and 7 in Figure 5.3.

5.2.1.4 Noise Source Groups

In order to verify that three to four independent noise sources account for the noise spectral behavior, a factor analysis (56) was performed on the Noy values for the 24 1/3 octave band levels (for the aircraft A data). The analysis indicated that 3 or 4 independent factors were sufficient and that these factors closely resembled the noise source groupings given in Table 5.5.

5.2.2 Comfort/Noise Source-Motion Models

The comfort noise source-motion models were obtained in a similar manner as the noise level-motion models were. Using regression analyses (56), comfort responses not explained by motion, ΔC_M, [Eqn. (5.2)] were related to the source noise values SN_i, defined as

$$SN_i = \sum_{j=1}^{m_i} \text{Noy}^* \ (dB_{ij}) \qquad (5.9)$$

These models were generated separately for aircraft A and the rest.

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*Computed by using standard Noy tables (47).

5.2.2.1 Aircraft A Model

The first version (Table 5.5), using 351 cases yielded,

$$\Delta C_M = -0.9 + 0.0051\ SN_1 - 0.012\ SN_2 + 0.045\ SN_3 + 0.06\ SN_4 + \Delta C_{MSN_4} \qquad (5.10)$$

where

ΔC_{MSN_4} - error in prediction

(SN subscript) i = 1 - Engine noise

2 - Aerodynamic noise

3 - Radio

4 - Misc. noise

In the equation, one of the coefficients is negative. This is because SN_2 and SN_4 were strongly related ($\rho_p = 0.72$ vs. $\rho_p < 0.3$ for other combinations). In order to ensure the independence of the noise sources, SN_2 and SN_4 were merged into a single variable (version II, Table 5.5).

With the new noise sources, regression analysis yielded,

$$\Delta C_M = -0.94 + 0.006\ SN_1 + 0.005\ SN_2 + 0.047\ SN_3 + \Delta C_{MSN} \qquad (5.11)$$

where

ΔC_{MSN} - error in prediction.

The Pearson's correlation for this model is 0.36, the error (ΔC_{MSN}) standard deviation 0.65 and the model significance 95%. Equation (5.10) was transformed with the aid of equations (5.1) and (5.2) to:

$$C'_{s_{MSN(A)}} = 1.56 + \begin{bmatrix} 17.85\ \bar{a}_V + 11.4\ \bar{a}_T, \text{ for } \bar{a}_V \geq 1.6\ \bar{a}_T \\ 1.5\ \bar{a}_V + 37.5\ \bar{a}_T, \text{ for } \bar{a}_V < 1.6\ \bar{a}_T \end{bmatrix} + 0.006\ SN_1 + 0.005\ SN_2 + 0.047\ SN_3 \quad (5.12)$$

where

$C'_{s_{MSN(A)}}$ - predicted subject comfort (co7) due to motion and three noise sources for aircraft A

$\bar{a}_V/\bar{a}_T$ - mean rms vertical/transverse acceleration, "g's".

SN_i - Source noise values, Noy

i = 1 - engine

2 - Aerodynamic

3 - Radio

The Pearson's correlation improved from 0.7 to 0.75, (variance explained 49% to 56.3%), and the Spearman's correlation from 0.66 to 0.7 with the inclusion of source noise in the model. Further, over 50% of the cases had an error less than 0.5 co7 and 86% less than 1.0 co7.

In Table 5.7, the relative importance of the noise sources are compared. The mean contributions were computed by

$$C_{SN_i} = K_{ni} \cdot \mu_{SN_i} \qquad (5.13)$$

where

C_{SN_i} - mean contribution to comfort from SN_i (co7/Noy)

K_{N_i} - coefficient of SN_i (co7/Noy)

μ_{SN_i} = Mean SN_i (Noy)

As the table shows, the noise sources in decreasing order of dominance are: radio, engine and aerodynamic noise. Since aircraft A is a slow speed aircraft, the aerodynamic noise contribution is expected to be low.

5.2.2.2 Other Aircraft Models

Using 93 cases, for aircraft B,C,D and E, analysis yielded

$$C'_{s_{MSN}}(c) = 0.92 + \begin{bmatrix} 17.85\ \bar{a}_V + 11.4\ \bar{a}_T, \text{ for } \bar{a}_V \geq 1.6\ \bar{a}_T \\ 1.5\ \bar{a}_V + 37.5\ \bar{a}_T, \text{ for } \bar{a}_V < 1.6\ \bar{a}_T \end{bmatrix} + 0.0072\ SN_1 + 0.038\ SN_2 \qquad (5.14)$$

where

TABLE 5.7

CONTRIBUTION OF NOISE SOURCE TO COMFORT

Noise Source	Coefficient (Co7/Noy)	Mean Contribution [Co7] =(coeff.) x (Mean Noise Value)
Engine	0.006	0.373
Aerodynamic	0.005	0.163
Radio	0.047	0.545

$C'_{s_{MSN}}$ (c) - predicted subject comfort (co7), due to and two noise sources, for commercial flights*.

SN_1/SN_2 - engine/aerodynamic source noise levels.

The error in prediction was 0.65 and the model significance better than 99.5%. The Pearson's correlation improved from 0.55 to 0.71 (30% to 50% variance explained) and the Spearman's correlation improved from 0.49 to 0.71 with the inclusion of noise sources. Thus the inclusion of noise sources resulted in significant improvements in both comfort models (aircraft A and the rest).

The comfort contributions [Equation (5.13)], are 0.44 co7 and 1.26 co7 for engine and aerodynamic noise, respectively. This is in contrast to the relative importance of sources in aircraft A.

5.3 Model Comparisons

The relative effectiveness of the motion-noise level model and the motion-noise source models were investigated. In addition, inter-aircraft and inter-subject difference in these models were examined.

Let

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*These data are in effect commercial flights, since no motion data was available on aircraft E.

$$C'_{s_{MSN}} = \begin{cases} C'_{s_{MSN\ (A)}} & \text{for aircraft A} \\ C'_{s_{MSN\ (c)}} & \text{for commercial flights} \end{cases} \quad (5.15)$$

where

$C_{s_{MSN}}$ - predicted comfort (co7) due to motion and noise sources for all data.

Using all data the following Pearson's correlations were obtained

$$\rho_p\ (C_s \cdot C'_{s_M}) = 0.65$$

$$\rho_p\ (C_s \cdot C'_{s_{MN_a}}) = 0.7$$

$$\rho_p\ (C_s \cdot C'_{s_{MSN}}) = 0.74$$

where

C_s - true subject responses

$C'_{s_M}/C'_{s_{MN_a}}$ - predicted comfort due to motion/motion and noise level, which are defined in Equation (5.1)/(5.5)

This indicates that the motion-noise source model is a better predictor of subject comfort responses than the motion-noise level model (accounting for 6% more of the variance).

Inter-aircraft comparison of these models are presented in Table 5.8, which indicates that, in all cases noise source model showed a higher correlation than noise level model, except for aircraft D. (But for aircraft D, Spearman's correlation improved from 0.47 to 0.57). Further, the table shows that the models are better predictors for aircraft A and C, than for B and D.

Similarly, models were compared for three subjects S_1,S_2 and S_3) with over 100 segment responses each (Appendix B), which indicated that subjects S_2 and S_3 were better predictors than S_1.

Although some inter-subject and inter-aircraft differences were observed, they were not substantial.

5.4 Subject Segment Comfort/Passenger Satisfaction Models

The models discussed so far in this chapter represent the first step in satisfaction modelling (Figure 4.2). The applicability of the models in the past studies (39,53) for the remaining three steps will be discussed next.

5.4.1 Subject Segment Comfort/Subject Overall Comfort Response Transfer Function

This transfer function (box 5, Figure 4.2) was modelled in the past studies as (39),

$$C'_{s_o} = \sum_{i=1}^{m_s} W(i)\ C_{s_i} \qquad (5.16)$$

TABLE 5.8

INTER-AIRCRAFT COMPARISON--PEARSON'S CORRELATION

Aircraft	Correlations (ρ_p)	
	Motion-Noise Level (dB_A) Model	Motion-Noise Source Model
All	0.7	0.74
A	0.7	0.71
B	0.65	0.71
C	0.66	0.75
D	0.62	0.61

$$W(i) = w(i) / \sum_{i=1}^{m_s} w(i), \text{ and} \tag{5.17}$$

$$w(i) = i^{0.75} \tag{5.18}$$

where m_s - # of segments in flight.

$W(i)/w(i)$ - normalized/unnormalized weight for segment i

C_{s_i} - subject segment comfort (co7), for segment #i

C'_{s_o} - predicted subject overall comfort (co7)

The Pearson's correlation between the observed and predicted overall comfort responses (C_{s_o}, C'_{s_o} respectively) for the present data was better than 0.84, and thus the transfer function is applicable to the present data.

5.4.2 Subject Overall Comfort Response/Passenger Comfort Response Transfer Function

The data scattergram (mean passenger comfort response vs. mean subject overall response), involving 26 commercial flights and 138 passengers is plotted in Figure 5.6 along with three alternative transfer functions. The three functions are: (a) mean subject response ($\bar{C}_{s_o}$) and mean passenger response ($\bar{C}_p$) being equal, (b) past studies' transfer function (39) in equivalent 7 point scale, and (c) the mean of (a) and (b). The percentage of cases with error greater than 1.0 co7 were 32%, 21% and 17% for the

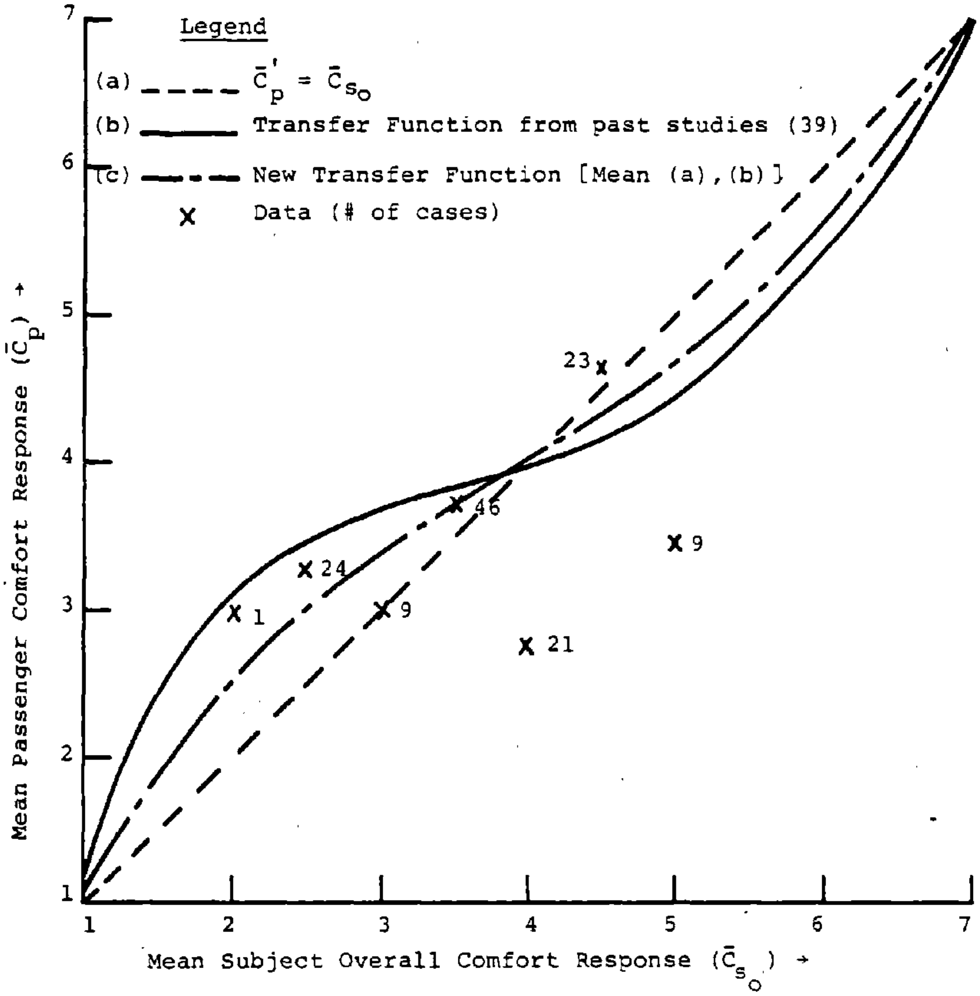


FIGURE 5.6 Mean Subject/Passenger Comfort Responses Scattergram.

three functions respectively. Only function (c) is nearly as good as the past data (15% with error < 0.5 co5). The discrepancy might be due to smaller data base (less than half the past studies) and subject differences [e.g. % of cases with error > 1.0 for function (c) were 38%, 30% and 14% for subjects S_1, S_2 and S_3 respectively]. Hence proper subject selection should improve data fit. Since, function (c) is the best, it was chosen as the transfer function (box 6, Figure 4.2).

5.4.3 Comfort Response/Satisfaction Transfer Function

The final step in the satisfaction modelling process (box 7, Figure 4.2), taken from past studies (53), is illustrated in Figure 5.7. This model was evaluated for the present data (C_p vs A_p)*, as shown in Figure 5.8.

Although the passenger data (Figure 5.8) showed some scatter (which may be due to fewer cases: 142 vs. 1520), it exhibited no consistent error; hence the past model (Figure 5.7) was chosen as the transfer function.

*Where C_p/A_p is the passenger comfort/satisfaction.

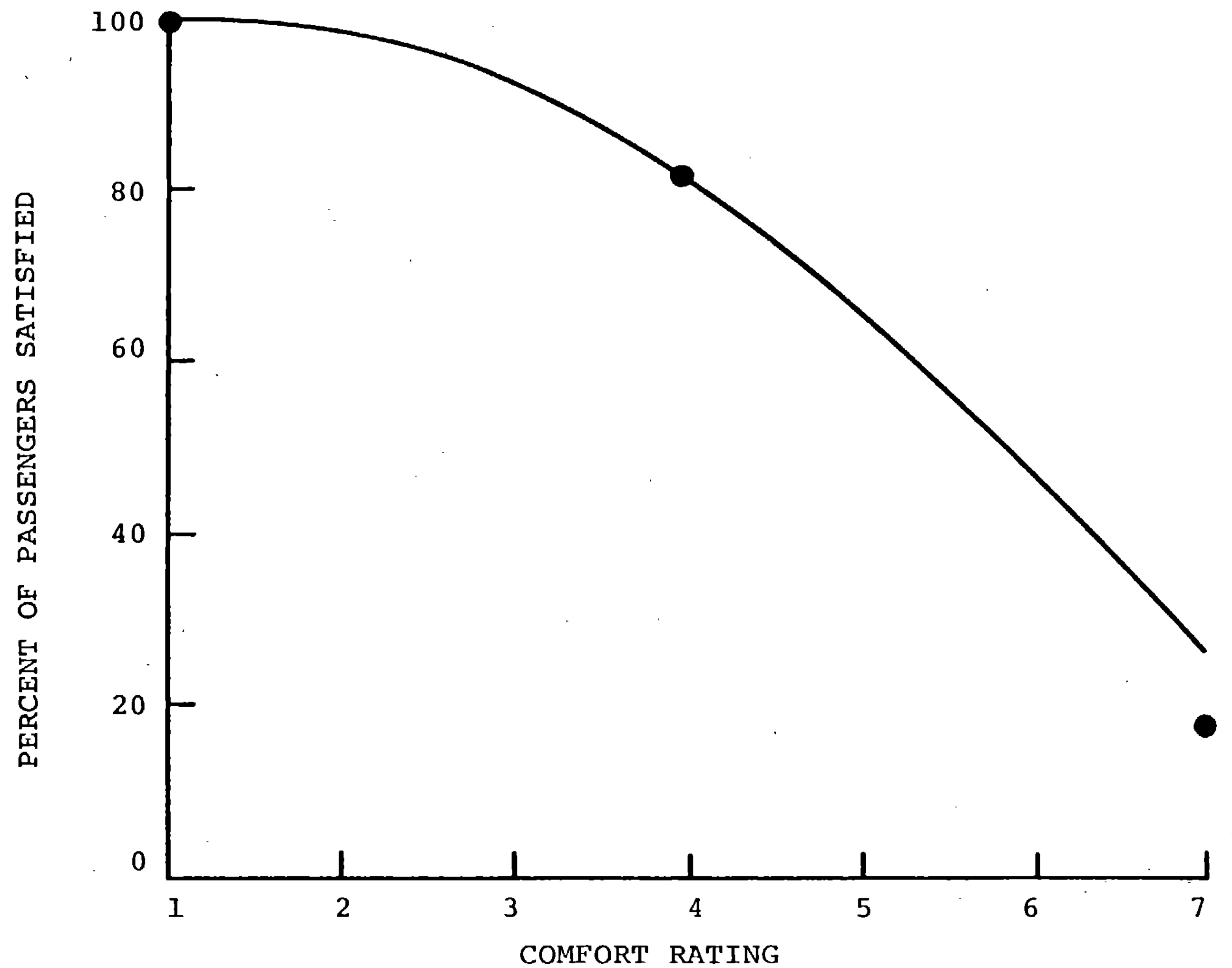


FIGURE 5.7 Percentage of Passengers Satisfied as a Function of Comfort Level--Past Studies (Ref. 53).

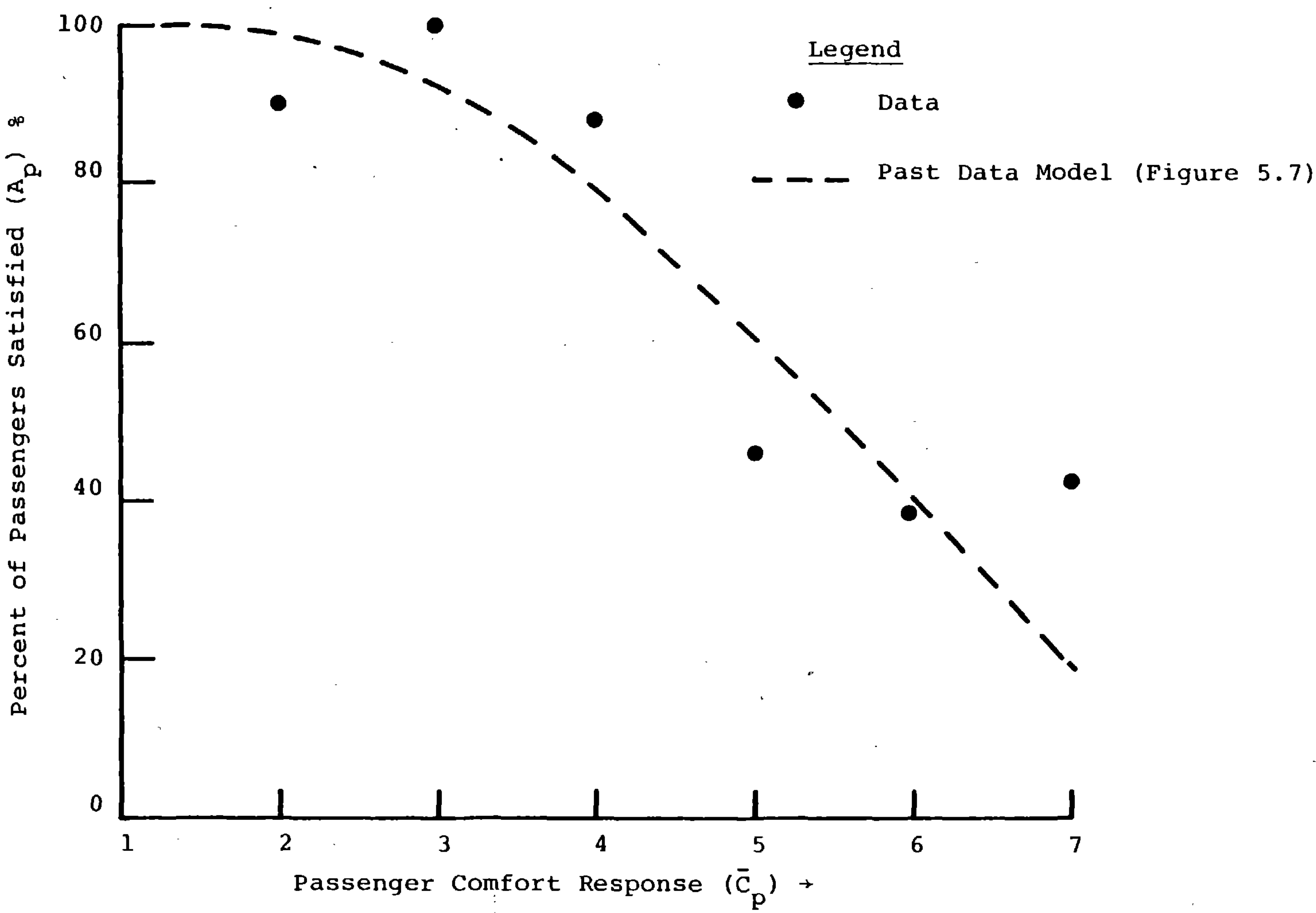


FIGURE 5.8 Percentage of Passengers Satisfied as a Function of Comfort Level--Commercial Data.

CHAPTER VI

DATA ANALYSIS-PART II: QUESTIONNAIRE INVESTIGATION

Questionnaire data was used to assess the effect of noise on task performance and to evaluate the semantic descriptors for determining the effect of the flight environment. These are discussed along with other questionnaire inferences.

6.1 Sample Comparison/Flight Factors

To ensure that the questionnaire data is based on an unbiased sample, passenger characteristics were compared with that of the general flying public (59) and previous flight programs (5,53), (see Table 6.1). A total of 152 questionnaires (Figure 2.7) were distributed to passengers on 32 commercial flights and 100 to subjects on 19 special flights. The table indicates a favourable comparison, except for age distribution in the special flights.

Further, the relative importance of system variables (Q. 10) and that of environmental variables effecting flight feelings (Q. 14), indicated an insignificant change with those of the past studies (Figures 1.3 and 1.7 respectively). The ability to converse, not part of previous studies, was judged more important than ability to work (i.e. read and write).

TABLE 6.1

COMPARISON OF QUESTIONNAIRE SAMPLE WITH PREVIOUS STUDIES AND GENERAL FLYING PUBLIC

		GENERAL FLYING PUBLIC/PREVIOUS FLIGHTS (Ref. #)	COMMERCIAL (THIS DATA SET)	SPECIAL FLIGHTS
A.	MALE/FEMALE SPLIT			
	MALE %	75 (69)	66	84
	FEMALE %	25 (69)	32	16
B.	TRIP PURPOSE			
	COMPANY BUS.	75* (69)	50	N/A
	PER. BUS.	25* (69)	25	N/A
	PLEASURE	--	25	N/A
C.	AGE			
	< 20	12 (69)	11	2
	21 - 40	40 (69)	42	93
	41 - 60	35 (69)	42	3
	> 60	13 (69)	5	2
D.	# OF FLIGHTS FLOWN			
	NONE	2.0 (5)	0.7	3.0
	1 - 3	6.0 (5)	4	17
	4 or MORE	92.0 (5)	95.4	80
E.	CAPTIVE PASSENGERS			
	YES	64 (53)	60	N/A
	NO	36 (53)	40	N/A
F.	NOISE LEVEL IN AIRCRAFT, COMPARISON WITH THEIR WORK ENVIRONMENT			
	MORE THAN	N/A	87	91
	SAME AS	N/A	5	5
	LESS THAN	N/A	8	4
G.	FEELINGS TOWARDS AIR TRAVEL			
	LIKE	57* (5)	76	79
	NEUTRAL	42* (5)	21	17
	DISLIKE	1* (5)	3	4

* Not Identical but Similar Questions.

These results indicated that although the sample size in the present study was small [252 questionnaires vs. 1500 in past studies (53)], the present data was a representative sample.

6.2 Activities

Effects on passenger activities, viz., both auditory (e.g. conversation) and non-auditory (e.g. reading and writing) activities were investigated. Three activity related questions, on importance (Q. 10-discussed before), on difficulty (Q. 12) and on time spent (Q. 13) were examined.

The relative difficulty of activities (on a three point scale): 1 - not difficult, 2 - somewhat difficult, and 3 - very difficult; and, the relative amount of time spent on activities (on a three point scale): 1 - little or none, 2 - some, and 3 - considerable, were examined. Conversation was the most difficult task, and looking out the window and thinking occupied the passengers' time the most.

In Figure 6.1, the rankings for activity difficulty due to the entire flight environment (including both noise and motion) are plotted against those of the time spent on each activity. With the exception of conversation, less time was spent on activities that were more difficult. Passengers spent more time on conversation than on writing,

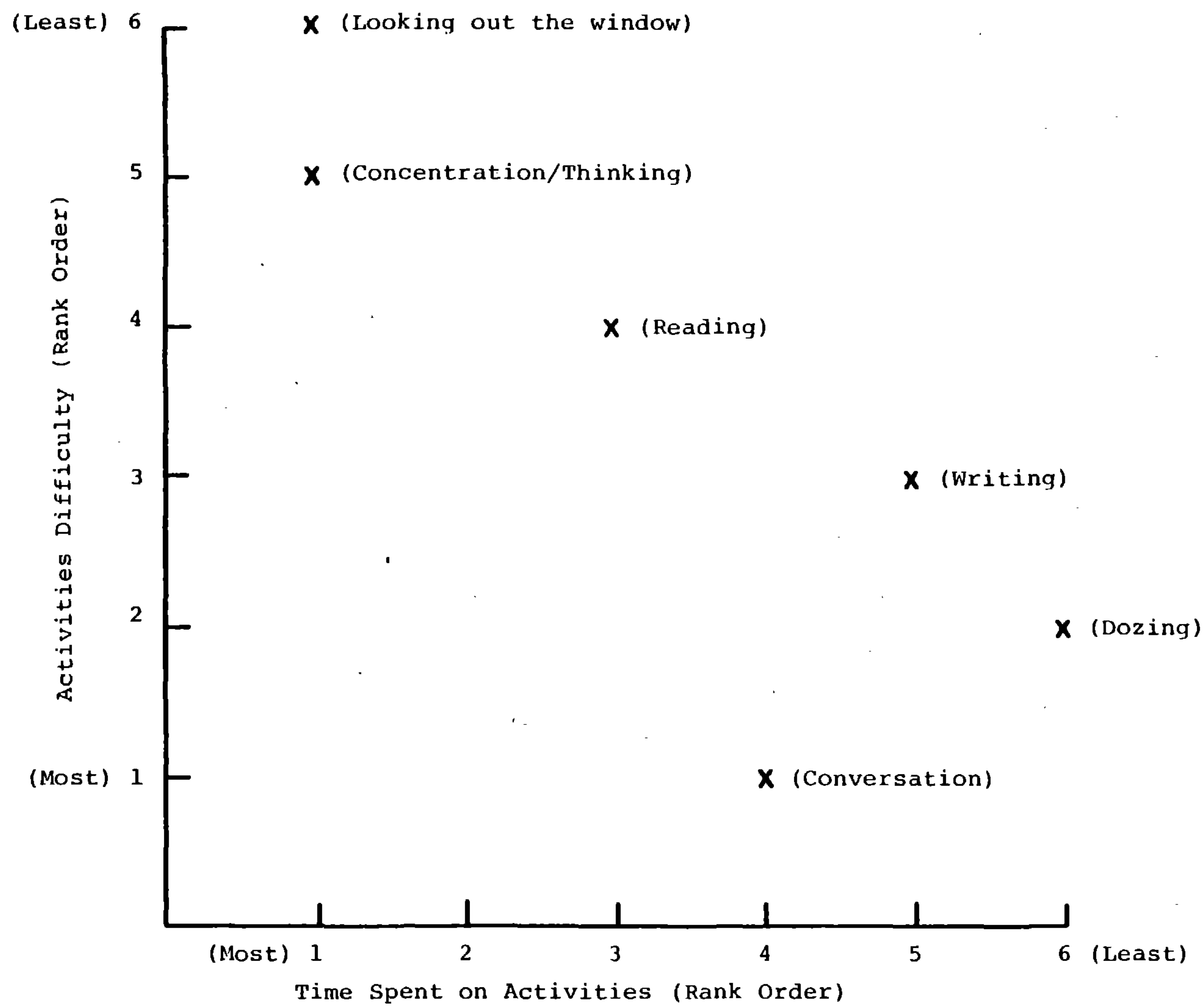


FIGURE 6.1 Comparison of Rank Order of the Activities Difficulty with the Time Spent on Activities.

and dozing, although it was more difficult, perhaps attributable to its importance.

Examination of conversation difficulty, importance and time spent indicated that greater conversation difficulty was associated with less time spent talking, ($|\gamma^*| = 0.69$ for passengers) and, conversation importance was associated with more time talking. No trend was observed in the special flights. The relationship between the conversation questions and the perceived noise annoyance was also examined and indicated that a higher level of noise annoyance was associated with greater conversation difficulty ($|\gamma^*| = 0.62/0.65$ for passenger/subject data respectively).

Correlations between activity difficulty and each of flight environment noise measures, flight environment motion measures and overall comfort reactions are presented in Table 6.2 for passengers. The following observations can be made:

(a) consistent deleterious noise effects were observed for conversation difficulty, whereas motion had no effect. This noise effect is reported by many investigators (e.g. 26-29,42,47).

---

* γ (Gamma correlation) is defined in Ref. (56). This is a nonparametric statistic requiring at least ordinal level of measurements (see footnote Ch.V , p. 70). It quantifies the relative association between two variables.

TABLE 6.2

PEARSON"S CORRELATIONS BETWEEN ACTIVITIES DIFFICULTY, AND NOISE, MOTION AND COMFORT VARIABLES

Activities* Difficulty	Noise Levels				Motion Levels		Overall Comfort
	dB_A	PNdB	SIL_1	SIL_2	Vertical ($\bar{a}_V$)	Tranverse ($\bar{a}_T$)	
Reading	-0.61	-0.61	-0.41	-0.52	0.52	0.37	0.6
Writing	-0.07	-0.12	0.23	0.1	0.62	0.69	0.78
Conversation	0.44	0.57	0.42	0.44	-0.02	0.21	0.313
Dozing	0	0	0.31	0.22	0.8	0.77	0.73
Looking out the window	-0.36	-0.34	-0.25	-0.29	0.34	0.34	0.07

*Activities difficulty, evaluated on a three point difficulty scale, represents the cumulative effect on activities due to the entire flight environment (including motion and noise). Thus the relative difficulty in dozing, which is the second most difficult activity (Figure 6.1), is not affected by noise level ($\rho_p \leq 0.31$) but is affected by motion level ($\rho_p \geq 0.77$).

(b) non-auditory tasks were either benefitted by noise or were not effected by it. However, motion had a delitarious effect on all of them except conversation. Beneficial effect for steady noise is reported by Harris (49) and others (26,27).

(c) discomfort was associated with all activities difficulty, except for "looking out the window".

Regression analysis (56) between the activities difficulty* (d_c) and noise levels, based on 109 cases, yielded,

$$d'_c = 1 + 0.09\ \{dB_A - 81\}$$
$$(\rho_p = 0.44 \text{ and } \sigma_\varepsilon = 0.38) \tag{6.1}$$

$$d'_c = 1 + 0.11\ \{PNdB - 98\}$$
$$(\rho_p = 0.57 \text{ and } \sigma_\varepsilon = 0.35), \text{ and} \tag{6.2}$$

$$d'_c = 1 + 0.044\ \{SIL_2 - 59\}$$
$$(\rho_p = 0.44 \text{ and } \sigma_\varepsilon = 0.38), \tag{6.3}$$

where,

---

*Although passenger difficulty responses were solicited at the ordinal level of measurement (55), it was assumed that the underlying phenomenon is at the interval level of measurement.

ρ_p - Pearson's correlation

σ_ε - standard deviation of the error

The models are significant at better than 99%. The SIL_1 model can be obtained by using,

$$SIL_1 = SIL_2 - 1.65 \tag{6.4}$$

The relationship between the noise levels and conversation difficulty is depicted in Table 6.3. These results indicate good agreement with published literature (e.g. 26-29,42,45, 51). These models can be used for noise impact assessment.

The Gamma correlations between dissatisfaction and activities difficulty for reading, writing, conversation, dozing and looking out the window were 0.54, 0.46, 0.37, 0.68 and 0.55 respectively. The relationships between the two are illustrated in Figure 6.2. These results indicate a consistent and a strong relationship between satisfaction and activities difficulty. However, satisfaction will be assessed based only on comfort (Figure 5.7), since no procedure for cumulative assessment is available and since comfort is judged more important than the activities (Figure 1.3).

TABLE 6.3

NOISE LEVELS CORRESPONDING TO CONVERSATION DIFFICULTIES AND VOICE EFFORT FOR ADEQUATE COMMUNICATION

Noise Measures	Difficulty Levels: Not Difficult	Somewhat Difficult	Very Difficult
dB_A	81	92	103
PNdB	98	107	116
SIL_1	57	79.5	102
SIL_2	59	81.5	104
Required Voice Effort at 1' Talker-listener distance for corresponding dB_A levels-Ref. (27)	Normal To raised	Loud	Shout

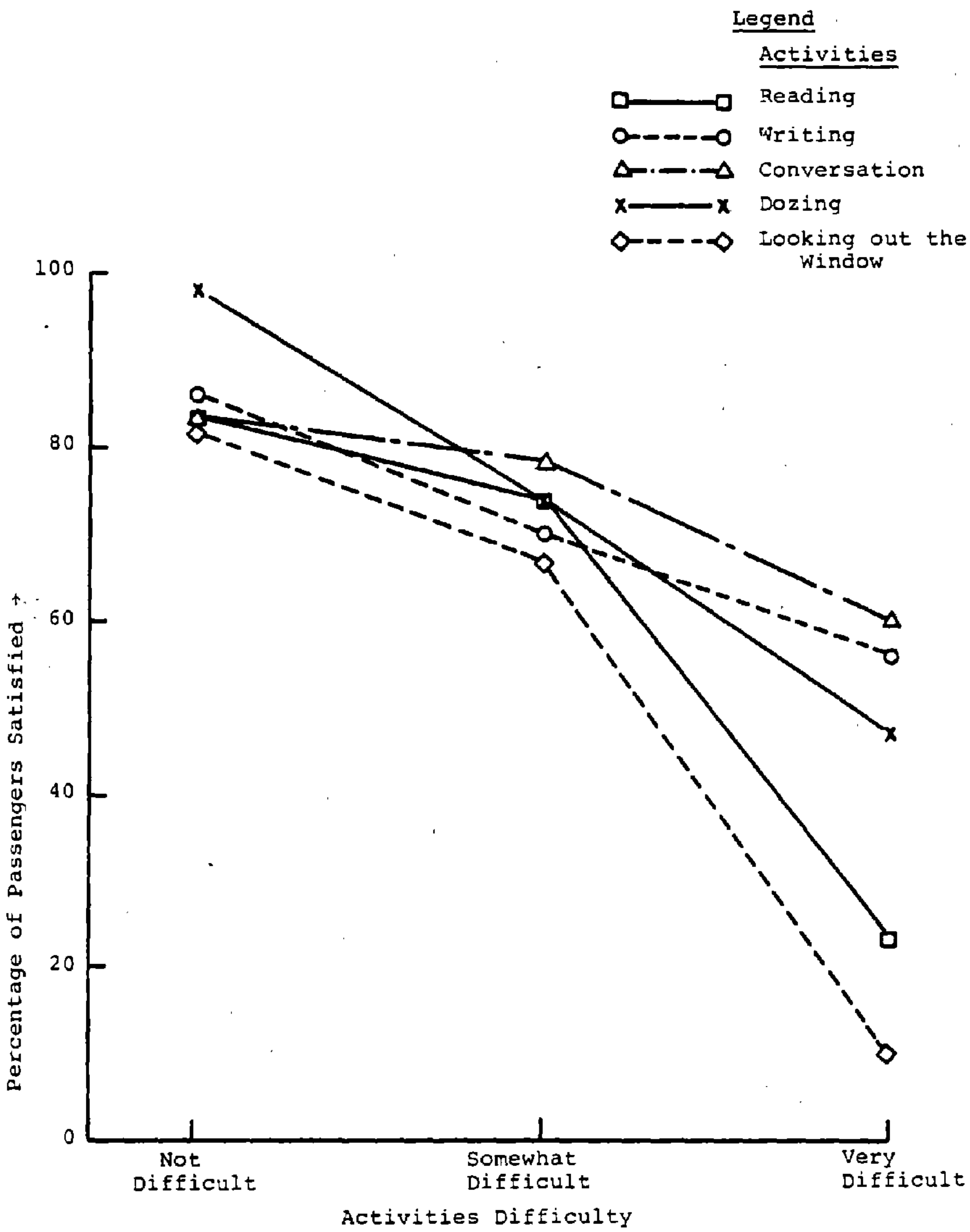


FIGURE 6.2 Activities Difficulty Vs. Satisfaction.

6.3 Appropriateness of Psychological Descriptors of Flight Feelings

Since the psychological variable used for flight feeling assessment is the link between the environmental variables and satisfaction, it should be related to both strongly. The relationships for the psychological variables, viz., comfort, pleasantness, motion annoyance and noise annoyance, are shown in Table 6.4. As shown in the table, noise annoyance is poorly correlated with all variables and hence is unsuitable. Although, motion annoyance is strongly correlated with motion and satisfaction, since it is uncorrelated with noise, it is unsuitable. Among the rest, pleasantness is better correlated with the environmental variables and comfort with satisfaction. Hence, either pleasantness or comfort can be chosen as the psychological descriptor for assessing the impact of the environment on satisfaction.

6.4 Noise Exposure at Work/Noise Exposure Criteria

The effect of noise exposure history (Q. 7, Figure 2.7) on other questionnaire responses indicated that, higher previous noise exposure was associated with:

(a) greater comfort ($|\gamma|$ = 0.47/0.62 for passenger/subjects respectively),

(b) lower noise annoyance ($|\gamma|$ = 0.57/0.68 respectively),

TABLE 6.4

RELATIONSHIP BETWEEN PASSENGER REACTIONS AND ENVIRONMENTAL VARIABLES/AND SATISFACTION

(Pearson's Correlation Coefficient)

Psychological Descriptors	Environmental Variables*			Satisfaction
	MOTION		Noise Level (dB_A)	
	Vertical rms($\bar{a}_V$)	Transverse rms($\bar{a}_T$)		
Comfort	0.63	0.62	0.11	0.78
Pleasantness†	-0.67	-0.63	-0.15	-0.75
Noise Annoyance	0.34	0.43	-0.05	0.2
Motion Annoyance	0.7	0.51	-0.05	0.71

*These environmental variables are flight equivalent values, which were obtained by segment data integration [as in Eqn. (5.16)-(5.18)].

†Because of scale reversal for pleasantness [see Fig. 2.7], the correlation coefficients are expected to be negative.

(c) lower estimated noise contribution to their flight feelings (γ = 0.28/0.46 resp.), and

(d) lower conversation difficulty ($|\gamma|$ = 0.52/0.4 resp.).

These results show that noise exposure has a consistent effect on psychological and noise related responses.

In addition, the noise exposure criteria to safeguard passenger hearing ability was obtained. This is discussed in Appendix J.

CHAPTER VII

SUMMARY OF MODELS AND APPLICATIONS

7.1 Noise Impact Models

Satisfaction modelling involves four steps. First, single event subjective comfort is related to the environment by the motion-noise level model,

$$C'_{s_{MN_a}} = 1 + \begin{bmatrix} 17.85\ \bar{a}_V + 11.4\ \bar{a}_T, \text{ for } \bar{a}_V \geq 1.6\ \bar{a}_T \\ 1.5\ \bar{a}_V + 37.5\ \bar{a}_T, \text{ for } \bar{a}_V < 1.6\ \bar{a}_T \end{bmatrix} + 0.105\ \{dB_A - 75\} \qquad (7.1)$$

(similar models for PNdB, dB_D, SIL_1, SIL_2, are in § 5.1.2), or by the motion-noise source model,

$$C'_{s_{MSN}} = \begin{bmatrix} 17.85\ \bar{a}_V + 11.4\ \bar{a}_T, \text{ for } \bar{a}_V \geq 1.6\ \bar{a}_T \\ 1.5\ \bar{a}_V + 37.5\ \bar{a}_T, \text{ for } \bar{a}_V < 1.6\ \bar{a}_T \end{bmatrix}$$

$$+ \begin{bmatrix} 0.92 + 0.0072SN_1 + 0.038SN_2, \text{ for commercial flights} \\ 1.56 + 0.006SN_1 + 0.005SN_2 + 0.047SN_3, \text{ for aircraft A} \end{bmatrix} \qquad (7.2)$$

Second, single events are combined into an overall reaction by

$$c'_{s_o} = \sum_{i=1}^{m_s} W\ (i)\ C_{s_i}, \text{ and} \qquad (7.3)$$

$$W(i) = i^{0.75} / \left(\sum_{i=1}^{m_s} i^{0.75} \right) \qquad (7.4)$$

Next, passenger comfort is determined from subject comfort (Figure 7.1) and lastly, satisfaction is calculated (Figure 7.2).

The relationship between conversation difficulty, d_c and noise level is,

$$d'_c = 1 + 0.09 \{dB_A - 81\} \qquad (7.5)$$

[Similar models for PNdB, SIL_1, and SIL_2 are in Eqn. (6.2) to (6.4)].

7.2 Applications

These models can be used for design or for impact prediction (Figure 7.3). In the design process, tradeoff analyses among the environmental variables can be conducted to achieve desired satisfaction level, whereas in impact prediction the effect of a known or measured environment is used to determine passenger satisfaction.

As an illustration, typical iso-satisfaction countours for the motion-noise level model (dB_A), are plotted in Figure 7.4 [as in Ref. (23)] for 58% and 80% satisfaction levels. Passengers and subjects were assumed to experience uniform environmental stimulus during the flight. This figure provides a framework for tradeoff analysis between motion and noise variables.

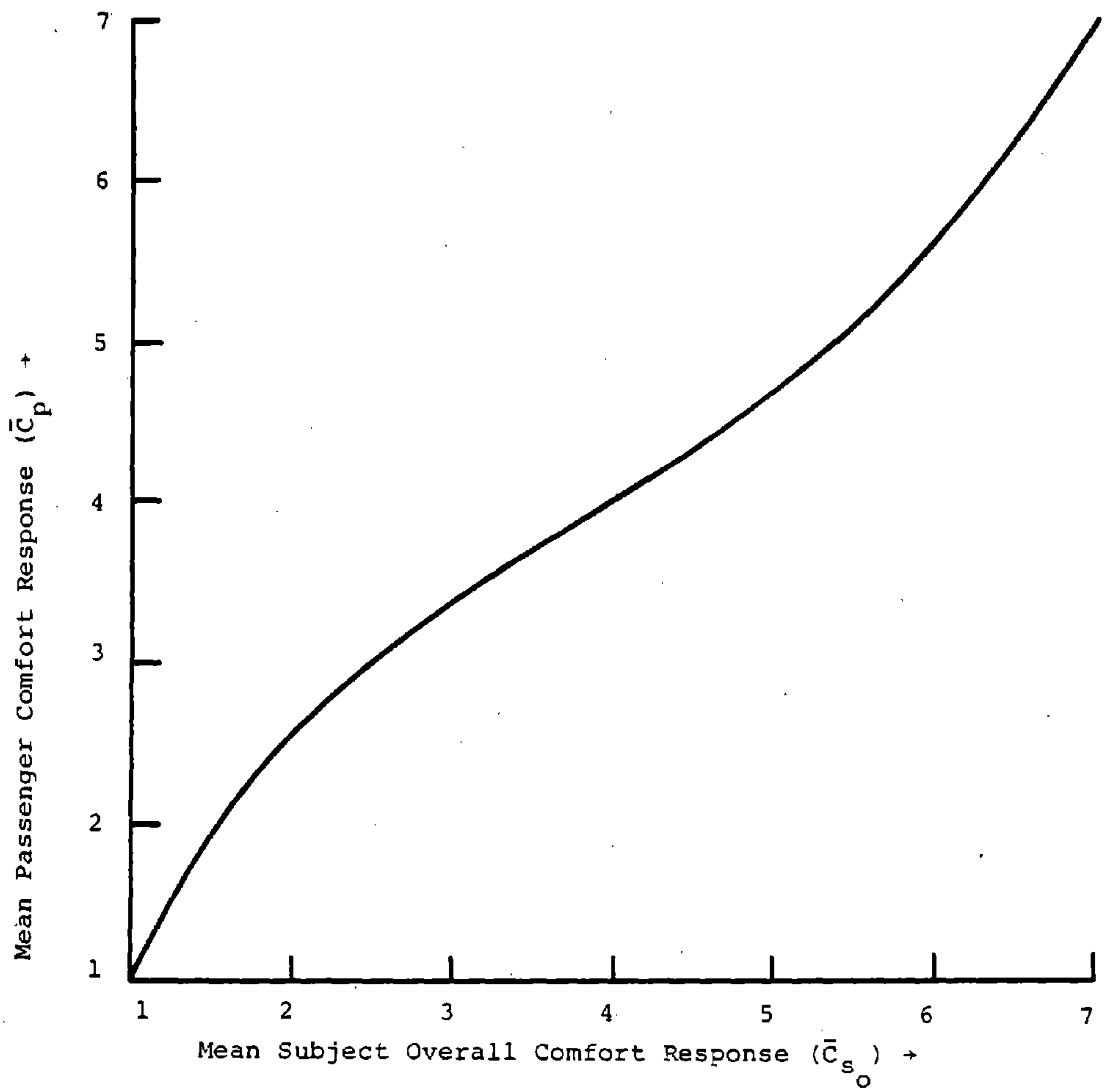


FIGURE 7.1 Mean Subject/Passenger Comfort Response Transfer Function.

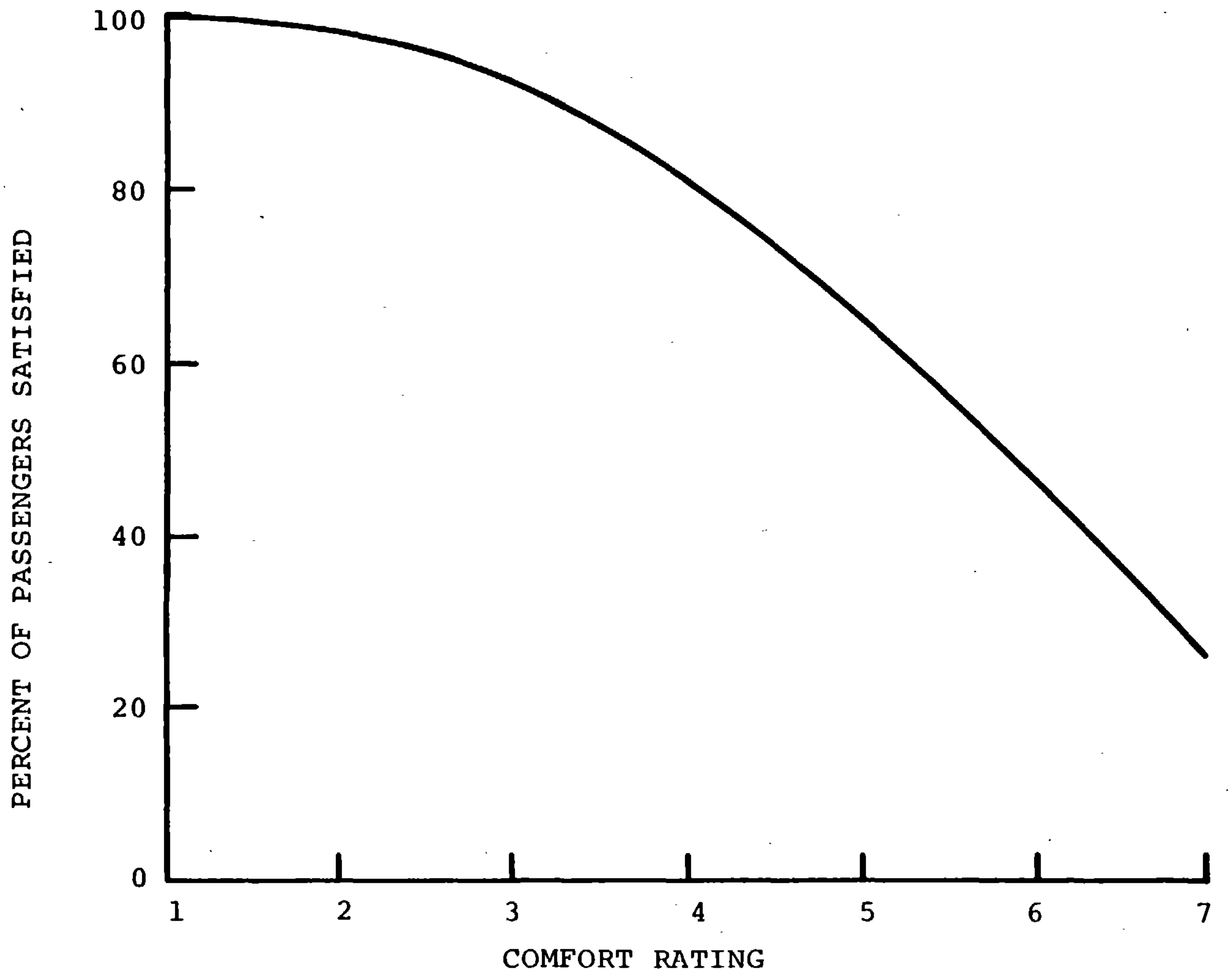


FIGURE 7.2 Passenger Comfort/Satisfaction Transfer Function.

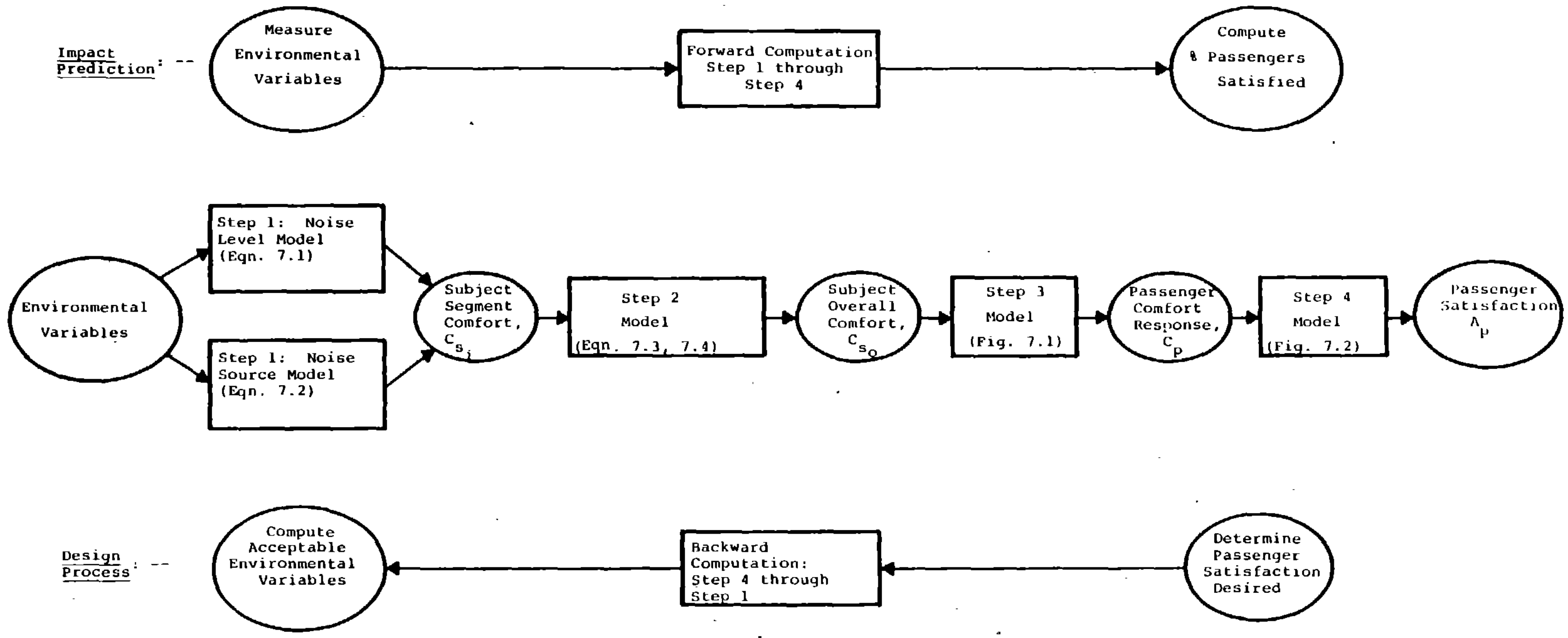


FIGURE 7.3 Application Procedure for Satisfaction Models.

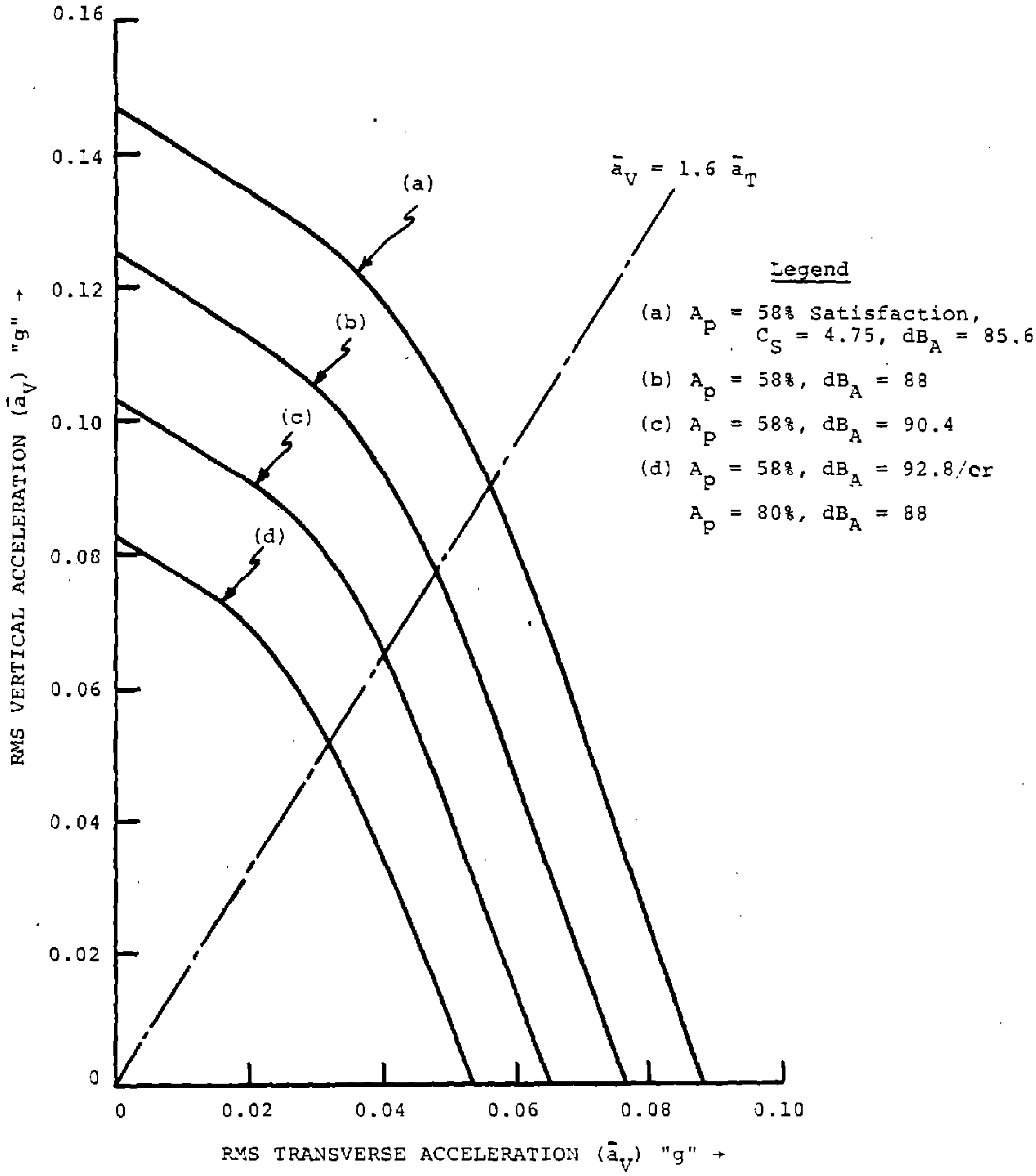


FIGURE 7.4 Iso-Satisfaction Contours--Noise Level Model.

The contribution of noise sources to comfort for aircraft A is shown in Figure 7.5. Iso-satisfaction contours for the motion-noise source model (Eqn. 7.2) are surfaces in a five dimensional space ($\bar{a}_V$, $\bar{a}_T$, SN_1, SN_2 and SN_3). Since it is difficult to plot and to visualize a five dimensional surface, the iso-satisfaction contours were obtained in a parametric form (with $\bar{a}_V$, $\bar{a}_T$ and aerodynamic noise SN_2 as fixed values) in a reduced two dimensional space (engine noise SN_1, and radio noise SN_3). Using Figure 7.5, these contours are plotted in Figure 7.6, for 58% and 80% satisfaction. Figure 7.6 illustrates a tradeoff analysis tool for noise reductions in radio and engine sources. Similar contours can be obtained for other combinations of variables; or, perhaps more useful, the analytic form can be used in engineering applications.

The motion-noise source model provides a more powerful design tool than the noise level model. For example, if the systems designer has selected A_p = 80% and if $\bar{a}_V$ = 0.073g and $\bar{a}_T$ = 0.02g, then Figure 7.4 indicates that noise level should be below 86dB_A whereas Figure 7.6 (for SN_2 = 32.4 Noy), indicates that this could be achieved by any combination on contour (a). Thus the motion-noise source model permits a tradeoff among noise source contributions. The optimum choice can be based on cost effectiveness.

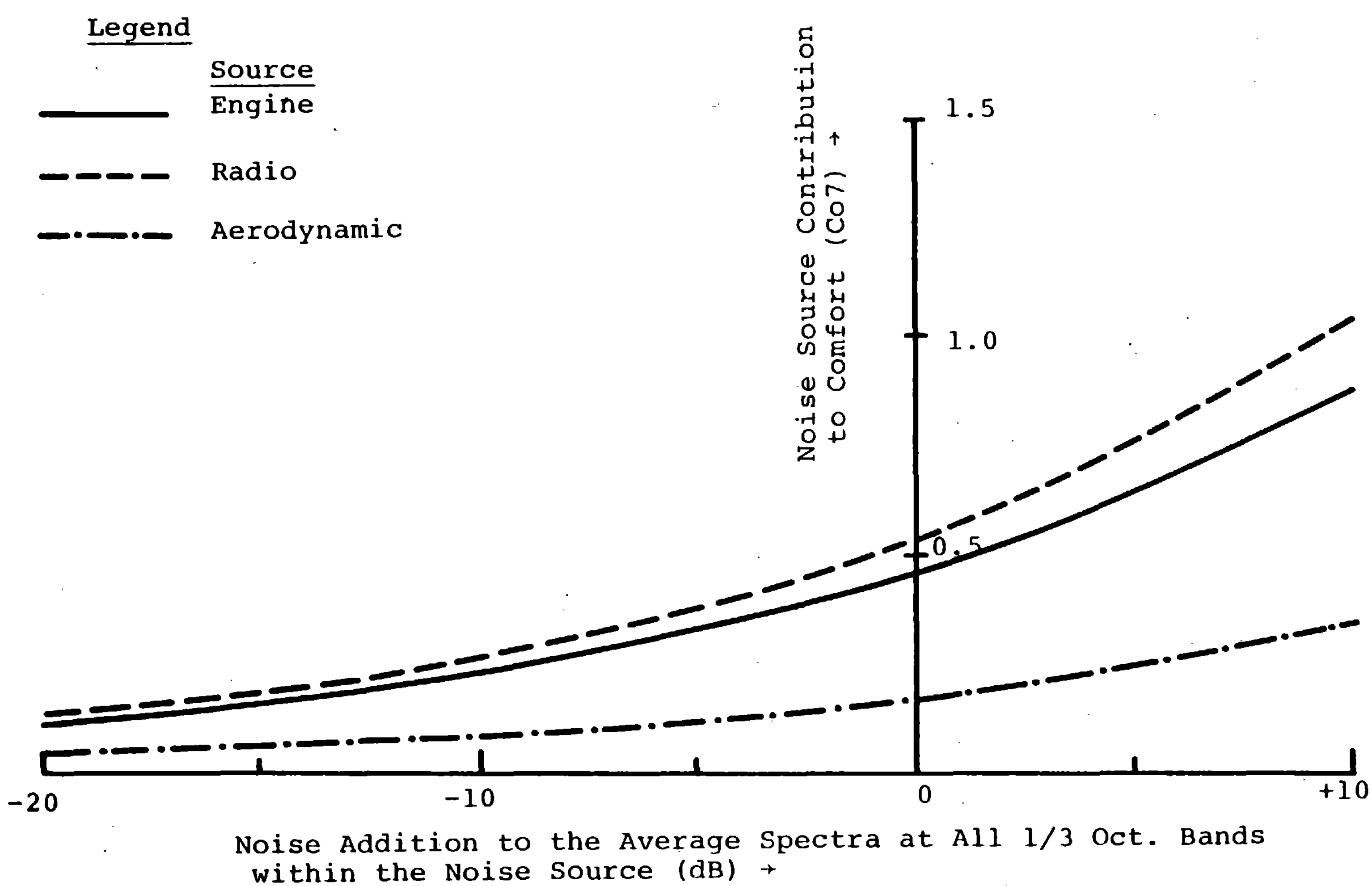
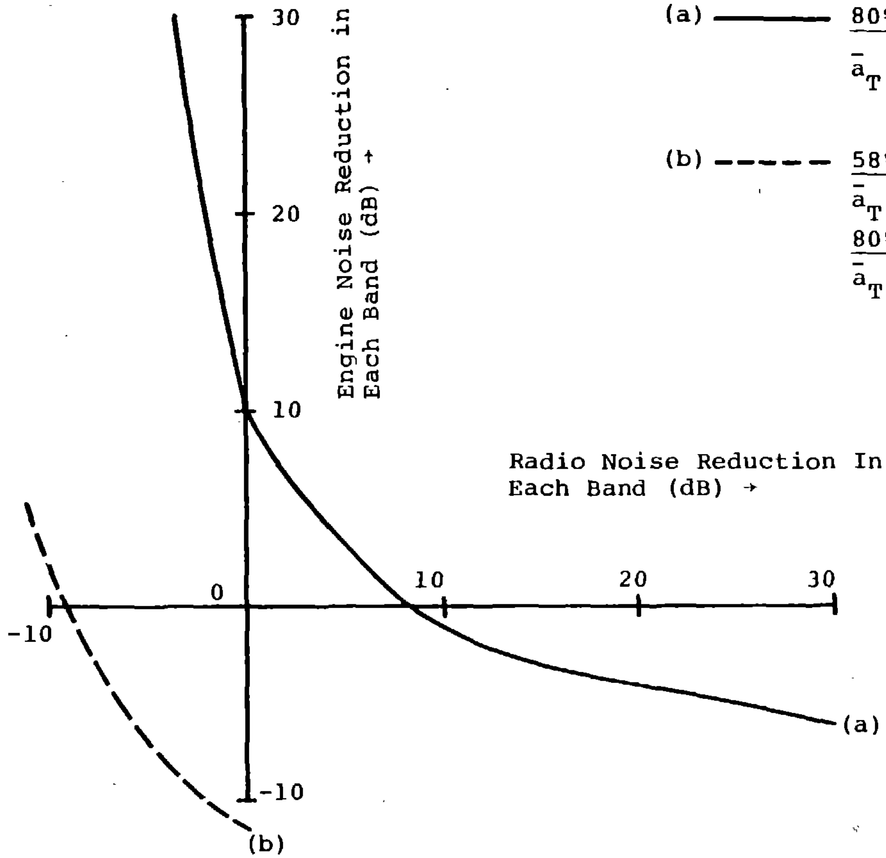


FIGURE 7.5 Effect of Source Noise on Comfort - Aircraft A.



<u>Legend</u>

(a) ——— <u>80% Satisfied</u> => $C_S = 4$, $\bar{a}_V = 0.073$, $\bar{a}_T = 0.02$, $SN_2 = 32.4$ Noy.

(b) - - - - <u>58% Satisfied</u> => $C_S = 4.75$, $\bar{a}_V = 0.073$, $\bar{a}_T = 0.02$, $SN_2 = 32.4$ Noy; or <u>80% Satisfied</u> => $C_S = 4$, $\bar{a}_V = 0.037$, $\bar{a}_T = 0.01$, $SN_2 = 32.4$ Noy.

FIGURE 7.6 Iso-Satisfaction Contours in the Engine Noise-Radio Noise Domain--Aircraft A.

Although the motion-noise source model is better correlated with comfort (ρ_p improves from 0.65 to 0.74 with noise source inclusion) than the motion-noise level (dB_A) model ($\rho_p = 0.7$), the motion-noise level model is more suitable for impact prediction. It requires only a single noise measurement (e.g. dB_A, PNdB) rather than an elaborate noise source and spectral analysis.

In addition, the satisfaction models can be used in cost-benefit analysis for optimum selection of the interior environment. The procedure is illustrated in Figure 7.7.

Similarly the conversation difficulty model (Eqn. 7.5) and noise exposure criteria (Figure J.1) can be used for impact prediction and for design.

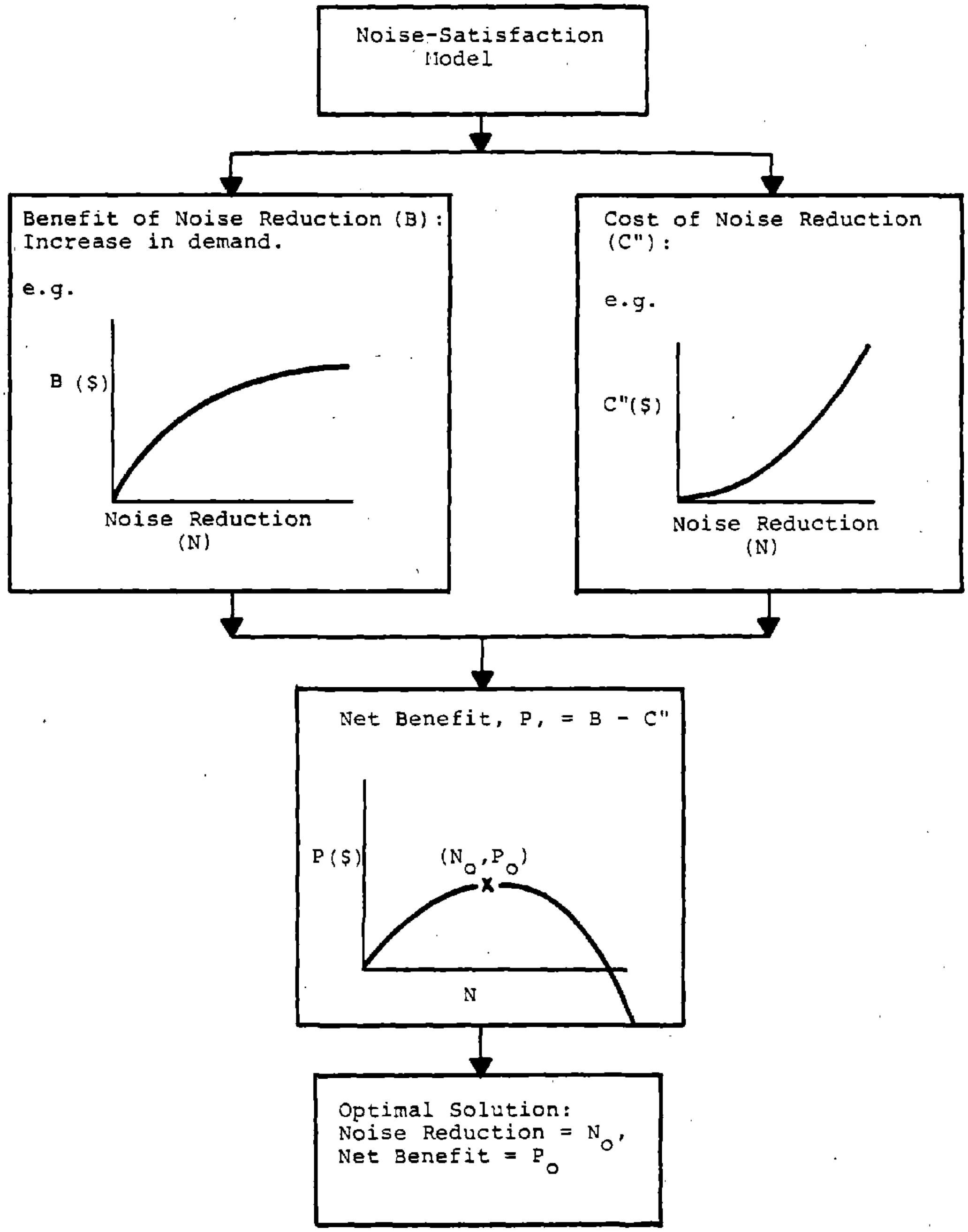


FIGURE 7.7 Schematic of the Satisfaction Models Application, for Cost-Benefit Analysis.

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The major conclusions of this study are:

(a) Procedures for separating noise effects have been established.

(b) Interior noise is important for passenger comfort and satisfaction.

(c) Comfort/motion-noise level (dB_A, dB_D, PNdB, SIL_1, SIL_2) models and comfort/motion-noise source models have been developed.

(d) The motion-noise source/comfort model is a better predictor than the motion-noise level/comfort model.

(e) The motion-noise source model can be used for design applications.

(f) The motion-noise level model can be used for impact assessment.

(g) Inter-aircraft and inter-subject differences in the motion-noise models are not significant.

(h) Conversation difficulty/noise level (dB_A, PNdB, SIL_1, SIL_2) models have been developed. These can be used for design and for impact assessment.

(i) Permissible exposure to safeguard hearing ability have been determined (Appendix J).

(j) Comfort and pleasantness are suitable psychological variables for relating noise and motion to satisfaction. Motion annoyance and noise annoyance are not effective in separating the corresponding effects.

(k) Relative importance of factors in satisfaction and comfort revealed little change from past studies.

(l) Relative importance of on-board-activities based on difficulty* and time spent have been obtained.

(m) Auditory task (conversation) is affected by noise but not by motion. Non-auditory tasks are either benefitted or are not affected by noise. Discomfort is associated with activities difficulty.

(n) Satisfaction is associated with lower levels of activities difficulty.*

(o) Higher levels of perceived noise annoyance are associated with greater conversation difficulty.

(p) Perceived ease in conversation and conversation importance are associated with more time spent talking.

(q) Passenger and subject work-noise-exposure, affects their psychological and noise related responses.

(r) Similar satisfaction models can be developed for other modes of transportation.

(s) Segment subject comfort/passenger satisfaction models from past studies were applicable with minor modification.

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*Activities difficulty, evaluated on a three point scale, represents the cumulative effect due to the entire flight environment.

8.2 Suggestions for Further Work

With a view toward answering some remaining questions the following suggestions are made for further work:

(a) Data should be obtained on turbofan and gliders. Both provide significantly different noise spectral characteristics and thus help increase confidence of the models discussed. Since glider tests are free of engine noise, glider data enables model evaluation on future aircraft with quiet engines.

(b) The feasibility of using ground based simulators should be studied. This would be useful since ground based simulators are comparatively inexpensive to operate and the environment is easy to control. They can be used for model validation and extension.

(c) The investigation of the utility of headphones with or without music to improve passenger comfort, would be extremely useful. If feasible, this would not only reduce the noise experienced by passengers, but also provide entertainment, and thus increase satisfaction. It would then provide a quick and inexpensive solution to the aircraft interior noise problem.

(d) A cumulative relationship between satisfaction and its underlying variables (e.g. comfort, activities difficulty and other factors) would provide systems designers with a more powerful design tool.

APPENDIX A

AIRCRAFT DATA

Details of the aircraft used in this test program are described in Table A.1 and Figure A.1, which have been obtained from Ref. (70). Types of data collected on the aircraft are described in Appendix C and Ref. (54).

AIRCRAFT TYPE	A	B	C	D	E
No. of Passengers	6	8	19	26	8
Pressurized	No	No	No	Yes	Yes
Wing Position	High	Low	High	High	Low
Overall Length (ft.)	32	33	52	63	40
Wing Span (ft.)	37	41	65	72	46
Ave. Wing Thickness (ft.)	0.55	0.75	1.04	1.38	0.84
Wing Area (ft.^{2})	175	229	420	592	280
Max. Wing Loading (lb/ft.^{2})	22	27	29	39	41
Empty Weight (lb.)	1858	3744	7400	15500	6405
Max. Takeoff Weight (lb.)	3800	6200	12000	23370	10600
Takeoff Distance (ft.)	1100	1010	1230	4100	1650
Landing Distance (ft.)	765	1725	1500	2060	1265
Cruising Speed (mph)	150	210	200	230	285
Overhead Radio Speaker	Yes	No	No	No	No

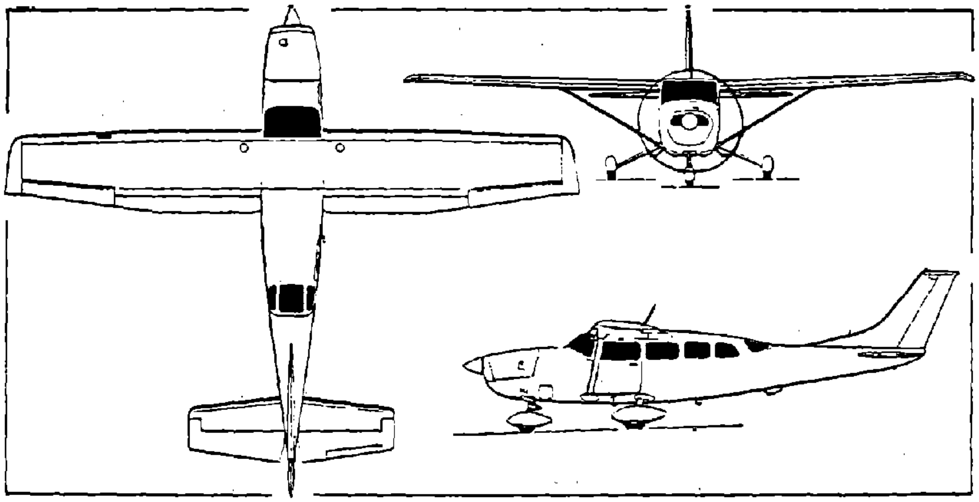
*From Janes, All The World's Aircraft (70)

TABLE A.1

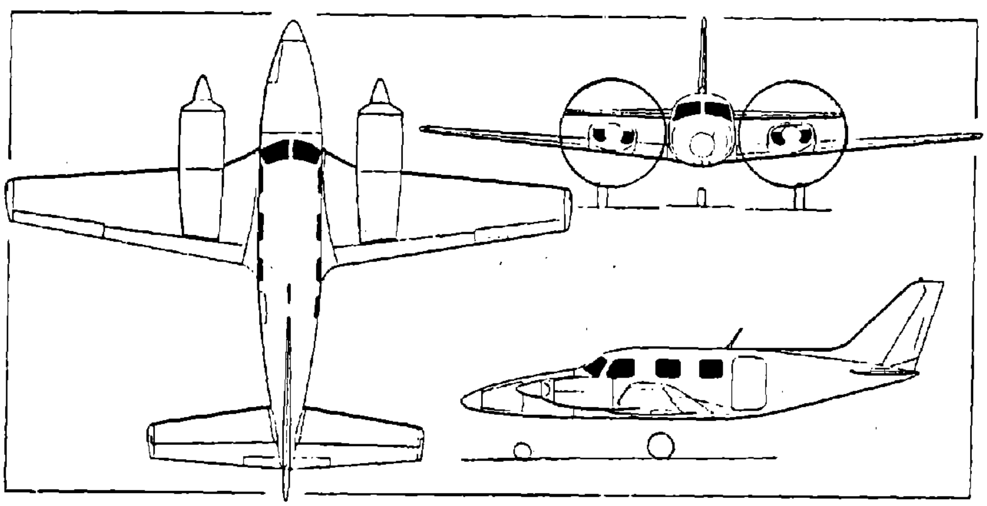
AIRCRAFT DATA*

TABLE A.1 CONCLUDED

AIRCRAFT TYPE	ENGINE DESCRIPTION
A	Single 3-blade propeller, constant speed (∿ 2400 RPM), 6 cylinder, horizontally opposed, 280 HP.
B	Two 2-blade propeller, constant speed (∿ 3000 RPM), 6 cylinder, horizontally opposed, fully feathering, 300 HP.
C	Two 3-blade turbo propeller, 2200 RPM, reversible pitch, fully feathering, 550 SHP, gear ratio - 15:1.
D	Two 3-blade turbo propeller, constant speed (preset), variable pitch, 1588 RPM, 986 SHP, gear ratio - 21.0957:1.
E	Two 3-blade turbo propeller, constant speed (2200 RPM), reversible pitch, fully feathering, 680 SHP, gear ratio - 15:1.

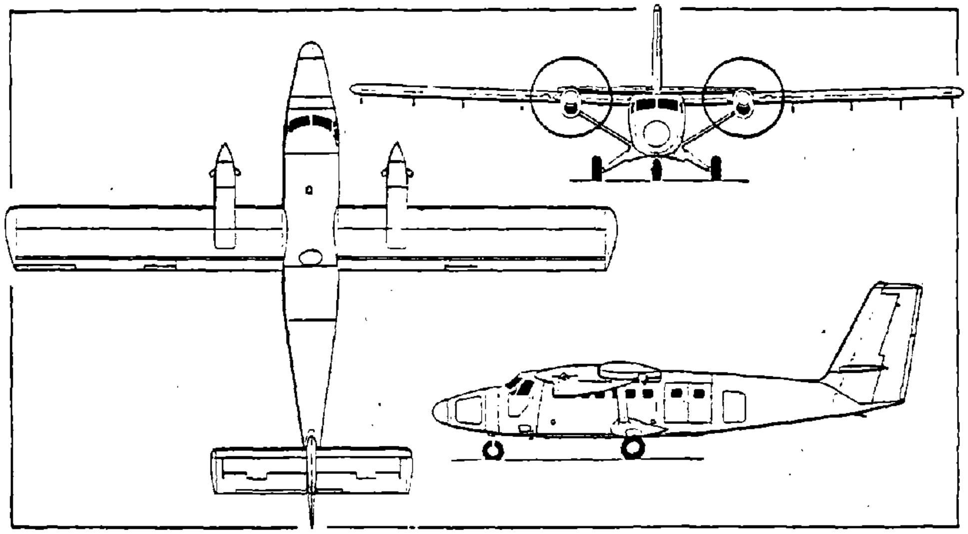


a. Aircraft A

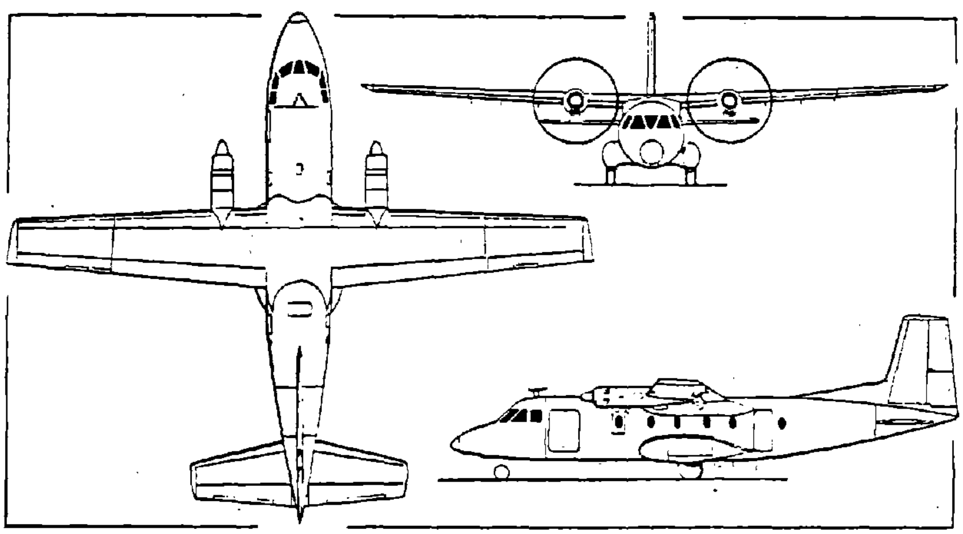


b. Aircraft B

FIGURE A-1. AIRCRAFT THREE-VIEW DRAWINGS

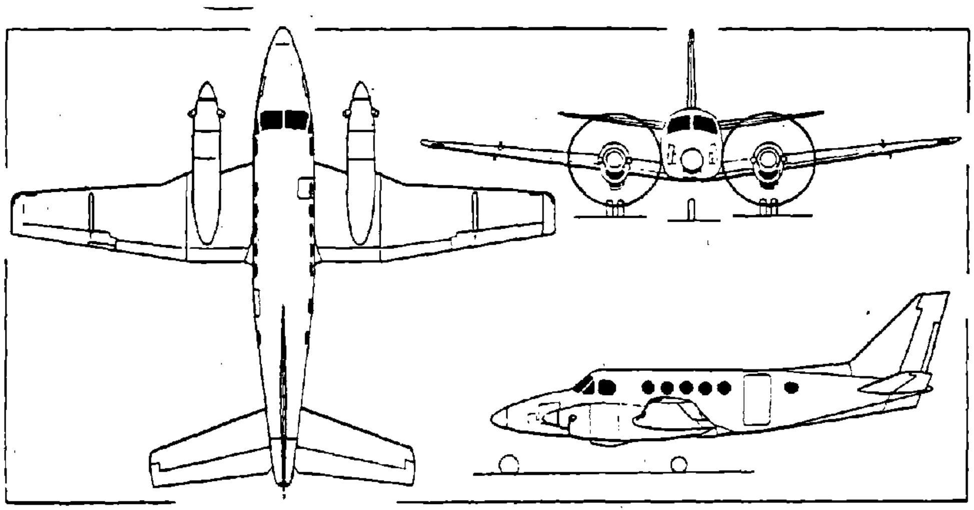


c. Aircraft C



d. Aircraft D

FIGURE A-1. CONTINUED



e. Aircraft E

FIGURE A-1. CONCLUDED

APPENDIX B

SUBJECT PROFILES

In all 38 subjects participated in the flight test program. The subject profiles along with the number of segments for which their responses are available, are given in Table B.1. All of these subjects participated in the special flights, whereas only subjects S_1, S_2, and S_3 participated in commercial flights. In addition to performing regular subject tasks (i.e. evaluation of every segment), the three subjects were also in charge of data collection, questionnaire distribution (on commercial flights) and other experimental tasks.

TABLE B.1 SUBJECT PROFILES

SUBJECT	SEX	AGE	PROFESSION	NO. OF SEGMENT RESPONSES
S_1	M	24	Student	286
S_2	M	26	Student	418
S_3	M	23	Student	122
S_4	M	29	Student	76
S_5	M	25	Student	56
S_6	M	23	Student	36
S_7	F	23	Student	36
S_8	M	23	Student	36
S_9	M	22	Student	32
S_{10}	M	22	Student	30
S_{11}	M	24	Student	30
S_{12}	M	24	Student	30
S_{13}	M	28	Student	26
S_{14}	F	26	Teacher	20
S_{15}	F	23	Teacher	20
S_{16}	M	23	Student	20
S_{17}	M	20	Student	20
S_{18}	M	26	Student	20
S_{19}	M	27	Student	20
S_{20}	M	43	Professor	16
S_{21}	M	58	Professor	16
S_{22}	F	29	Secretary	16

TABLE B.1 (CONTINUED)

SUBJECT	SEX	AGE	PROFESSION	NO. OF SEGMENT RESPONSES
S_{23}	M	23	Salesman	16
S_{24}	M	21	Student	16
S_{25}	M	26	Student	16
S_{26}	F	22	Student	16
S_{27}	M	23	Student	16
S_{28}	M	23	Student	16
S_{29}	F	22	Student	16
S_{30}	M	22	Student	16
S_{31}	M	25	Student	16
S_{32}	M	25	Student	10
S_{33}	M	24	Student	10
S_{34}	M	24	Student	10
S_{35}	M	24	Student	10
S_{36}	M	29	Student	10
S_{37}	F	26	Student	10
S_{38}	M	23	Student	10

APPENDIX C

TEST DATA

Field test data were catalogued by tests and by segments (within tests). Test (flight) data is tabulated in Table C.1 and the test segment data in Table C.2. See Ref. (54) for more details.

TABLE C.1 TEST (FLIGHT) DATA

Test Type	Commercial, Semicontrolled, Controlled or Environmental
Date	Month, Day and Year
Ori-dest	
Airline	(if any, A through D)
Aircraft	A through E (Appendix A)
Subject	S_1 through S_{38} (Appendix B)
Rate of climb/descent	Ft/min
Cruise altitude	Ft.
Cruise velo.	MPH
Wind speed/direction	MPH/deg.
Weather	Clear, cloudy or rainy
Arrival/departure time	
Terrain	Flat, hilly or mountainous
Turbulence	Smooth, moderate or rough
Subject/measurement location	
Subject overall responses	co7 units
Questionnaire data	
Miscellaneous	# of pass., # of subj.

TABLE C.2 TEST SEGMENT DATA

Segment #	0-11
Flight Phase	Taxi, takeoff, climb, cruise, descent or landing
Temperature	°F
Subject responses	co7
Noise data	OSPL, dB_A, 1/3 octave band spectra
Motion data	3 rms angular velocities (pitch, roll, yaw), and 3 rms linear acceleration (vertical, transverse and longitudinal)
Miscellaneous	Location of measurement, Noise source factor (in environmental tests).

APPENDIX D

SAMPLE SIZE ESTIMATION

The following types of sample size estimates (71,72) were made in this study:

D.1 Number in sample (n) needed to obtain a reliable estimate of the true mean of a population of size N.

Here we test the null hypothesis:

H_0: "The sample mean does not differ significantly from the true mean of the population".

In order to establish the hypothesis H_0, let, the probability that the sample mean, $\bar{X}_n$, differs from the true mean, μ_X (= $\bar{X}_N$), by an error greater than δ_X, be less than or equal to α.

Further, let

X - the variable being measured

$\bar{X}_n$ - average of X based on a sample of n

n/N - sample/population size

$\mu_X = \bar{X}_N$ - population mean

σ_X^2 - true variance of X

s_x^2 - variance based on a sample

δ_X - maximum permissible error

α - probability of type I error (i.e., rejecting the hypothesis that the means do not differ falsely).

Thus the hypothesis is

$$H_0: \ \Pr\{|\bar{X}_n - \mu_X| > \delta_X\} \leq \alpha \tag{D.1}$$

Letting

$$Z = \frac{\bar{X}_n - \mu_X}{\sigma_{\bar{X}_n}} \quad , \tag{D.2}$$

Where Z is normally distributed (71) with zero mean and standard deviation of one, and letting

$$\sigma_{\bar{X}_n} = \sigma_X \sqrt{\frac{(N-n)}{(n-1)n}} \tag{D.3}$$

yields,

$$H_0: \Pr\{|Z| > Z_\alpha\} \leq \alpha \ , \tag{D.4}$$

where

$$Z_\alpha = \frac{\delta_X}{\sigma_{\bar{X}_n}} \tag{D.5}$$

Knowing α, Z_α can be obtained from normal distribution tables. Equation (D.4) can be satisfied by, [using Eqn. (D.3) and (D.5)]

$$n \geq \frac{(n')^2 N}{[N-1 + (n')^2]} \tag{D.6}$$

where $n' = Z_{\alpha} \sigma_X / \delta_X$ (D.7)

If σ_X is unknown, the estimate s_X, can be used instead of σ_X. In such a case, Equation (D.2) is modified to,

$$t = \frac{\bar{X}_n - \mu_X}{s_{\bar{X}}} \qquad (D.8)$$

where

$$s_{\bar{X}} = s_X / \sqrt{n} \quad , \qquad (D.9)$$

and, t is from a student's t distribution with (n-1) degrees of freedom.

Hence,

$$n \geq \frac{(n'')^2 N}{[N-1 + (n'')^2]} \qquad (D.10)$$

where

$$n'' = \frac{t_{\alpha,n-1} \cdot s_X}{\delta_X} \qquad (D.11)$$

and $t_{\alpha,n-1}$ can be obtained from tables.

Hence the smallest integer given by Equation (D.6) or Equation (D.10) (depending on whether σ_X or s_X is known) is the sample size required to test the hypothesis H_0.

D.2 <u>Sample size required in two groups to compare their means</u>.

Let the population size in each group be infinite, further let the true and sample variance for the two groups be the same* (σ^2 and s^2, respectively). Lex X_1 and X_2 be the two variables from the two groups.

Hpyothesis: There is a significant difference between the means of the two sets.

The null hypothesis is given as

$$H_0: \text{pr} \{ |\mu_{X_1} - \mu_{X_2}| < \delta \} < \alpha \qquad (D.12)$$

where

μ - true means

δ - acceptable error

α - level of significance (prob. of type I error)

Let

$$Z = \frac{\mu_{X_1} - \mu_{X_2}}{[\frac{\sigma^2}{n_1} + \frac{\sigma^2}{n_2}]^{\frac{1}{2}}} \qquad (D.13)$$

*The generalized case is described in Ref. (71,72).

and

$$t = \frac{\mu_{X_1} - \mu_{X_2}}{[\frac{s^2}{n_1} + \frac{s^2}{n_2}]^{\frac{1}{2}}} \quad \text{(D.14)}$$

where

n_1/n_2 - sample size for groups 1 and 2.

Here Z and t follow normal and student's t distributions ($n_1 + n_2 - 2$ degrees of freedom), respectively.

If we choose to minimize $(n_1 + n_2)$, then

$$n_1 = n_2 \geq 2 \left(\frac{Z_\alpha \cdot \sigma}{\delta}\right)^2 \quad \text{(D.15)}$$

or

$$n_1 = n_2 \geq 2 \left[\frac{t_{\alpha,(2n_1-2)} \cdot s}{\delta}\right]^2 \quad \text{(D.16)}$$

Equations (D.15) or (D.16) should be used depending on whether σ or s is known.

APPENDIX E

NOISE INDICES

Among a large number of noise indices* available in the literature (26-31,42,47,73), only those used in this study are described here. Many of these indices have multiple definitions and a variety of correction factors (26,47), which are useful in specific situations. Hence, only the definitions pertinent to this study are given next.

E.1 Overall Sound Pressure Level [OSPL (dB)]

$$OSPL = 20 \log_{10} (p/p_{ref}) \qquad (E.1)$$

where,

p - rms sound pressure ($\mu N/m^2$)

$p_{ref} = 20\ \mu N/m^2 = (0.0002\ \mu\ bar)$

It can also be calculated from,

dB_i - one-third octave frequency band sound pressure level (dB), by using,

$$OSPL = 10 \log_{10} [\sum_{\text{all bands}} 10^{(0.1 \ell_d)}] \qquad (E.2)$$

*All of the noise indices, except OSPL, are used both as variables and units interchangeably in the text.

where

$$\ell_d = dB_i \tag{E.3}$$

E.2 A-Level/D-Level (dB_A/dB_D)

Both A-level and D-level are the sound pressure levels with corresponding frequency weights. The frequency corrections are given in Table E.1 (47). The dB_A and dB_D values are obtained by using Eqn. (E.2) with

$$\ell_d = dB_i + \Delta\ell_A, \tag{E.4}$$

and

$$\ell_d = dB_i + \Delta\ell_D, \tag{E.5}$$

for dB_A and dB_D respectively.

E.3 Noy/Sone Values (Noy/Sone)

The Noy (/Sone) level for each 1/3 octave band level Noy_i ($Sone_i$), are obtained by using the appropriate tables given in the literature (47). Then the overall (masked) Noy and Sone values are computed by

$$Noy_{total} = Noy_{max} + 0.15 \left[\sum_{\substack{all \\ bands}} (Noy_i) - Noy_{max} \right] \tag{E.6}$$

and $$Sone_{total} = Sone_{max} + F \left[\sum_{\substack{all \\ bands}} (Sone_i) - Sone_{max} \right] \tag{E.7}$$

respectively, where

$Noy_{max}/Sone_{max}$ - maximum Noy/Sone Value among all bands, and F - Masking Factor, given in Ref. (47).

TABLE E.1 A-/D- WEIGHTING FUNCTIONS (47)

1/3 Octave Band Center Frequency (Hz)	$\Delta \ell_A$, A-Level Corrections, (dB)	$\Delta \ell_D$, D-Level Corrections, (dB)	1/3 Oct. Band Center Frequency (Hz)	$\Delta \ell_A$, A-Level Corrections, (dB)	$\Delta \ell_D$, D-Level Corrections, (dB)
50	-30.2	-12.8	1K	0	0
63	-26.2	-10.9	1.25K	0.6	2.0
80	-22.5	- 9.0	1.6K	1.0	4.9
100	-19.1	- 7.2	2K	1.2	7.9
125	-16.1	- 5.5	2.5K	1.3	10.6
160	-13.4	- 4.0	3.15K	1.2	11.5
200	-10.9	- 2.6	4K	1.0	11.1
250	- 8.6	- 1.6	5K	0.5	9.6
315	- 6.6	- 0.8	6.3K	-0.1	7.6
400	- 4.8	- 0.4	8K	-1.1	5.5
500	- 3.2	- 0.3	10K	-2.5	3.4
630	-1.9	- 0.5	12.5K	-4.3	-1.4
800	-0.8	- 0.6			

E.4 Perceived noise level (PNdB)

PNdB is obtained by ,

$$PNdB = 40 + 33.22 \log_{10} (Noy_{total}) \qquad (E.8)$$

where, Noy_{total} is given in Eqn. (E.6)

E.5 Speech interference levels (SIL_1/SIL_2)

These are defined as,

$$SIL_1 = 1/3 \; [dB_i^o(500) + dB_i^o(1K) + dB_i^o(2K)], \qquad (E.9)$$

$$\text{and} \quad SIL_2 = 1/4 \; [dB_i^o(500) + dB_i^o(1K) + dB_i^o(2K) + dB_i^o(4K)] \qquad (E.10)$$

where

$dB_i^o(f)$ - octave band sound pressure level (dB) centered at f Hz.

E.6 Equivalent Sound Level (L_{eq})

Equivalent Sound Level is defined as the energy averaged (over some period of time) sound pressure level (OSPL, dB_A or any weighting desired). In this study only A-weighted equivalent level L_{eq_A} is used, and is defined as,

$$L_{eq_A} = 10 \log_{10} \frac{\int_0^T [10^{(0.1dB_A(t))}] \, dt}{T} \qquad (E.11)$$

where

$dB_A(t)$ - A-level at time t

T - Period of interest (e.g. 8 hrs., 24 hrs., 1 yr.)

Similar equivalent levels can be obtained for other weighted sound levels.

APPENDIX F

EFFECTS OF NOISE ON PEOPLE

A brief summary of noise effects, relevent for this study, are given below. [See Ref. (19,26,27,29,42,43,45) for more details].

Responses to noise can be classified in general as:

I Threshold responses,

II Psychological responses,

III Performance decrement (auditory and non-auditory tasks),

IV Hearing loss, and

V Physiological responses.

Each of these effects are described next, along with recommended criteria from the literature. These criteria are defined (in the literature) in terms of dB_A, dB_D, PNdB, Noy, Sone, SIL_1, SIL_2, L_{eq_A} (Appendix E), L_{dn}, Loudness level, noise criteria, articulation index (AI), DRC, EDRL, CDR, EWI (26,43,45,47,74).

F.1 Threshold Levels

A typical threshold curve is shown in Figure F.1 (29). No ill-effects are experienced at these levels.

F.2 Psychological Levels

These effects are frequently described as loud, noisy, annoying, uncomfortable, unpleasant, intrusive, unacceptable, etc. (26).

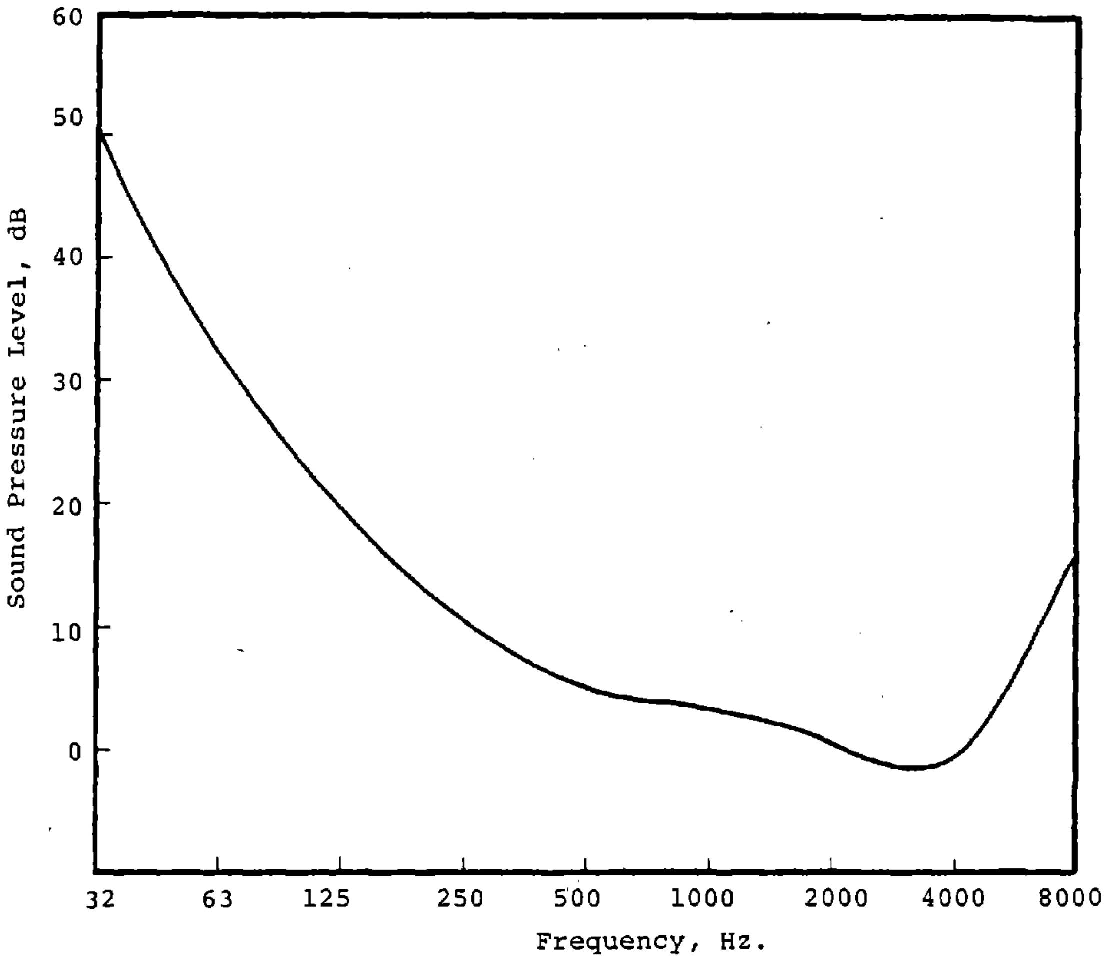


FIGURE F.1 Threshold of Hearing Sensitivity (29).

Levels: Noise criteria for these responses depend on place (outdoor, indoor, work, travelling, etc.), and time (day, night) of exposure.

In general, aversiveness begins at noise levels between 30 to 70 dB_A, and above $70dB_A$ most people are affected (26). Ref. (45) recommends L_{dn} (day-night average) $\leq 55dB_A$ (for outdoor-residential areas), $L_{eq(8)} \leq 55dB_A$ (for outdoor-recreational areas, school yards, etc.), $L_{dn} \leq 45dB_A$ (for indoor-residential areas) and L_{eq} (24) ≤ 45 dB_A (for other indoor areas - schools, etc.).

Frequencies: 50 Hz - 10 k Hz is adequate, and pure tones are important.

F.3 Performance Decrement

F.3.1 Auditory Effect

Primarily there are two facets to this noise effect:

(a) Disadvantage: interferes with communication.

(b) Advantage: aids in private conversation, since it prevents people at greater distance from hearing.

Levels: Speech communication criteria depends on talker-listner distance, voice effort, background noise, type of information (e.g. familiarity) and desired intelligibility. A typical noise criteria is shown in Figure F.2 (27), which is based on an articulation index (AI) of 0.4 [∿ 95% intelligibility of sentences (26)]. Similar criteria are available for other noise indices (26-29,42, 47).

Frequency: Primarily, 350 Hz - 5.6 KHz

F.3.2 Non-Auditory Effects

Noise affects sleep and performance.

Levels:

(a) Sleep. Low to moderate (< ∿ 55 dB_A) levels of steady noise is soothing, masks disturbing noise and hence aids in sleeping. However, brief and fluctuating sounds at $40dB_A$ disturbs approximately 10% of the population (at $75dB_A$ - 90%). Fluctuations and pure tones are especially disturbing (27). Recommended criteria is $L_{dn} \leq 45dB_A$ (45).

(b) Tasks. The effect of noise on tasks is unclear. Work efficiency improves for noise levels below $67dB_A$ due to arousal and masking of distracting noise (26). Steady noise below approximately 90 dB_A are not disruptive, but steady noise above $90dB_A$ and unsteady noise > ∿ 67 dB_A are often disruptive. Further, higher frequency

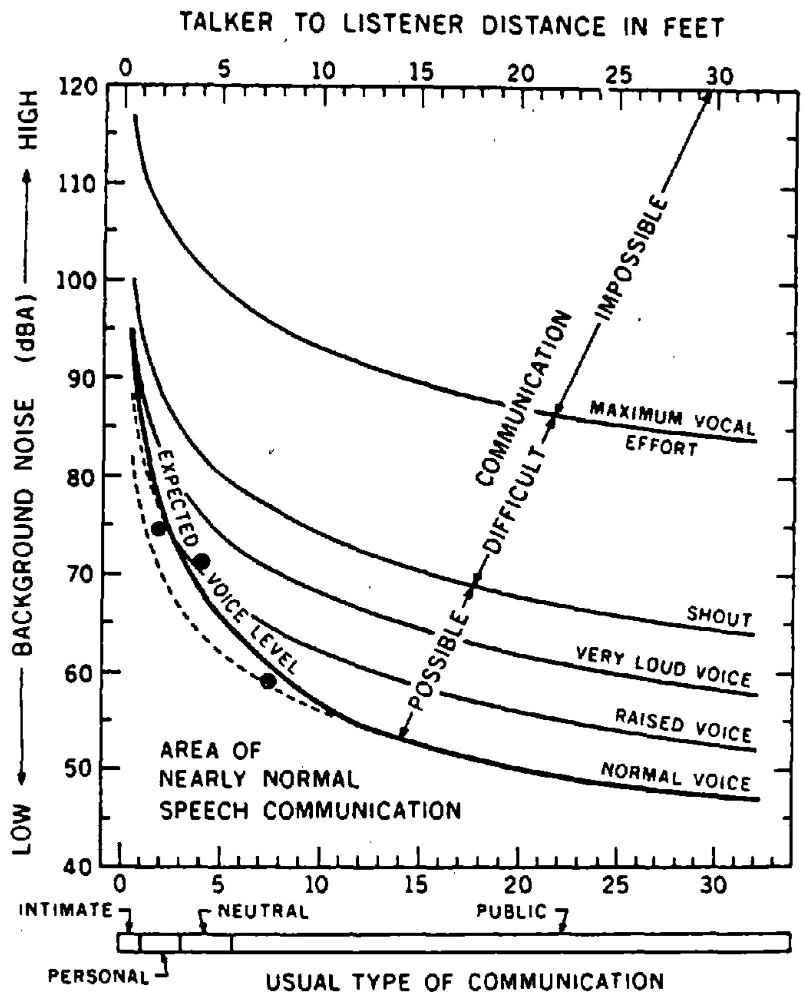


FIGURE F.2 Relationship Between Voice Effort, Background Noise Level (dB_A) and Talker-Listener Distance. (27).

noise (> ∿ 1K Hz) and pure tones are more disturbing (27).

F.4 Hearing Loss Effects

Two types of hearing losses are encountered, viz., temporary (TTS) or permanent (PTS) threshold shifts. Only PTS effects are discussed.

Levels: Losses are a function of noise level, exposure history and frequency content. Most criteria are designed to protect a certain percentage of individuals from occupational noise (75), against PTS between 500 Hz to 2 KHz at some prespecified level (43,45). They do not include 3-4 KHz losses, although the ear is most sensitive in these frequencies. Further they assume natural losses due to aging (presbycusis), although much of the loss might be due to general noise exposure (43-45). EPA (45) and Cohen (43) propose 70 dB_A as the long term energy average noise limits (L_{eq}) and $L_{eq(8)}$ of 75dB_A for occupational settings.

F.5 Physiological Effects

Many effects are observed such as inter-sensory effects, changes in body functions, and state of health etc. No specific indices have been developed for this purpose.

Levels: At noise levels, no greater than those experienced in daily living activities, physiological changes have been observed (19,27). These include, fast muscle reactions (due to startle); changes in blood flow rate, organ secretions, heart rate changes, etc. (for brief repetitive sounds > 70dB). However, such changes are usually transitory, and because of the adaptability of the human body, no consistent delitarious effects on health and well-being have emerged (19). At much higher levels (> ∿ 115 dB), exposures for longer durations, result in a variety of effects, such as loss of equilibrium (> 130 dB), nausea, vertigo (> 130 dB for short durations, or > ∿ 100 for more than 24 hrs.) etc. (19-27). These result in a lowering of body resistence and general health.

APPENDIX G

EQUIPMENT

In this appendix, equipment needed to measure and/or record motion, noise, temperature, pressure, general flight information, etc. are described. The equipment was selected based on the experimental needs and ease of operation in the field (independent power supply, portable, etc.). The needs of each variable along with equipment selected are described below. A summary is given in Table 3.1.

G.1 Noise

Literature (34,35,40,76) revealed that passengers in commercial aircraft are exposed to noise in the range of 70 to 105 dB_A, but most often in the range of 75 to 95 dB_A (with OSPL < 110 dB). Further the frequency range of interest (for audio-frequency passenger noise effects) is 50 Hz to 10 kHz (40,62). In fact, many noise indicies, viz., dB_A, dB_D, PNdB, etc. (26,47, Appendix E), are defined only for this range. Hence the equipment was selected for these needs.

A schematic diagram of the sound measuring and recording system selected for this study is shown in Figure G.1. Its requirements and capability is summerized in Table G.1. Further, its signal/noise ratio, harmonic distortion and

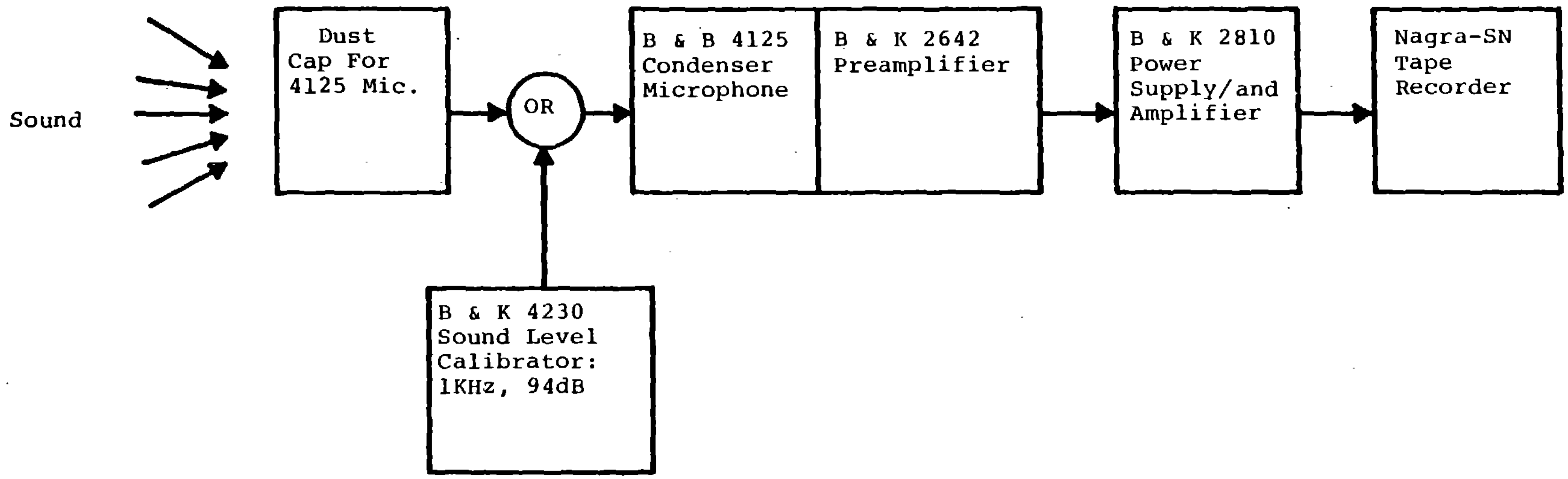


FIGURE G.1 Block Diagram of the Sound Recording System.

TABLE G.1 COMPARISON OF THE REQUIREMENTS AND THE CAPABILITY OF THE SOUND RECORDING SYSTEM

	Requirements	Capability of the Equipment
Dynamic Range	$70\text{-}105dB_A$, < 110dB	65dB(S/N* = 10) to 110 dB
Frequency Response	50 Hz - 10 KHz	30 Hz - > 10 KHz (± 3dB) 32 Hz - > 10 KHz (± 2dB)

*S/N → Signal to noise ratio

tape wow-flutter levels are also adequate. This system provides interior noise time histories.

A General Radio Real-Time Analyser Model #1921 was used to analyse the noise recordings, subsequently. Since all the noise measures used in this study (Appendix E) can be computed from 1/3 octave band sound pressure levels (dB_i), (26-29,42,47) dB_i's were obtained for eight second samples of all test segments. The 1/3 octave band center frequencies are listed in Table G.2. In addition to the dB_i's, OSPL, dB_A and 1/3 octave spectral plots were also obtained.

In addition, noise levels (dB_A) were measured for every flight segment, using a Scott Sound Level Meter Type 451 and recorded on log sheets. This provided on the spot noise levels and a double check on the sound recordings.

G.2 Motion

Motion measurement involved sensing, recording and reduction.

The motion sensing equipment, designed and fabricated at the University of Virginia, measured three linear accelerations (vertical, transverse and longitudinal) and three angular velocities (pitch, roll and yaw). These continuous measurements along with subject comfort responses were FM-multiplexed and recorded on a UHER 4400 stereo tape recorder. A description of the equipment is given in Ref. (22,77,78).

TABLE G.2 NOISE DATA -- 1/3 OCTAVE BAND CENTER FREQUENCIES

Band #	Center Frequency (Hz)	Band #	Center Frequency (Hz)
1	25	15	630
2	31.5	16	800
3	40	17	1K
4	50	18	1.25K
5	63	19	1.6K
6	80	20	2.0K
7	100	21	2.5K
8	125	22	3.15K
9	160	23	4.0K
10	200	24	5.0K
11	250	25	6.3K
12	315	26	8.0K
13	400	27	10.0K
14	500	28	12.5K

Since rms values of the motion variables accounts for most of the variance in passenger reactions (22,23), and since the motion spectra neither changes much (76) nor contributes significantly to variance in comfort reaction (22), only rms values were obtained. The FM-multiplexed data were processed by discriminators, analog to digital converters and a PDP-11 computer. With the aid of a Time Series Analysis Computer program (70), the rms values of the six-degrees-of-freedom motion variables were obtained for every flight segment. [See Ref. (22) for more details].

G.3 Other Data

Temperature (measured using a thermometer for every segment), general flight information (once a flight - see Appendix C), pressure (from flight information) and subject segment comfort responses were recorded on log sheets. In addition, questionnaires were used to obtain overall flight reactions from passengers in commercial flights and subjects in special flights.

APPENDIX H

AIRCRAFT INTERIOR NOISE SOURCE CHARACTERISTICS

In this appendix, noise sources are identified and their characteristics described from the literature.

Noise-generating mechanisms within aircraft can be broadly classified as (40,62) primary and secondary. The primary mechanisms include: propeller, engine (exhaust, structural propagation, etc.) and aerodynamic noise. The secondary noise-generating mechanisms are associated with: radio, vent/cooling/heating/pressurization systems and auxialiary power systems (e.g. hydraulic systems, starter/ generator units, etc.). In this study, the sources have been grouped together as shown in Table H.1

H.1 Engine Noise

Both reciprocating propeller and turboprop types of engines are considered, both of which drive propellers. The frequencies associated with the engine noise peaks are listed in Table H.2. Among these frequencies, blade passage frequency usually dominates the interior noise (3,16,40,63). In addition, frequencies between these peaks are often included, since they are part of the engine broad band noise (63).

The engine noise frequencies (Table H.2) for each aircraft [see Appendix A] used in this test program is presented in Table H.3.

TABLE H.1

INTERIOR NOISE SOURCES

Engine (includes the entire propulsion mechanism and propeller

Aerodynamic Noise

Radio

Vent

Auxilliary Equipment

Propeller Rotational Frequency:	$f_{pr} = (r/60)$ Hz	(H.1)
Engine Rotational Frequency:	$f_{er} = f_{pr} \cdot G$ Hz	(H.2)
Blade Passage Frequency:	$f_{bp} = b \cdot f_{pr}$ Hz	(H.3)
Blade Passage Harmonics:	$h \cdot f_{bp}$ Hz	(H.4)
Engine Firing Frequency:	(Depends on the engine design)	(H.5)

where

r - propeller rpm   g - transmission gear ratio

b - # of blades   h - harmonic number (integer)

TABLE H.2

ENGINE NOISE DOMINANT FREQUENCIES

TABLE H.3 ENGINE NOISE DOMINANT FREQUENCIES DURING CRUISE FOR FIVE AIRCRAFT

(All frequencies in Hz.)

Aircraft	Number and Type of Engine	Propeller (rpm/# of Blades)	Propeller Rotation Freq.	Blade Passage Freq.	Engine Rotation Freq.	Engine Firing Freq.	Blade Passage Harmonic Freq. (h integer)
A	1 Reciprocating Prop.	2400/ 3	40	120	40	120	120 x h = 250, ---
B	2 Reciprocating Prop.	3000/2	50	100	50	150	100 x h = 200, ---
C	2 Turbo-prop.	2200/3	37	110	550	-	110 x h = 220, ---
D	2 Turbo-prop.	1588/3	26.7	80	558	-	80 x h = 160, ---
E	2 Turbo-prop.	2200/3	37	110	550	-	110 x h = 220

H.2 Aerodynamic Noise

Aerodynamic noise arises due to pressure fluctuations in the turbulent boundary layer (41), which causes the aircraft skin to vibrate, which then is transmitted into the cabin as a roaring noise (80,81). The resulting acoustic pressure is proportional to the free stream dynamic pressure (= $1/2\ \rho\ V^2$) (35,41,57-60,80,81) and its spectral shape is given in Figure H.1 (64-67). The spectra peaks at

$$f_{an_{max}} = \frac{1.609 \times V}{t} \qquad \text{(H.6)}$$

where,

V = cruise velocity (mph)

t - average wing thickness

1.609 - Strouhal number

The $f_{an_{max}}$ values, for the five aircraft used in these tests, are reported in Table H.4, which can be used (with Figure H.1) to estimate the range of aerodynamic noise.

H.3 Other Sources

The noise from radio, vent and auxilliary equipment vary considerably from one aircraft to another.

Radio noise affects passengers only in aircraft A since it has loudspeakers. The radio output level in such a case has to be above the already noisy interior

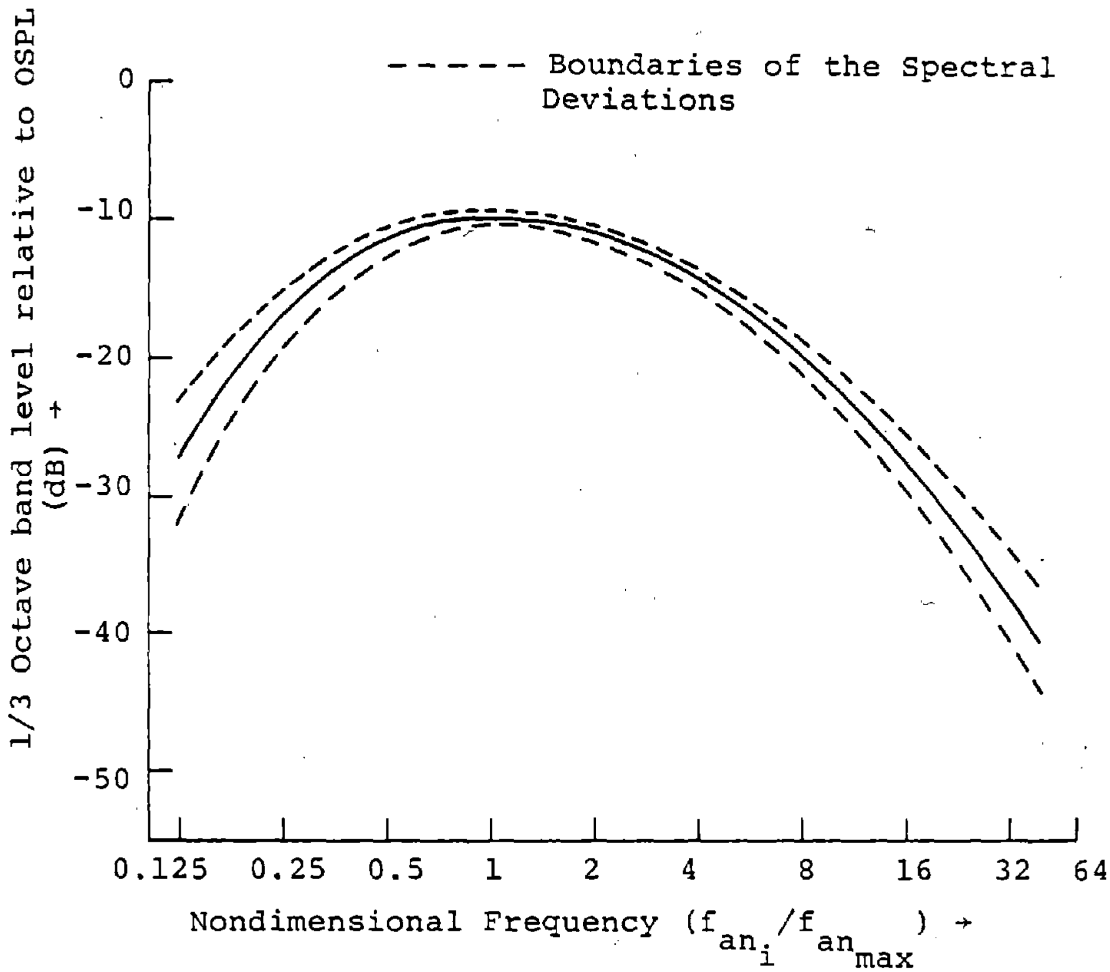


FIGURE H.1 Nondimensional Aerodynamic Noise Spectrum (Ref. 64).

TABLE H.4 AERODYNAMIC NOISE DOMINANT FREQUENCY FOR FIVE AIRCRAFT

Aircraft	Cruise Velocity (MPH)	Average Wing Thickness (ft)	Frequency Corresponding to Max Aerodynamic Noise $f_{an_{max}}$ (Hz.)
A	155	0.548	456
B	180	0.754	384
C	175	1.04	270
D	175/190	1.377	241/262
E	180/220	0.844	343/420

noise in order to be effective for communication, and hence adds to passenger discomfort.

Vent noise resembles aerodynamic noise, since it involves turbulent flow through ventilating ducts (41). Its effect is felt only in the mid to high frequency range (82), usually above 300 Hz.

Interior noise contributions from auxilliary equipment (e.g. hydraulic, electrical systems) are usually negligible in propeller driven aircraft and hence their effects are not specifically included in this study.

APPENDIX I

SPECTRAL COMPARISONS - CONTROLLED AND ENVIRONMENTAL TESTS

In this appendix, the effect of variation of noise source factors are discussed, the data for which were collected on aircraft A (Appendix A).

I.1 Ground Test

Spectral analysis of the background and gyroscope noise revealed that they are at least as low as the equipment noise (60 to 65 dB, Appendix G), which is at least 25dB below the engine noise, as shown below.

Table I.1 illustrates the relationship between engine power settings and noise level (dB_A) as a function of location. The table indicates that,

(a) noise level decreases with engine power, and

(b) ground test noise levels are higher than the corresponding flight test noise levels (Figure 5.1). This has also been observed by Metzger (83).

Typical 1/3 octave band engine noise spectra for the ground tests at the locations 1R and 3R are displayed respectively in Figures I.1 and I.2, which exhibit peaks corresponding to the engine noise frequencies (Table H.3). Further, the engine noise (no aerodynamic noise in these

TABLE I.1 THE EFFECT OF ENGINE POWER SETTING ON INTERIOR NOISE LEVEL AS A FUNCTION OF LOCATION ON GROUND TEST

Engine Power Setting, Manifold Pressure (")	Location Noise Level (dB_A)			
	1R	2L	3R	4L
19	90.25	91.75	92	89.25
21	92.5	93	94.25	92.5
23	92.75	93.75	96	92.75
Mean	91.8	92.8	94.1	91.5

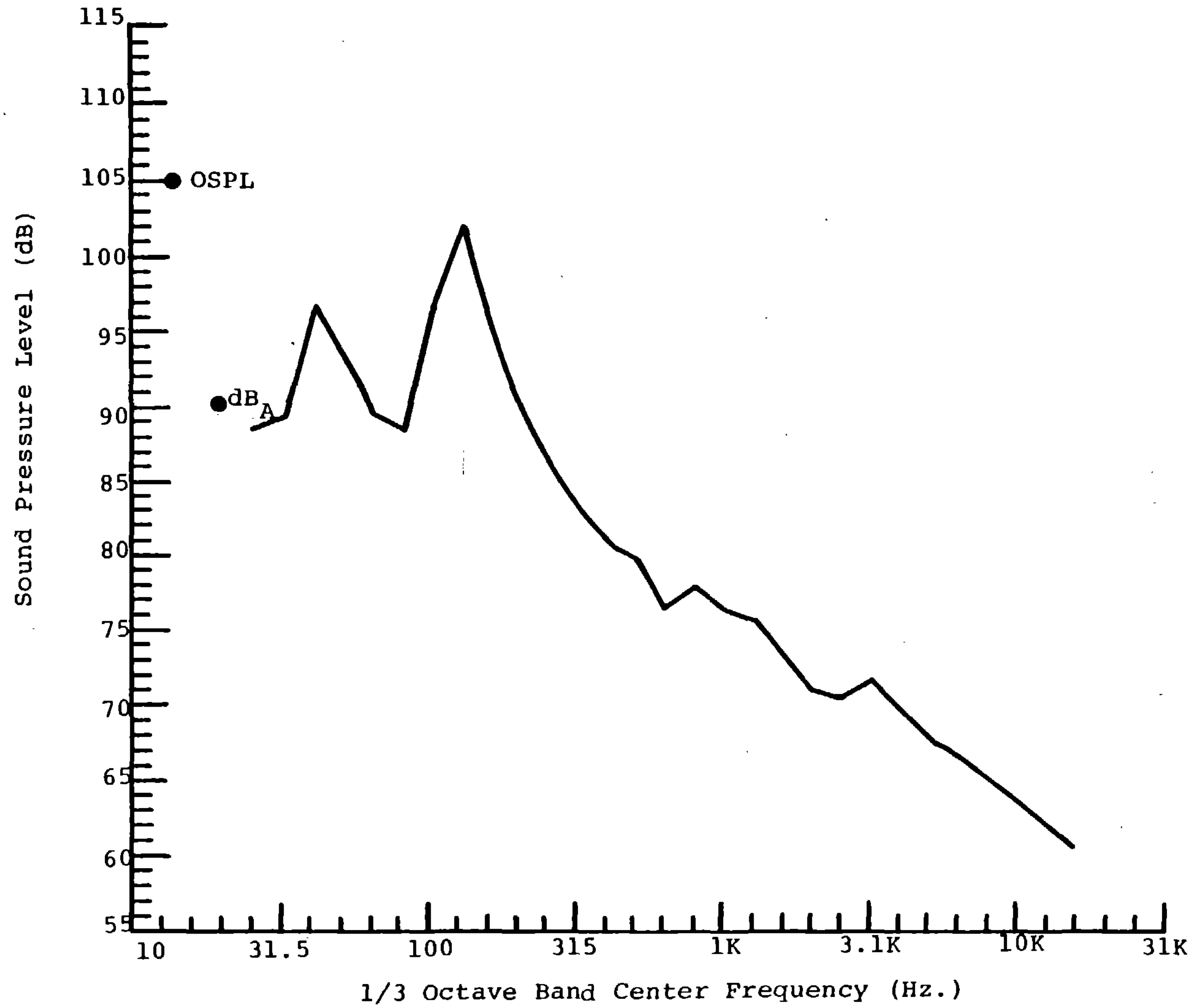


FIGURE I.1 Typical Engine Noise Spectra on Ground Test--Front Seat (Loc.1R).

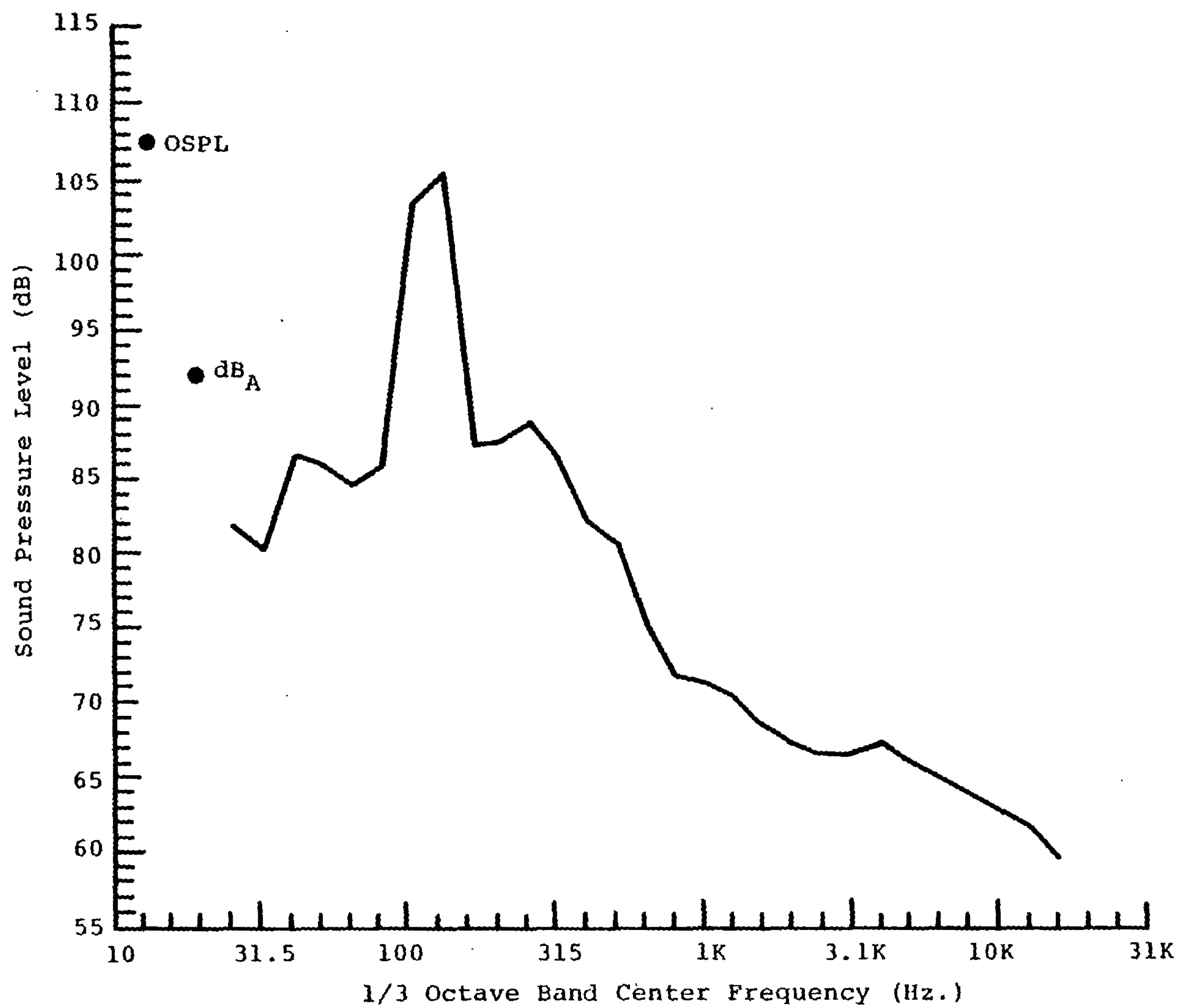


FIGURE I.2 Typical Engine Noise Spectra on Ground Test--Rear tests) shows little contribution beyond 250 Hz (drops at ∿ 40dB/decade).

I.2 Spectral Comparisons on Controlled Flights

The effect of variations of noise source factors (Table 2.5) on noise spectra and comfort responses are discussed next.

Figure I.3a illustrates the spectral difference between the segments involving cruise at 5000' and that at 9000'. Due to higher aerodynamic noise contribution (at 5000') noise levels (dB_i) beyond the 315 Hz, OSPL and dB_A are higher. The valleys at 40, 62, 125 and 250 Hz may be due to higher power requirement at 9000'. The net effect is no change in comfort response (C_s).

Spectral difference in the climb segments, (0 to 3000' and 7000 to 9000') illustrated in Figure I.3b, indicates only the effect of aerodynamic noise (> 250 Hz). Hence OSPL, dB_A and C_s are higher at lower altitudes.

The noise spectral difference between climb and descent segments is shown in Figure I.3c. It shows that during descent, the engine noise (40,125,250 Hz peaks), the aerodynamic noise (> 250 Hz), OSPL and dB_A are lower. However, due to pressure effects (pain in ear etc.), anxiety, and frequent occurrence of motion sickness (19), C_s is higher.

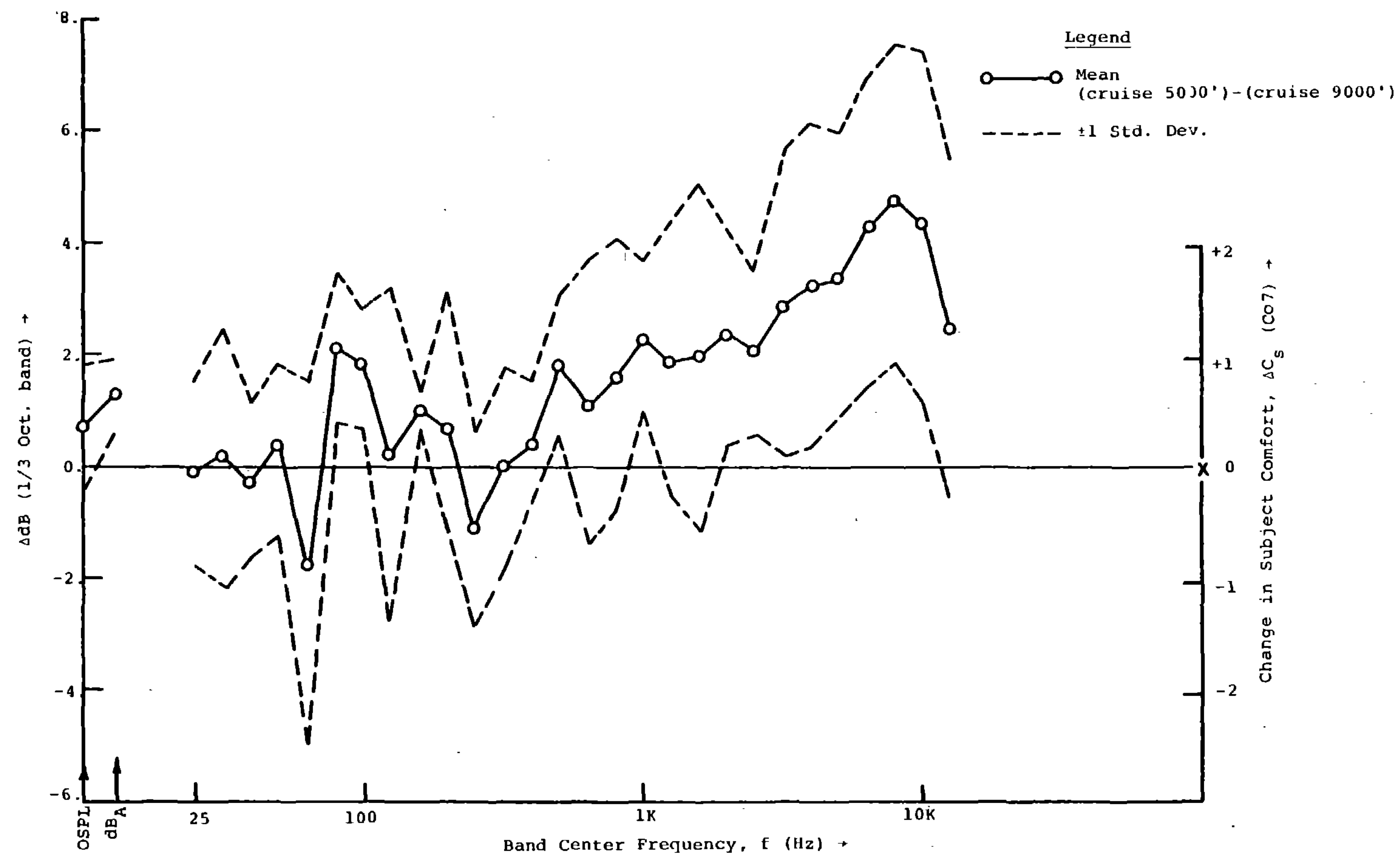


FIGURE I.3a Noise Spectra and Comfort Response Comparison of Cruise at 5000' with that at 9000'.

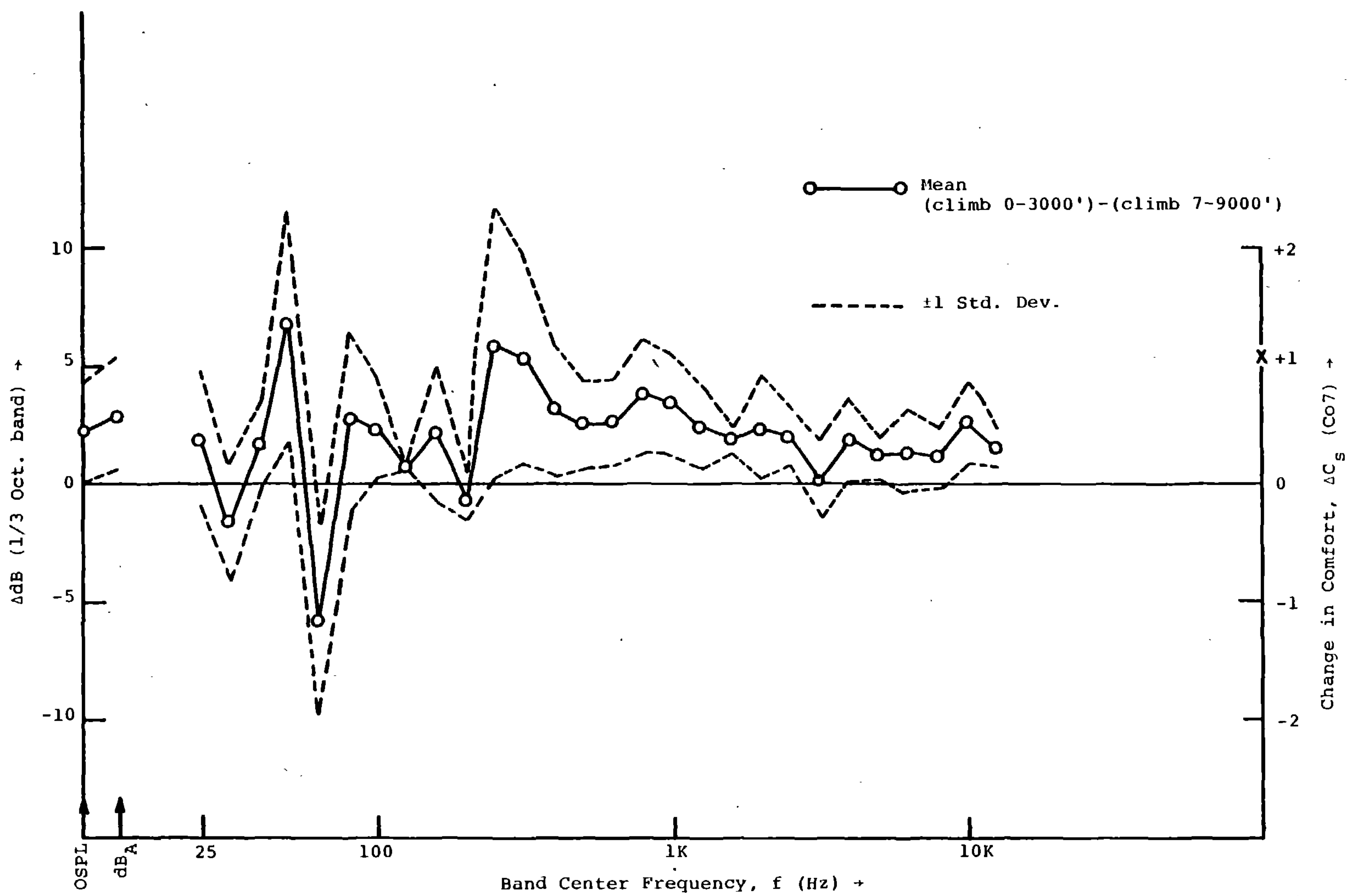


FIGURE I.3b Noise Spectra and Comfort Response Comparison of Climb from 0 to 3000' with climb from 7 to 9000'.

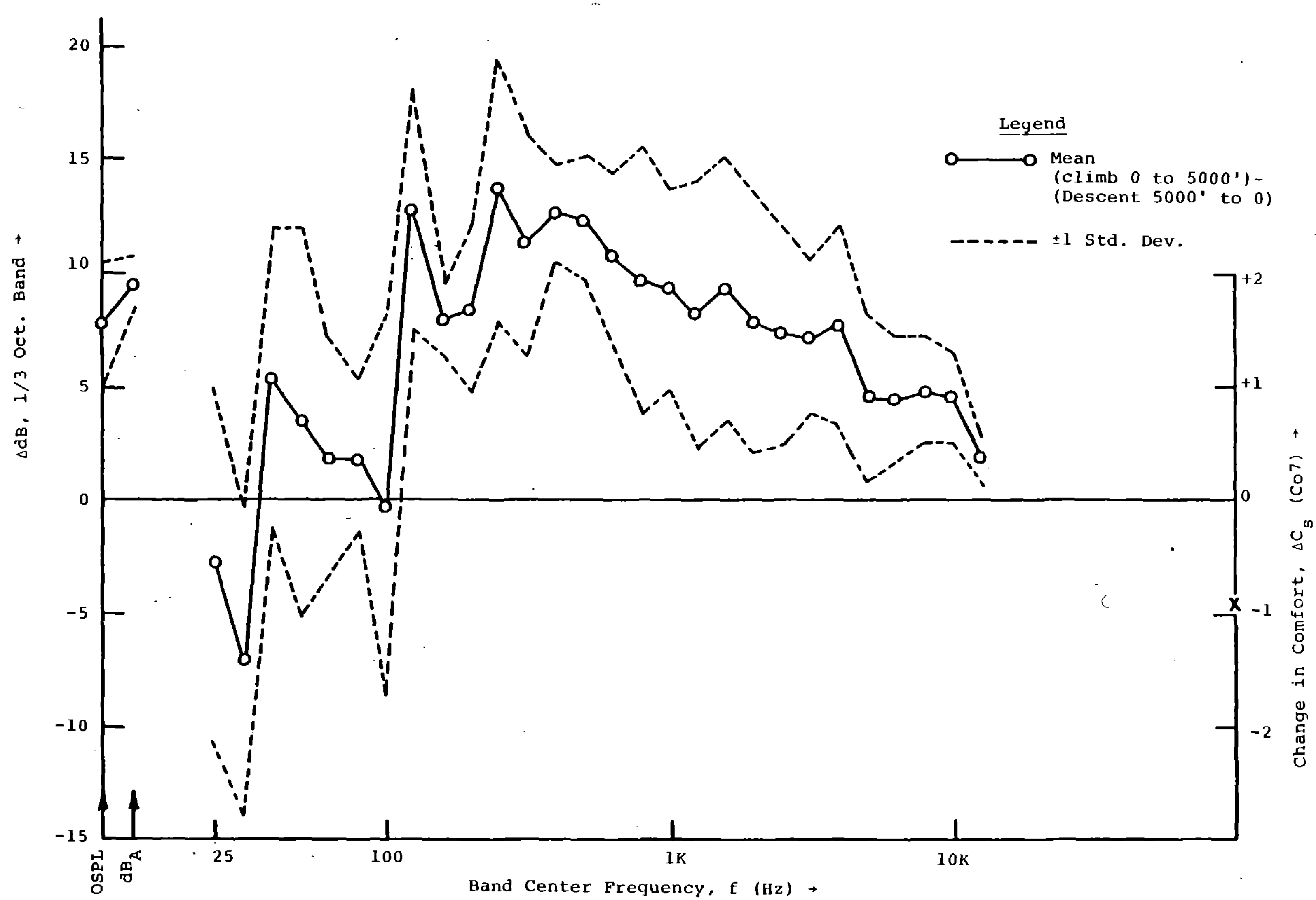


FIGURE I.3c Noise Spectral and Comfort Response Comparison of Climb with Descent.

Spectral comparison at two velocities (Figure I.3d) shows that, the engine noise (40,62,250 Hz) and OSPL are higher, and the aerodynamic noise and dB_A lower at lower velocity. Due to the dominance of mid and high frequency noise effects, a net reduction in C_s (comfort) is observed.

Spectral effects of radio (Figure I.3e) indicates that radio contributes to noise in the range of 1.25 K to 2.5 K Hz, which results in a higher dB_A, OSPL and C_s.

Although closing the vent (Figure I.3f) results in a lower OSPL and dB_A, due to a reduction in fresh air (17,19, 20) and a feeling of stuffiness, C_s increases.

No change at 125 Hz is seen at higher engine power settings (Figure I.3g), although a higher OSPL, dB_A and C_s are observed.

Inter-location noise spectral differences are shown in Figure I.4. The noise levels at all locations exceed the background noise level which shows that the noise levels at all bands are valid. Further, a consistent reduction in noise from the front to the rear is observed for OSPL, dB_A, the engine noise (125 Hz, due to relative proximity) and the aerodynamic noise [400 to 1000 Hz - also reported by Bishop (59)]. However, the inter-location differences were small (< 5dB) and were within 1 σ of the cruise noise spectra (Figure 5.4). The corresponding changes in C_s was also consistent (Figure 5.1).

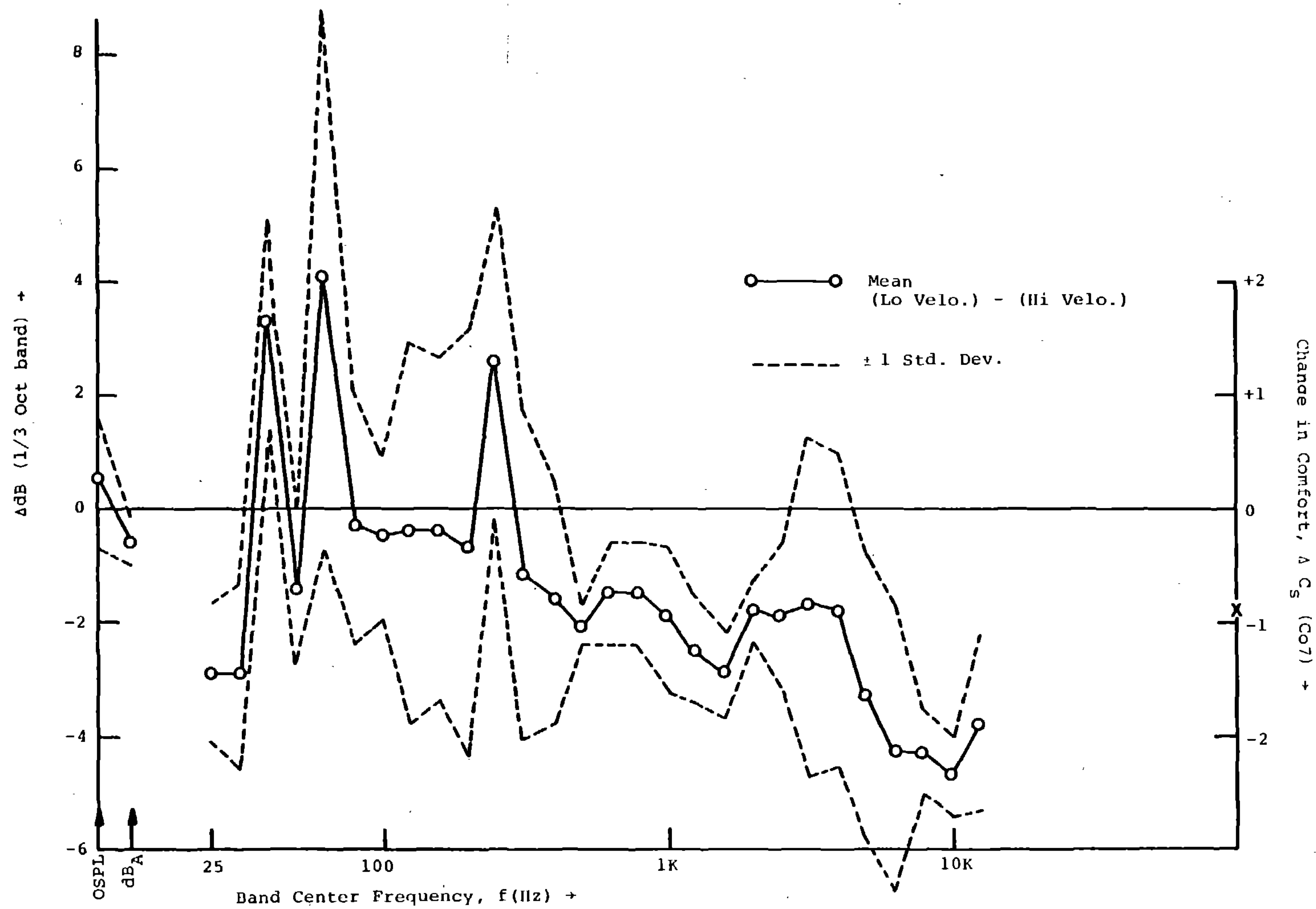


FIGURE I.3d Noise Spectral and Comfort Response Comparison of Low Velocity with High Velocity.

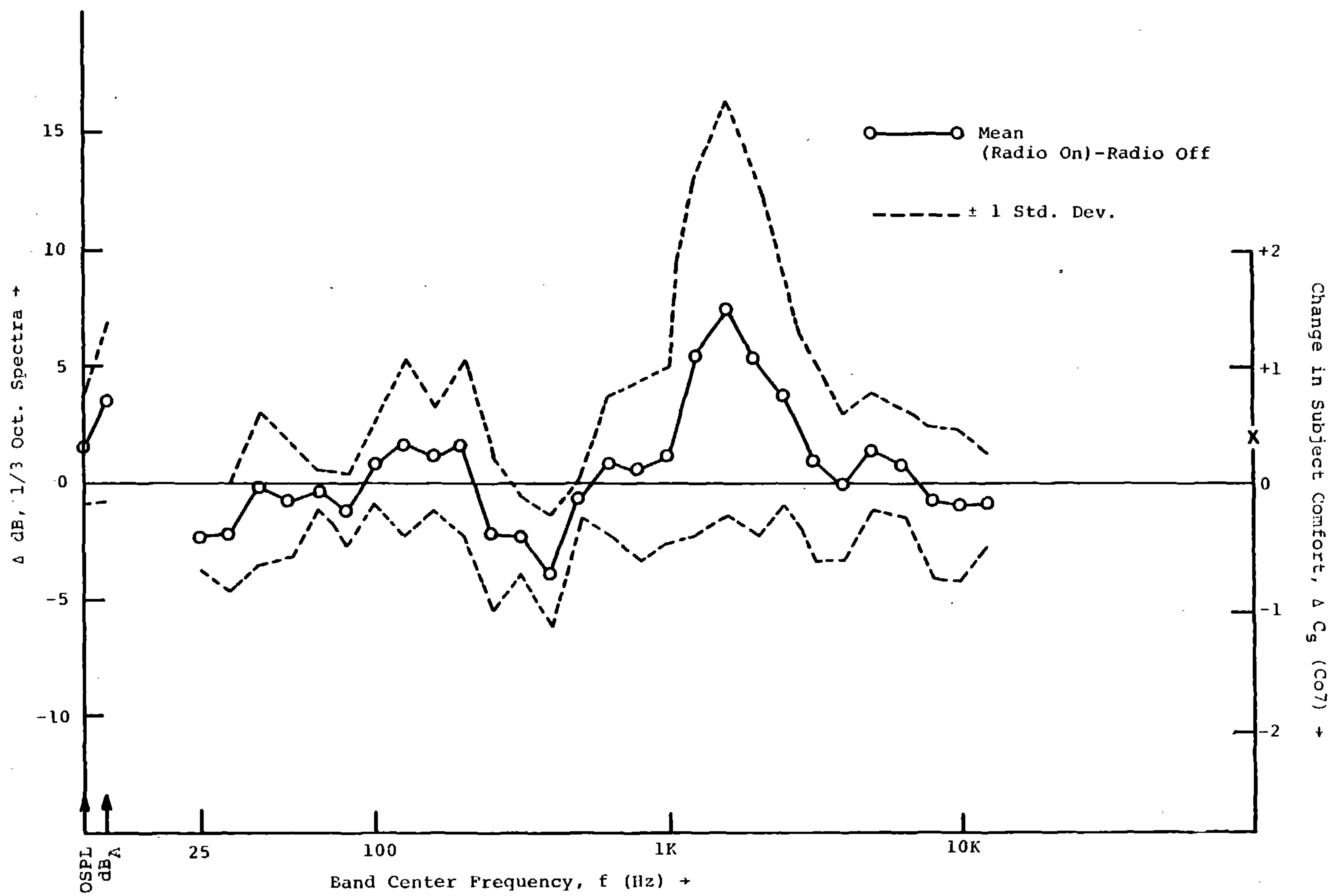


FIGURE I.3e Noise Spectral and Comfort Response Comparison of Radio on With Radio Off.

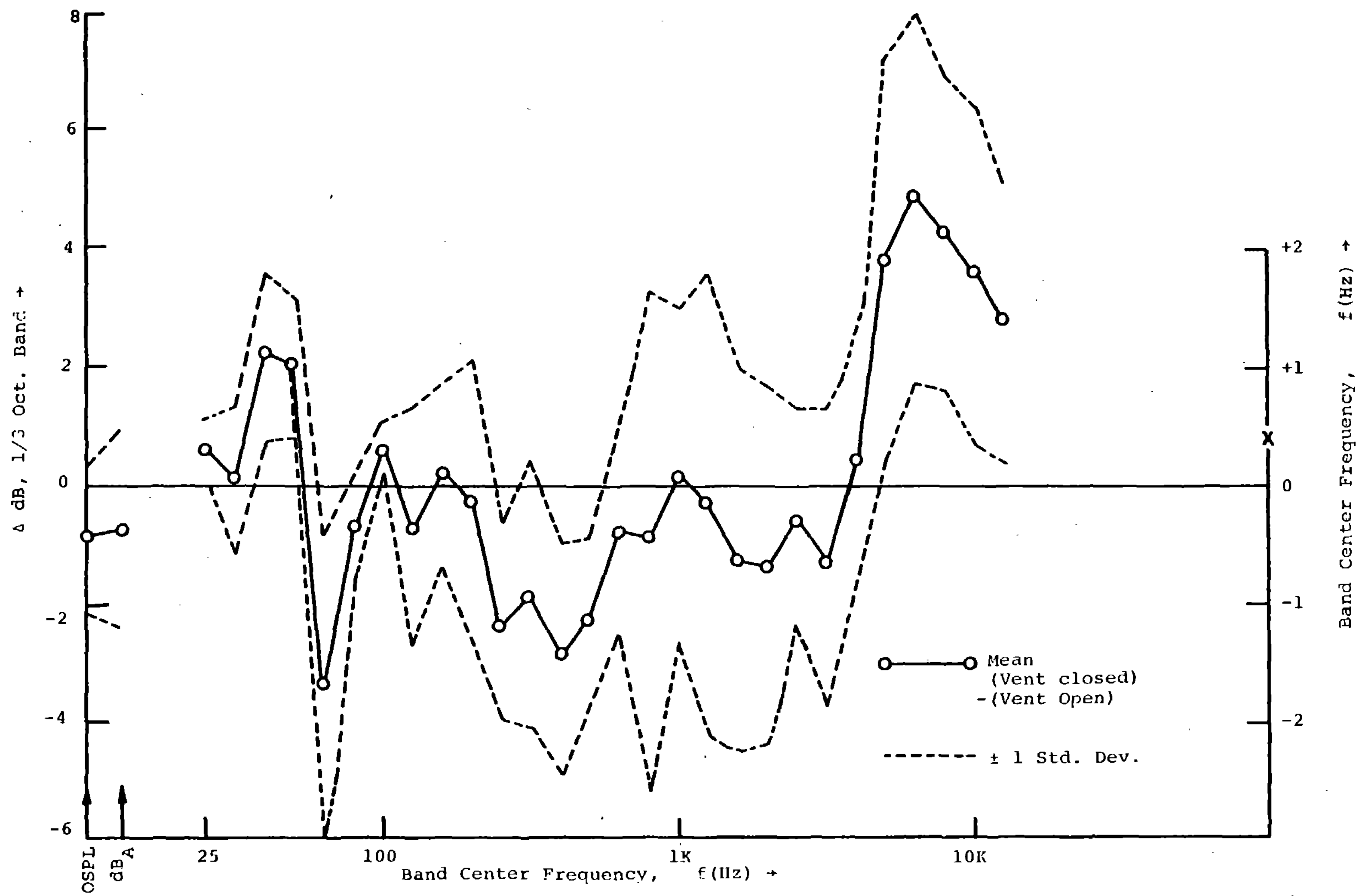


FIGURE I.3f Noise Spectral and Comfort Response Comparison of Vent Closed with Vent Open.

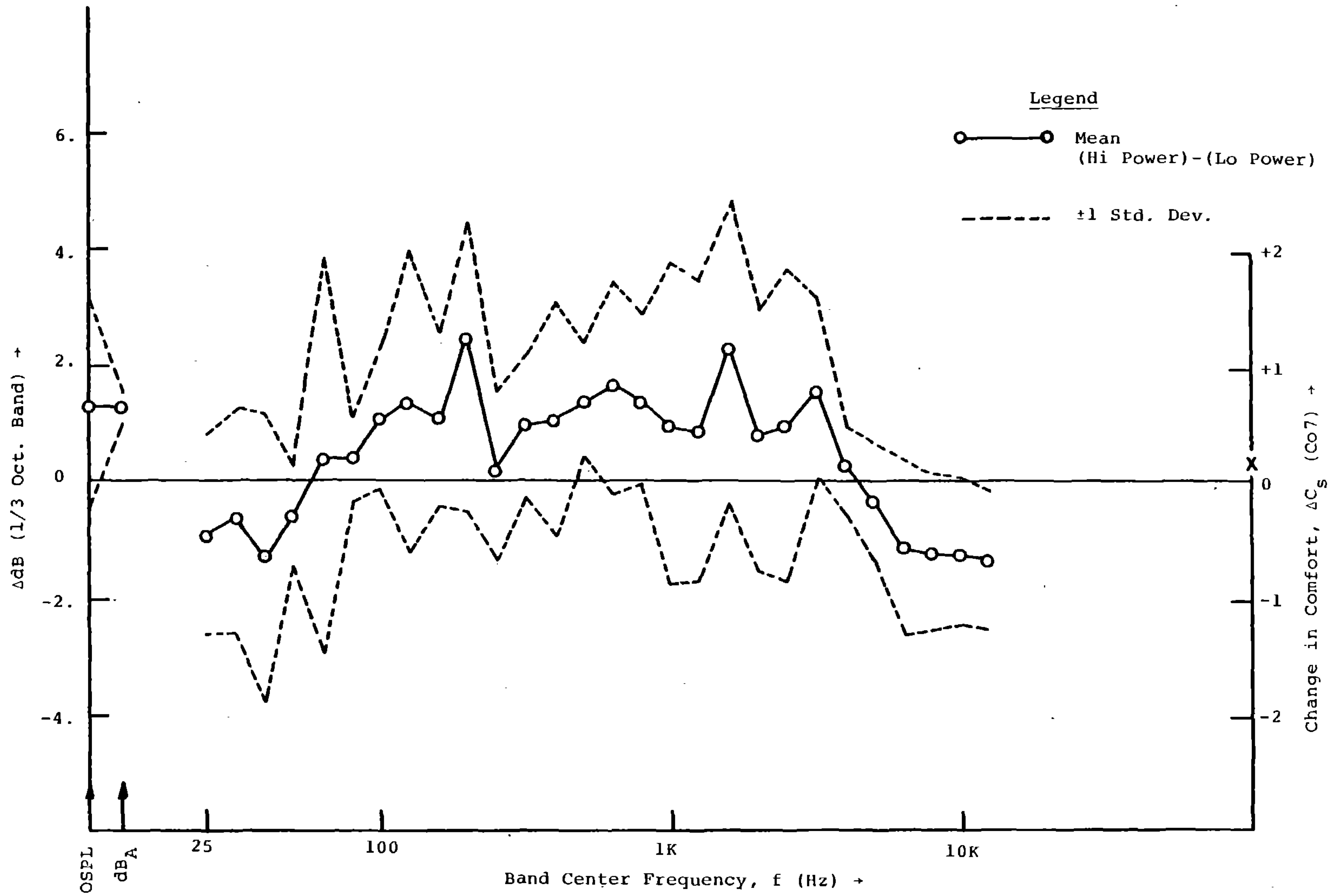


FIGURE I.3g Noise Spectral and Comfort Response Comparison of High Engine Power with Low Engine Power.

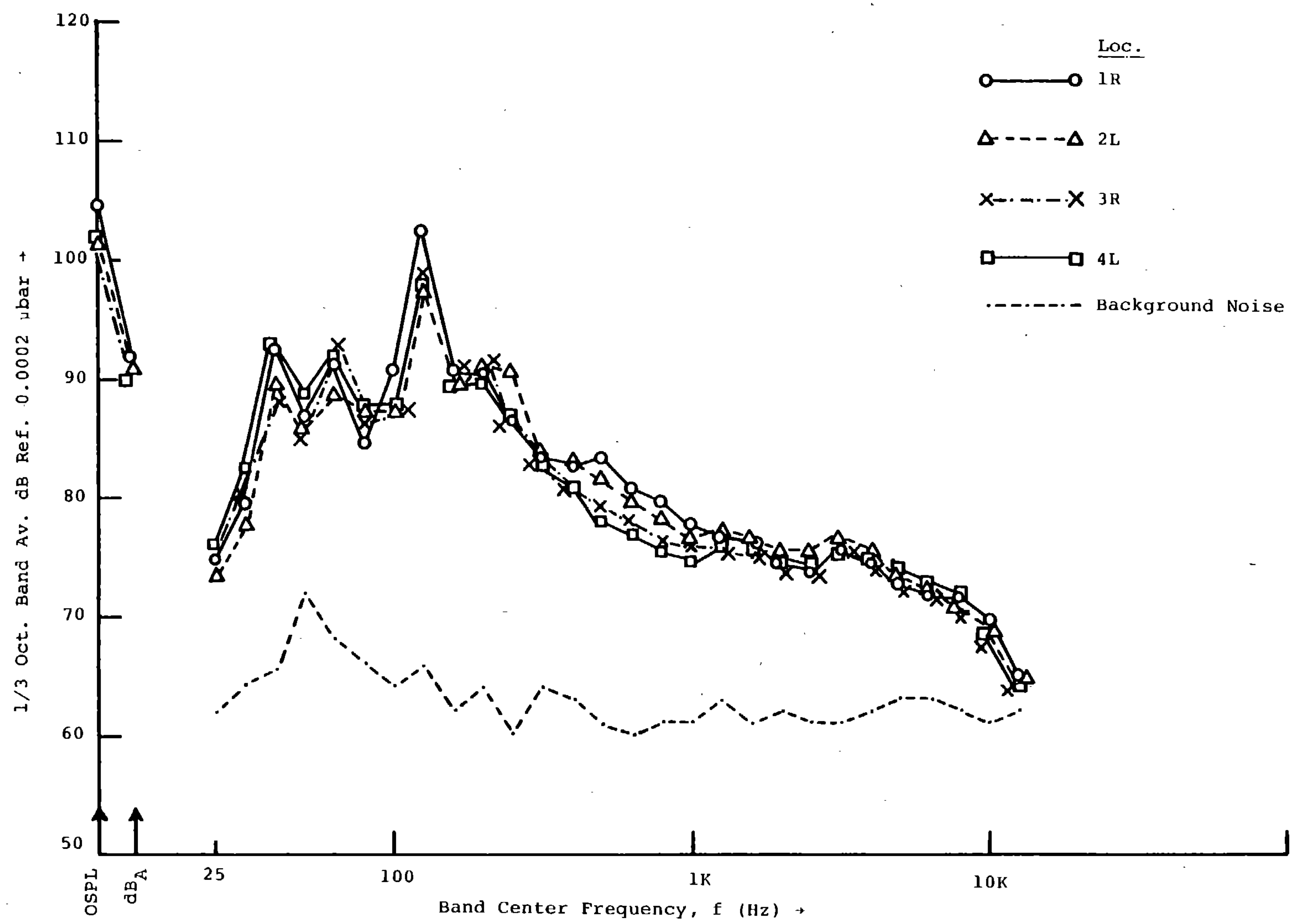


FIGURE I.4 Inter-Location Noise Spectral Comparison--Aircraft A.

APPENDIX J

EFFECT ON HEARING ABILITY

In addition to the effect of interior noise on passenger psychological responses and performance decrement, they are also exposed to noise levels which can cause hearing damage [Appendix F, Ref. (44)]. This effect is discussed next.

In the literature, many methods are available for evaluating the effect of noise on hearing; prominent among them are Damage Risk criteria (84), Effective Damage Risk criteria (26), OSHA criteria [Walsh-Healey Act, Ref. (75)], Early Loss Index (74) and Hearing Level Index (74). However, these are designed to predict the hearing loss experienced, or to protect hearing ability, at the end of the working life when people are exposed to occupational noise for eight hours every working day of their life. None of these criteria are useful in evaluating the hearing noise effects of the commuter flights.

But an EPA criteria (45) was useful in determining hearing noise effects on these flights. It establishes 70 dB_A as the long-term-energy-average-noise-limit (L_{eq_A}). This establishes a limit, on a combination of noise level, noise spectra and exposure history (Appendix F). Hence, the limit to safeguard passenger hearing ability is not only a function of the noise level and duration of exposure on the commuter flights, but also that of the noise encountered when not on the system.

The relationship between these factors to safeguard passenger hearing ability, is plotted in Figure J.1 for typical noise levels and durations experienced in commuter flights (see text). Safe exposure durations on the commuter flights are expressed in terms of the flight noise levels and the noise levels experienced when not on the system. Maximum durations for each flight noise level are also given in the figure, corresponding to the absence of non-system noise. In addition, typical daily noise exposures for office workers, housewives and children (85,86) are plotted on the figure, which can be used to determine safe noise exposures for them. Thus, a typical business traveller (office worker) should travel, on commuter flights with average noise level of $85dB_A$, no more than 122 hrs./year on an average. Similar limits can be determined for other flight noise environments and for various non-system noise exposure patterns.

Hence, a methodology for establishing permissible noise exposure has been demonstrated. These can be used to safeguard passenger hearing ability.

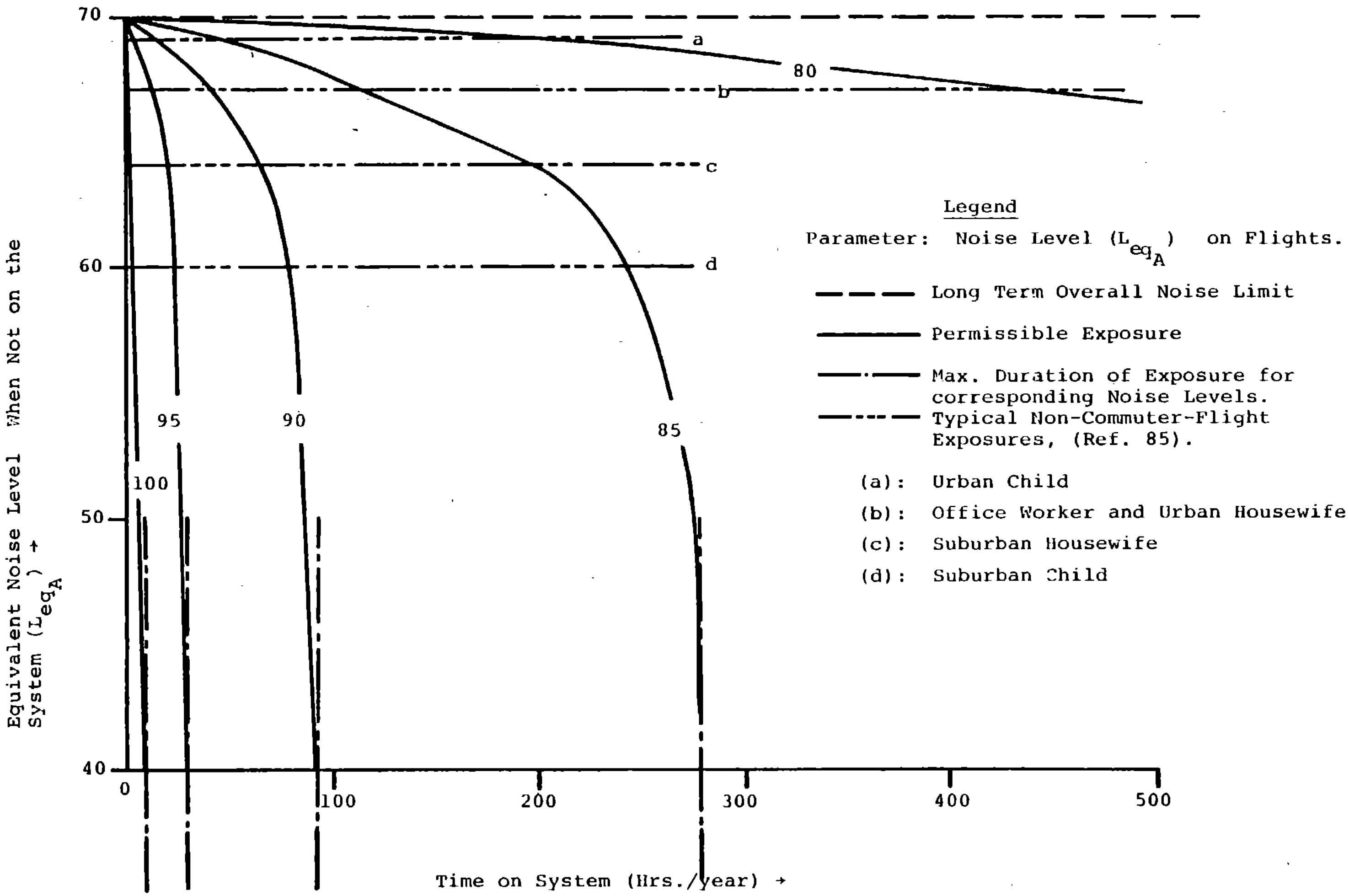


FIGURE J.1 Permissible Noise Exposure on Commuter Flights.

REFERENCES

1. I. D. Jacobson, General Aviation Technology Assessment, Rep. No. ESS-4039-103-75, University of Virginia, Charlottesville, Va., October 1975.

2. Anon, Passenger Noise Environments of Enclosed Transportation Systems, USEPA Rep. No. 550/9-75-205, Wash. D. C., June 1975.

3. Anon, Slides Presented at the General Aviation Interior Noise Workshop, Langley Research Center, NASA, Hampton, Virginia, October 6-7, 1975.

4. D. G. Stephens, General Aviation Interior Noise Studies, presented at 1976 SAE Business Aircraft Meeting, Witchita, Ka., April 6-9, 1976.

5. L. G. Richards and I. D. Jacobson, Ride Quality Evaluation: 1. Questionnaire Studies of Airline Passenger Comfort, Engonomics, 1975, Vol. 18, No. 2, pp. 129-150.

6. R. K. McMillan and H. Assad, National Survey of Transportation Attitudes and Behavior, Phase I, NCHRP Report No. 49, 1968.

7. R. K. McMillan and H. Assad, National Survey of Transportation Attitudes and Behavior, Phase II, NCHRP Rep. No. 82, 1969.

8. R. L. Creighton, Transportation and Community Values, Highway Res. Board, Special Rep. # 105, 1969, pp. 3-16.

9. I. D. Jacobson and A. R. Kuhlthau, Mathematical Modeling to Determine Criteria for Evaluating Human Acceptance of Transportation Systems, Technical Report 403206, Dept. of ESS, University of Va., August 1972.

10. J. R. Binkley, J. R. Freeman, Jr., E. D. Pittelkau and A. N. Rudrapatna, A Framework for Comparing Urban Transportation Systems, Project Report for Course # CE703, School of Engineering, Univ. of Virginia, May 5, 1975.

11. V. R. Vuchic and R. M. Stanger, Lindenwald Rail Line and the Shirley Busway: A Comparison, Highway Research Record No. 459, pp. 13-28.

12. Anon., New Jersey Dial-a-Ride System Building Ridership in Second Year, Highway Research Board, Highway Research News No. 51, 1973, pp. 24-28.

13. I. D. Jacobson, Environmental Criteria for Human Comfort - A Study of the Related Literature, Rep. No. BE-4088-101-74, University of Virginia, 1974.

14. K. B. DeGreen, ed., System Psychology, McGraw-Hill Book Co., New York, 1970.

15. K. M. Solomon, R. J. Solomon and J. S. Silien, Passenger Psychological Dynamics, American Society of Civil Engineers, Rep. No. 3, June 1968.

16. A. N. Rudrapatna and I. D. Jacobson, The Impact of Interior Cabin Noise on Passenger Acceptance, #760466 SAE Business Aircraft Meeting, Wichita, Kansas, April 6-9, 1976.

17. R. A. McFarland, Human Factors in Air Transportation, McGraw-Hill Book Co., New York, 1953.

18. Ernest J. McCormick, Human Factors in Engineering and Design, McGraw-Hill Book Co., New York, 4th Ed., 1976.

19. Melvin Calvin and Oleg. G. Gazenko, ed., Foundations of Space Biology and Medicine, Joint USA/USSR Publication, Vol. I-III, NASA, Wash. D. C., 1975.

20. J. F. Parker, Jr., V. R. West, ed., Bioastronautics Data Book, Second edition, NASA SP-3006, Wash. D. C., 1973.

21. D. W. Conner and I. D. Jacobson, Passenger Ride Comfort Technology for Transport Aircraft Situations, NASA TMX-73953, Hampton, Va., October 1976.

22. A. N. Rudrapatna, Modelling of Aircraft Ride Quality, M. S. Thesis, School of Engineering and Applied Science, University of Virginia, June 1973.

23. I. D. Jacobson and L. G. Richards, Ride Quality Evaluation 2, Modeling Airline Passenger Comfort, Engonomics, in press. (Available as STOL Mem. Rep. #403217, School of Engr. and Applied Science, Univ. of Va., December 1974.

24. A. R. Kuhlthau and I. D. Jacobson, Analysis of Passenger Acceptance of Commercial Flights having Characteristics Similar to STOL, Canadian Aeronautics and Space Journal, Vol. 19, No. 8, Oct. 1973.

25. L. G. Richards, A. R. Kuhlthau, I. D. Jacobson, Passenger Ride Quality Determined from Commercial Airline Flights, 1975 Ride Quality Symposium NASA TMX-3295, 1975, pp. 409-436.

26. K. D. Kryter, The Effects of Noise on Man, Academic Press, New York, 1970.

27. J. D. Miller, Effects of Noise on People, U. S. EPA Report # NTID 300.7, Washington, D. C., Dec. 1971.

28. R. H. Lyon, Lectures in Transportation Noise, Grazier Publishing Co., Cambridge, Mass., 1973.

29. D. O. Dickerson, ed., Transportation Noise Pollution, Control and Abatement, NASA Contract NGT 47-003-028, 1970.

30. M. H. L. Hecker et al., Comparisons Between Subjective Ratings of Aircraft Noise and Various Objective Measures, Stanford Res. Institute, Menlo Park, Ca., AD673-682, April 1968.

31. J. B. Ollerhead, Scaling Aircraft Noise Perception, Journal of Sound and Vibration,26(3), 1973, pp. 361-388.

32. S. Lippert and M. M. Miller, "An Acoustical Comfort Index for Aircraft Noise," Journal of Acoustical Society of America, Vol. 23, No. 4, 1951, p. 478.

33. D. C. Gasaway, Bioacoustic Noise Problems During Operation of C-74 Caribou Aircraft, USAF School of Aerospace Med., Brooks A.F. Base, Tex., SAM-TR-71-12, Dec. 1971.

34. S. R. Lane, Comparison of Noise Levels in Passenger Cabins of Commercial Jet Aircraft and Other Public Transportation Vehicles to Speech Communication Hearing and Health Criteria, 29500 Heathercliff Rd., Malibu, Ca., 1974.

35. D. E. Bray, Noise Environments in Public Transportation, Sound and Vibration, April 1974, pp. 16-20.

36. R. B. Stone, Cockpit Noise Environment of Airline Aircraft, Aerospace Medicine, Sept. 1969, pp. 989-996.

37. J. V. Tobias, Cockpit Noise Intensity: Fifteen Single Engine Light Aircraft, Aerospace Medicine, 40(9), 1969, pp. 963-966.

38. G. J. Kidera and P. B. Gaskill, Hearing Threshold Sensitivity in Airline Pilots, Aerospace Medicine, July 1974, pp. 780-781.

39. I. D. Jacobson and A. N. Rudrapatna, The Applicability of Special Subject Groups for Assessing Passenger Reaction to Flight Environments, Mem. Rep. #403211, NASA CR-132433, Nov. 1973.

40. I. D. Jacobson, A. N. Rudrapatna and A. R. Kuhlthau, Interior Aircraft Cabin Noise -- A Field Study, Third Interagency Symposium on University Research in Transportation Noise, The University of Utah, Salt Lake City, Utah, Nov. 12-14, 1975, pp. 84-94.

41. N. Ganesan, Evaluation of Aircraft Interior Noise, SAE, Business Aircraft Meeting, Wichita, Ka., Pap. # 740360, April 1974.

42. L. L. Beranek, Noise and Vibration Control, McGraw-Hill Book Co., New York, 1971.

43. A. Cohen, J. Anticaglia, and H. H. Jones, "Sociocusis" - Hearing Loss from Non-Occupational Noise Exposure, Sound and Vibration, Nov. 1970, pp. 12-20.

44. S. R. Lane, Reply to Criticism by V. E. Callaway of papers MM1 and MM11 at the 86th Meeting of ASA, Journal of Acoustical Society of America, Vol. 55, No. 6, June 1974, pp. 1346-1348.

45. Anon, Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety, USEPA, PB-239 429, Mar. 1974.

46. W. E. Schoonover, Jr., Ride Quality of Terminal-Area Flight Maneuvers, Ride Quality Symposium, NASA TMX-3295, Wash., D. C., Nov. 1975.

47. K. S. Pearsons and R. L. Bennett, Handbook of Noise Ratings, NASA-CR-2376, Wash. D. C., April 1974.

48. S. F. Schaedel, Human Factors in Design of Passenger Seats for Commercial Aircraft - A Review, Tech. Rep., NASA Grant No. NGR 47-005-181, University of Va., RLES Report # UVA/528060/ESS77/107, Mar. 1977.

49. C. S. Harris and H. C. Sommers, Interactive Effects of Intense Noise and Low-Level Vibration on Tracking Performance and Response Time, Aerospace Medicine, 44(9), 1973, pp. 1013-1016.

50. W. R. Pierson, Noise and Aircrew Effectiveness, Aerospace Medicine, 42(8), 1971, pp. 861-864.

51. J. H. Wafford, Guidelines for Establishing Interior Noise Level Criteria for Air Force Aircraft, Wright-Patterson A.F. Base, Aeronautical Systems Division, SEG-TR-67-57, Ohio, March 1968.

52. N. R. Draper and H. Smith, Applied Regression Analysis, John Wiley and Sons, Inc., New York, 1966.

53. L. G. Richards and I. D. Jacobson, Ride Quality Assessment III: Questionnaire Results of a Second Flight Program, Submitted to Ergonomics, Aug. 1975.

54. P. A. Liakos and S. F. Schaedel, Aircraft Motion, Noise and Passenger Comfort Data from Scheduled Commercial Airlines and Controlled Flights, Available from the Author at University of Virginia.

55. S. S. Stevens, On the Theory of Scales of Measurements, Science, 103, 1946, pp. 677-680.

56. N. H. Nie, C. H. Hull, J. G. Jenkins, K. Steinbrenner, and D. H. Bent, Statistical Package for the Social Sciences, II ed., McGraw-Hill Book Co., New York, 1975.

57. P. A. Franken and E. M. Kerwin, Methods of Flight Vehicle Noise Prediction, WADC Tech. Rep. # 58-343, Nov. 1958.

58. B. V. Bhatt and J. F. Wilby, Interior Noise Radiated by an Airplane Fuselage Subjected to Turbulent Boundary Layer Excitation and Evaluation of Noise Reduction Treatments, Journal of Sound and Vibration, 18(4), 1971, pp. 449-464.

59. D. E. Bishop, Cruise Flight Noise Levels in a Turbojet Transport Airplane, Noise Control, Mar./April 1961, pp. 37-42.

60. J. F. Wilby, An Approach to the Prediction of Aircraft Interior Noise, AIAA Paper #76-538, III AIAA Aero-Acoustic Conference, Palo Alto, Calif., July 20-23, 1976.

61. J. S. Bendet and A. G. Piersol, Measurement and Analysis of Random Data, John Wiley and Sons, Inc., New York, 1966.

62. D. C. Gasaway, Noise Within Fixed Wing Utility Aircraft Used by the Military, SAM-TR-71-43, USAF School of Aerospace Medicine, Brooks A.F. Base, Texas, December 1971.

63. J. J. Catherines and S. K. Jha, Sources and Characteristics of Interior Noise in General Aviation Aircraft, NASA TMX-72839, Hampton, Va., April 1976.

64. J. C. Hardin, D. J. Fratello, R. E. Hayden, Y. Kadman, and S. Africk, Prediction of Airframe Noise, NASA TND-7821, Hampton, Va., February 1975.

65. J. S. Gibson, Non-Engine Aerodynamic Noise: The Limit to Aircraft Noise Reduction, Presented at INTER-NOISE 73, Tech. University of Denmark, Copenhagen, 22-24, August 1973.

66. J. S. Gibson, Non-Engine Aerodynamic Noise Investigation of a Large Aircraft, NASA CR-2378, Oct. 1974.

67. G. J. Healy, Measurement and Analysis of Aircraft far-Field Aerodynamic Noise, NASA CR-2377, 1974.

68. B. Berglund, U. Berglund, T. Lindvell, Scaling Loudness, Noisiness, and Annoyance of Aircraft Noise, Journal of Acoustical Society of America, Vol. 57, No. 4, April 1975.

69. W. Lee and I. D. Jacobson, Characteristic of the Air Traveller -- A Selective Review, University of Virginia, Short-Haul Air Transportation Program, Mem. Rep. #403204, 1972.

70. J. W. R. Taylor, Ed., Janes, All The World's Aircraft, Yearbooks, London, ed. 1969-70 and 1974-75.

71. S. L. Meyer, Data Analysis for Scientists and Engineers, John Wiley and Sons, Inc., New York, 1975.

72. M. G. Natrella, Experimental Statistics, National Bureau of Standards, Handbook #91, Aug. 1963.

73. A. P. G. Peterson and E. E. Gross, Jr., Handbook of Noise Measurement, Concord, Ma., 4th Edition, 1974.

74. E. R. Hermann, Biomechanics of Human Hearing, Noise Control Engineering, Jan.-Feb. 1976, pp. 10-21.

75. Anon, Walsh-Healey Public Contracts Act, Federal Register, 34, #96, May 20, 1969, Wash. D. C.

76. M. G. Gruesbeck and D. F. Sullivan, Aircraft Motion and Passenger Comfort Data from Scheduled Commercial Airline Flights, NASA CR-2612, Wash. D. C., March 1976.

77. S. A. Clevenson, D. J. Martin and A. C. Dibble, Low-Frequency Portable Measuring and Recording System, Paper presented at the 40th Shock and Vibration Symposium, Hampton, Va., Oct. 1969.

78. J. J. Catherines, S. A. Clevenson, and H. F. Scholl, A Method for the Measurement and Analysis of Ride Vibrations of Transportation Systems, NASA TN D-6785, May 1972.

79. R. C. Ward, Dynamic Data Analysis Techniques Used in the Langley Time Series Analysis Computer Program, NASA TM X-2160, Feb. 1971.

80. H. S. Ribner, The Noise of Aircraft, In the Proceedings of the 4th Congress of the International Council of the Aeronautical Sciences, Aug. 24-28, 1964, Paris, Spartan Books, Inc., Wash. D. C., 1965, pp. 13-72.

81. H. S. Ribner, Noise Generation Mechanisms, Canadian Aeronautics and Space Institute Journal, Vol. 12, Jan. 1966, pp. 1-6.

82. H. W. Rudmose and L. L. Beranek, Noise Reduction in Aircraft, Journal of Aeronautical Sciences, Feb. 1947.

83. F. B. Metzger, B. Magliozzi, R. J. Pegg, SAE Business Aircraft Meeting, Paper #760454, Wichita, Ka., April 6-9, 1976.

84. K. D. Kryter, W. D. Ward, J. D. Miller, D. H. Eldridge, Hazardous Exposure to Intermittent and Steady-State Noise, Journal of Acoustical Society of America, #39, 1966, pp. 451-464.

85. Anon., Impact Characterization of Noise Including Implications of Identifying and Achieving Levels of Cumulative Noise Exposure, USEPA, NTID 73-4, July 27, 1973.

86. Anon., Transportation Noise and Noise from Equipment Powered by Internal Combustion Engines, Wyle Labs., Inc., USEPA, NTID 300.13, Dec. 31, 1971.

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