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DEVELOPMENT OF TECHNIQUES AND DATA FOR EVALUATING RIDE QUALITY
Volume II: Ride-Quality Research

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16. Abstract

Ride-quality models for city buses and intercity trains are presented and discussed in terms of their ability to predict passenger comfort and ride acceptability.

This, the second of three volumes, contains a technical discussion, of the ride-quality models developed during the research effort using the data gathered on city buses and intercity trains. The methods and procedures employed to derive the models are also presented, together with examples of how models are used to evaluate the ride quality of existing and future transportation systems. The raw data used as a basis for the models are presented in the appendixes to this volume.

Volume I is a summary, and Volume III contains procedural guidelines to be employed by transportation specialists in developing ride-quality models and in using them to evaluate passenger comfort in existing or future systems.

17. Key Words

Ride Quality (Bus/Train)
Passenger Comfort
Ride Acceptance
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PREFACE

This study of ride quality, which developed predictive models of passenger comfort and ride acceptability, was conducted by Dunlap and Associates, Inc., under Contract No. DOT-TSC-1090 in close cooperation with the University of Virginia as subcontractor. The project was under the direction of Dr. Richard D. Pepler, Vice President of Dunlap and Associates, Inc. The design and conduct of the field data collection was the prime responsibility of Mr. Leroy L. Vallerie, Principal Associate of Dunlap and Associates, Inc., and the data analysis and model development was the responsibility of Dr. Ira D. Jacobson, Associate Professor, Department of Engineering Science and Systems, University of Virginia. Mr. Vallerie was supported by Ms. Joan M. Edwards, and Messrs. Charles A. Goransson and John J. Henschel of Dunlap's professional staff. Dr. Jacobson was assisted by Drs. Richard W. Barber and Larry G. Richards and by Messrs. Steven Troester, Steven Schaedel and George Cushnie of the University of Virginia.

The success of the project depended on help of many kinds from many people. In particular, we would like to acknowledge the cooperation and assistance received from Mr. Charles Abell, Mr. Raymond Binheimer and the bus drivers of Connecticut Transit in arranging for and collecting data on city buses during the experimental trials and on regular scheduled services. Similarly, we thank Mr. Joseph Schmidt, Mr. Ross Higginbotham and Mr. Robert Breese in Washington and Mr. Thomas Fortier and Mr. Tim Salveson in the Hartford office of the National Railroad Passenger Corporation (AMTRAK) for their assistance in arranging our use of selected passenger rail cars and in contacting AMTRAK passengers. We are especially grateful to those men and women who volunteered to participate in our experiments and to those groups of passengers on scheduled services who had agreed in advance to provide additional ride quality data.

Finally, we would like to express appreciation for the support, guidance and encouragement that we received from Dr. E. Donald Sussman, Technical Monitor and Ride Quality Project Manager, and Mr. Edward A. Sands, Contracting Officer, Transportation Systems Center, U.S. Department of Transportation; and from Dr. Robert J. Ravera, Transportation Advanced Research Program (TARP) Manager, Office of Systems Engineering, Office of Secretary, U.S. Department of Transportation, Washington, D.C.

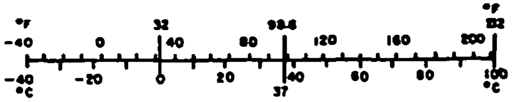
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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SYMBOLS AND ABBREVIATIONS

a_T = RMS transverse acceleration of vehicle

a_V = RMS vertical acceleration of vehicle

a_L = RMS longitudinal acceleration of vehicle

ω_R = RMS roll rate (rotation around longitudinal axis)

ω_P = RMS pitch rate (rotation around transverse axis)

ω_Y = RMS yaw rate (rotation around vertical axis)

m_T = mean transverse acceleration (sustained component)

m_Y = mean yaw rate (sustained component)

g = gravities, or 9.8 meters per second squared

°C = degrees Celsius

°F = degrees Fahrenheit

R^2 = the proportion of variance in comfort judgments "explained" by regression equation; the square of the multiple correlation coefficient.

dB(A) = decibels measured using the A-weighting system

deg/sec = degrees per second, a measure of angular velocity

RMS = root mean square; the data are processed to remove the long time constant (the mean)

$\bar{C}$ = mean comfort rating (empirically derived)

C' = mean comfort response predicted by a model

CPR = predicted comfort response

α = the level of significance for a hypothesis test

σ = standard error of the coefficient

E_β = that value of a variable (say roll, ω_R) such that some percent in the sample lies within the range $\bar{\omega}_R \pm E_\beta$, that is within E_β units from $\tilde{\omega}_R$.

GLOSSARY

ACCEPTABILITY: Degree to which a vehicle or system will be used by passengers.

BANDWIDTH: Range of frequences contained in a given motion.

COMFORT: A subjective state of the passenger, assessed in the present research with a seven-point rating scale.

DECIBEL: A unit of measurement of sound intensity or power level.

EXCEDANCE COUNTS: Number of times a variable exceeds some chosen level in some unit of time.

FACTOR ANALYSIS: A set of techniques for determining the dimensionality of a set of variables, usually by finding the rank of the matrix of intercorrelations among the variables.

g-LEVEL: Amount of acceleration referred to the acceleration of gravity.

JERK: Rate of change of acceleration, usually pertains to the longitudinal direction.

LATERAL DIRECTION: In an x, y, z coordinate system, with x oriented in the direction of travel of the vehicle, and z oriented perpendicular to the plane of the vehicle and idrected into the supporting surface, the y axis represents the lateral direction.

LONGITUDINAL DIRECTION: In an x, y, z coordinate system, with x oriented in the direction of travel of the vehicle, and z oriented perpendicular to the plane of the vehicle and directed into the supporting surface, the x axis represents the longitudinal direction.

MODEL: A mathematical (abstract) representation of some object, event or process.

PEAK VALUE: The maximum value of a variable.

PITCH: Rotation about the lateral axis (see lateral direction).

POINT OF PERCUSSION: Point about which vehicle can be considered to be in pure rotation giving rise to equivalent motion.

ROLL: Angular motion about an axis in the direction of travel, i.e., the x axis in the coordinate system adopted in this report (see longitudinal direction).

RMS: Root mean square of a variable.

SPECTRUM: The distribution of the values of any quantity.

TRANSVERSE DIRECTION: In an x, y, z coordinate system, with x oriented in the direction of travel of the vehicle, and z oriented perpendicular to the plane of the vehicle and directed into the supporting surface, a transverse direction would be somewhere in the yz plane.

VEHICLE INPUT: The inputs to the vehicle from external sources, e.g., road roughness, track irregularities, winds, turbulence, sea state, etc.

VERTICAL DIRECTION: In an x, y, z coordinate system, with x oriented in the direction of travel of the vehicle, and z oriented perpendicular to the plane of the vehicle and directed into the supporting surface, the z axis represents the vertical direction.

YAW: Rotation about the vertical axis (see vertical direction).

I. INTRODUCTION

For many years, transportation specialists have recognized the need to develop a quantitative tool for measuring and evaluating the ride quality of existing and proposed vehicles. Such a tool would permit them to compare the relative merits of two competing systems, to write vehicle specifications and to initiate cost effective design changes. Currently, designers and planners of transportation systems must rely on the use of comparative "as good as" criteria, subjective rating methods and guidelines established for human tolerance to vibration, none of which can reliably be employed to assess or predict passenger comfort or acceptability of ride.

A. Background

In general, the existing guidelines for ride quality provide little information that can be used for tradeoff analysis or design purposes. In fact, none of the guidelines has been validated on actual vehicles in the field. The most well known guidelines available are those presented by the International Standards Organization (ISO) (1969). These guidelines present acceleration/frequency curves for three linear degrees of freedom which are not to be exceeded for acceptable ride comfort. As will be shown in this study, there is no reason to believe that this method of assessing ride quality should apply in cases where any of the angular degrees of freedom become important. In addition, the guidelines give no means of combining vibration in more than one degree of freedom, the assumption being that they are independent and not additive. This is intuitively difficult to accept. The applicability of present day guidelines is reviewed by McKenzie and Brumaghim (1976).

Ride quality research through 1972 has been reviewed in Jacobson (1974). Most of the relevant work since then has been summarized in the proceedings of the first and second ride quality symposia (NASA, 1972 and 1975). Until most recently, the study of ride quality was undertaken as a laboratory exercise, primarily to determine the influence of vibration (almost exclusively in the vertical direction) on subjective judgments of motion and comfort. More recent laboratory work (Dempsey, 1976a and b; Stone, 1975) using simulation facilities at Langley Research Center is aimed at determining the way in which various components of motion, as well as noise, combine to influence subjects' judgment of comfort.

Field studies aimed at determining the comfort of passengers have also been conducted. Most of the work has been carried out in this country by Jacobson and Richards (1975, 1976 and 1977) and Kuhlthau and Jacobson (1972). In the United Kingdom, Clarke and Oborne (1975 and 1976) have studied passenger reaction to public service vehicles, particularly cross-channel hovercraft, helicopters and trains. Manenica and Corlett (1973) assessed rider reaction to traveling on a hovercraft and a local bus service. In Japan, panels of experts have been employed to evaluate specific vehicles (Miwa, 1967).

Richards and Jacobson (1975 and 1977) surveyed airline passengers concerning their reactions to the flight environment and their perceptions of factors influencing their level of comfort. On one questionnaire, passengers were asked to rank the importance of various factors in influencing their comfort; seat factors were seen as most important, followed by noise, temperature and motion. A second questionnaire allowed passengers to indicate the degree of discomfort they associated with each of a set of environmental factors. These passengers also rated the comfort of their flight and their satisfaction with the trip. Ratings concerning noise, vibration, motion and seat variables were significantly associated with comfort judgments and trip evaluation. Passenger comfort was also strongly related to willingness to fly again. Comfort helped determine the acceptability or attractiveness of the mode of transportation, in this case, aircraft.

Jacobson and Richards (1976 and 1977) obtained continuous recordings of the motion characteristics of planes while test subjects rated their level of comfort at intervals throughout the flight. Regression equations in the form of ride quality models, involving RMS values for vertical and transverse accelerations, were found to predict the comfort ratings of the test subjects.

Jacobson, Kuhlthau and Richards (1975) showed how quantitative models of this sort could be used as a tool by system designers and evaluators to evaluate or predict passenger satisfaction with the ride environment of a vehicle. The general method, as outlined, has been proposed as a general approach to ride quality evaluation (McKenzie and Brumaghim, 1976) in other contexts. This approach was used in the current research effort involving city buses and inter-city trains.

B. Research Objectives

The goal of this program of research was to develop quantitative models of the subjective reaction to the ride environment of city buses and inter-city trains using field data obtained from both paid subjects as well as regular passengers. The goal has been to develop a model which can be used for a variety of purposes. Among these are:

- Provide a quantitative basis for ride quality specifications.
- Evaluate ride environments on current transportation vehicles.

Provide tradeoff data on alternative design approaches.

Evaluate relative effectiveness of roadbed (guideway) vs. vehicle specifications in providing acceptable ride quality.

To meet these aims, the program was designed to have several objectives. These were:

Collect field data on passenger comfort responses to bus/train ride environments.

Generate ride quality model(s) able to predict comfort responses from vehicle motion inputs.

Validate model(s) using data from passengers on commercial services.

The model(s) developed in this program are not meant to apply to all transportation vehicles--past, present and future; rather, they are specific to the city bus and inter-city train. There has been some attempt, as discussed below, to develop a composite model for hybrid types of transportation systems that might be applied more broadly than any of the vehicle specific models. More work is needed, however, on combining the data for many transportation modes (e. g., air, high speed train, automobile and ship) to evolve a general model for predicting the reactions of passengers to future systems.

II. METHOD

The goal of the program of research was to develop ride quality models for city buses and inter-city trains that can accurately predict those levels of vehicle motion considered both comfortable and acceptable to the majority of potential passengers. To achieve this goal, the research program was carried out in two phases as shown in Figure II-1. The first phase dealt with model development and the second phase dealt with model validation. Both phases included the collection of data on passenger comfort and vehicle motion. In Phase 1, selected riders were employed to judge ride comfort and acceptability over a wide range of vehicle motion conditions. Independent variables associated with the vehicles' ride environment and subject characteristics were carefully controlled in experimental settings. In Phase 2, actual passengers provided the judgments of ride comfort and acceptability on vehicles in actual revenue service. In this way, it was possible to validate the models developed in Phase 1.

A. Research Design

The passenger's perception of ride comfort and acceptability depends on the ride environment and on his own physical and psychological characteristics. The ride environment consists of a large number of variables which fall into three major categories: the external inputs to the vehicle, the characteristics of the vehicle itself, and the internal environmental conditions to which the passenger is exposed. Figure II-2 illustrates these three categories as well as the procedures used to measure and control them.

In Phase 1, a wide range of these external variables and vehicle characteristics were included in the research design; otherwise, models would be developed using too limited a sample of the ride environments for the particular transportation mode. Also, selected variables, e. g., temperature, noise, time duration and sequence, known to influence the ride environment and passenger comfort, were systematically controlled in accordance with good experimental practices. In this way, any possible effects of the order in which ride motions change that might bias passenger judgment of ride comfort were attenuated, and the major external and vehicular variable(s) responsible for the differences in vehicle motion identified.

Both the physical and psychological traits of passengers are known to influence their perceptions of comfort and ride acceptability. Passenger traits per se and their influence on ride comfort were not of primary interest in this research effort. Nevertheless, age, sex and riding experience, known to influence passenger judgment of ride quality, were accounted for in Phase 1 of the study by stratifying riders with these traits across the various experimental conditions in a systematic manner. In this way, it was

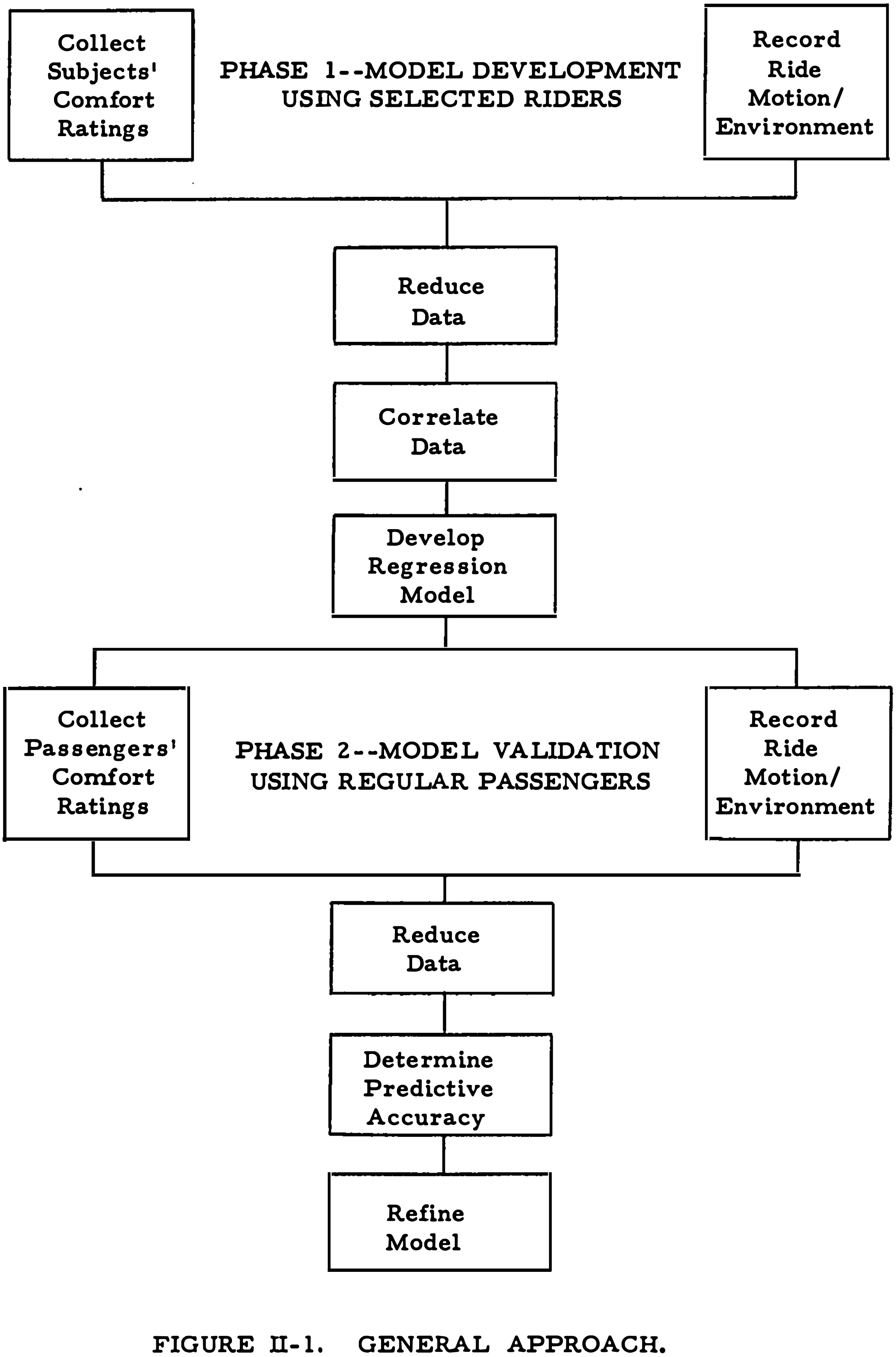

FIGURE II-1. GENERAL APPROACH.

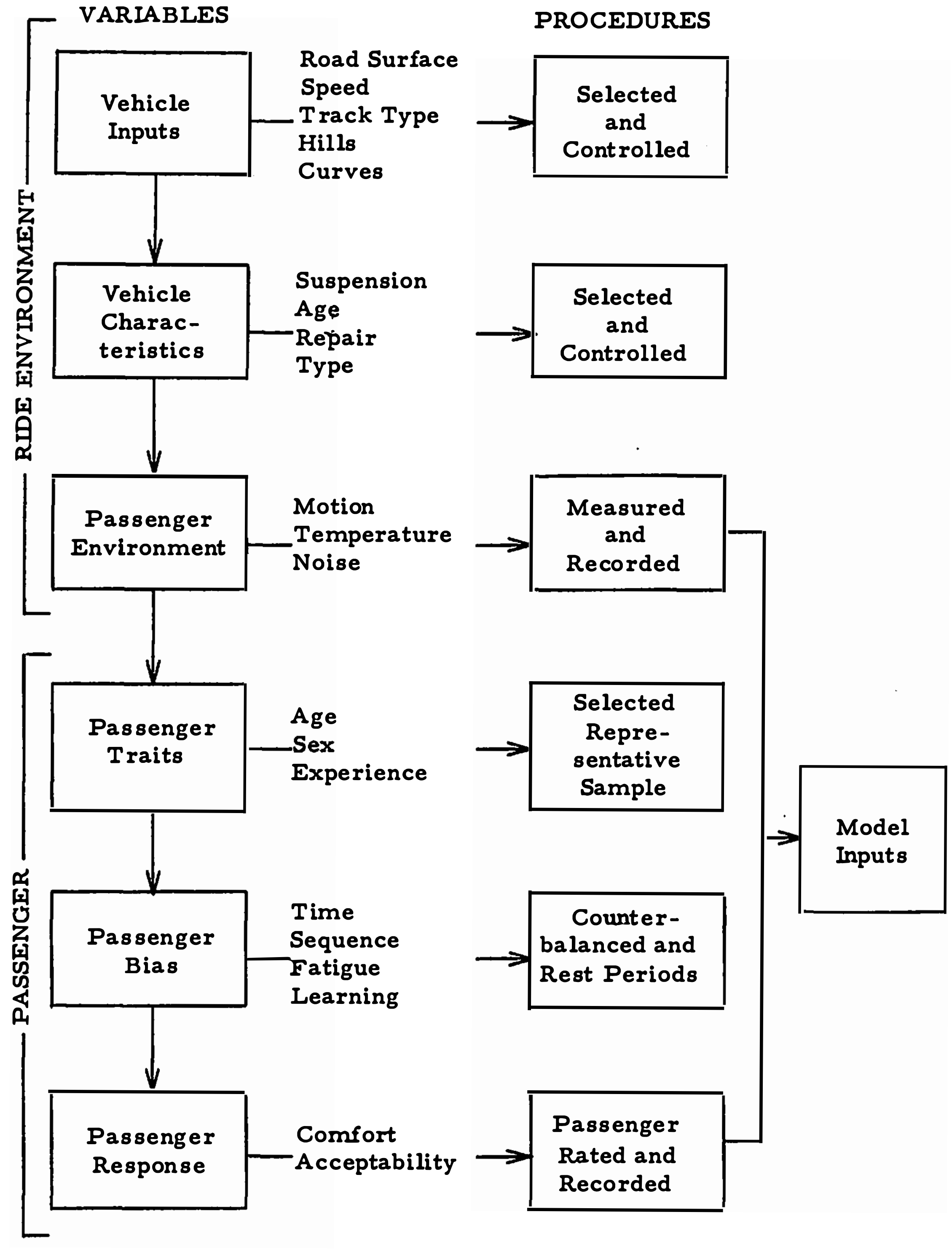

FIGURE II-2. GENERAL RESEARCH DESIGN.

possible to ensure that the selected riders were representative of the traveling public.

1. Phase 1 Bus Study

The design used for the development of the bus models during Phase 1 is shown in Table II-1. In this design, a route was carefully selected so that it contained good, intermediate and bad road surfaces in terms of smoothness and condition of repair, as judged and measured by the experimenter. A total of nine road segments, three of each surface condition, were presented to two groups of approximately 30 subjects each, using two different buses, one with good suspension and the other with poor suspension, as determined by vehicle, age and condition of repair. Subjects were selected to represent approximately equal numbers of males and females; young, middle-aged and older persons; and frequent and infrequent riders of city buses. To attenuate order effects, the sequence of segments was different for each bus. Each segment lasted approximately one minute, during which time vehicle motion, noise, temperature and speed were recorded, and the subjects rated ride comfort on a seven-point scale, as described in Section II. C. Average time between segments was approximately five minutes. Subjects were given a 20-minute rest period after completion of the first nine segments on one bus (about one hour) and before starting the next nine segments on the next bus.

Since different ride quality models might be appropriate under different driving situations, data were collected under several types of conditions: straight/level roads and hills, curves and acceleration/deceleration. Section III. A. discusses the results of the straight/level roads and hills experiments as well as those for acceleration/deceleration (Part 1). Section III. D. discusses the curved roadway experiments (Part 2). The above design was replicated for Part 2, using two additional subject groups each consisting of 30 subjects.

2. Phase 1 Train Study

Essentially the same design was used for the train study as shown in Table II-1. for buses. The train study utilized four different passenger coaches on the New York City to Boston train line between Stamford and New London, Connecticut. Since it was impossible to control the route in this case, data were gathered for one-minute segments at intervals of four to six minutes for the duration of the trip. Again, different coaches were used with different suspension characteristics. The train route included a good cross-section of track characteristics, with some good and some poor track, welded and unwelded sections, and switch areas. Two matched groups of 30 subjects each were employed to provide comfort data during the Phase 1 train study. As in the bus study, subjects were selected to represent approximately equal numbers of males and females; young, middle-aged and older persons; and frequent and infrequent riders of trains.

TABLE II-1. PHASE 1 DESIGN FOR PARTS 1 AND 2 OF THE BUS STUDY.

Route Segment*	Group A (30 Subjects)		Group B (30 Subjects)	
	Bus P	Bus G	Bus G	Bus P
1	a	b	a	b
2	b	a	b	a
3	c	c	c	c
4	b	a	b	a
5	c	c	c	c
6	a	b	a	b
7	c	c	c	c
8	a	b	a	b
9	b	a	b	a
Total:	9	9	9	9 = 36

36 Segments x 30 Subjects = 1080 Comfort Ratings**

* Each road segment was approximately 1 minute in duration.

** Design was replicated for Part 2--curved roadways.

a Good (smooth, new) surface condition

b Intermediate (some cracks, holes) surface condition

c Bad (pot holes, bumps, needs repair) surface condition

P Poor Suspension (> 10 years old and in poor repair)

G Good Suspension (< 2 years old and in good repair)

3. Phase 2 Bus Validation Study

In an attempt to assess and validate the ride quality model developed on the initial bus data gathered during Phase 1, additional data were collected from volunteer passengers on regularly scheduled city, commuter buses operating in the Hartford, Connecticut, area. Data were gathered in the morning and afternoon on two consecutive days. There were 113 passengers in all; 59 male and 54 female; 101 of them used the bus daily and represented a wide range of age levels (16-24 years, 15 persons; 25-34, 44 persons; 35-48, 31 persons; 49 and older, 23 persons). Since the bus routes were established and fixed, motion characteristics were not under experimental control. Less extreme motions were therefore to be expected for this study. Data were obtained on a total of 29 segments of road.

4. Phase 2 Train Validation Study

Attempts to obtain train validation data resulted in only limited success. On two occasions, the data collection effort had to be aborted; in one instance due to power failure and in the other due to excessive passenger drinking. On a run between New Haven, Connecticut, and New York City, reliable data were obtained from 49 passengers over 14 segments of track. Track was sampled for one-minute intervals every 3-4 minutes. Among the passengers were 16 males and 33 females; all but 3 were licensed drivers; 26 used the train monthly, 2 rode weekly, and 21 said their use was "seldom." Nine persons were between 16 and 24 years old; 17 between 25 and 48 years old; and 23 persons, 49 years and older.

B. Environmental Measurements

The instrumentation, used to collect ride environment data throughout the various phases of the study, consisted of the Portable Environmental Measuring System (PEMS) developed by the University of Virginia. The PEMS is battery operated, contains three linear accelerometer, three rate gyros, a temperature transducer, two channel tape recorder and a 7 interval pulse generator. All of the data were FM multiplexed and stored on a single channel of the recorder. The other channel was used for voice entry of vehicle speed, temperature and noise level. A hand-held sound level (dB) meter was used for measuring noise and a thermometer for measuring temperature. The instrumentation was calibrated and tested using a standard test facility prior to its use in the field.

The motion data consisted of analog recordings of motion in six degrees of freedom. These data included accelerations along the three linear directions and angular rates about the three rotational axes. The environmental measurements taken and their units of measure are shown on the following page.

Environmental Characteristics	Variable	Measure
Longitudinal Acceleration	RMS about the mean	g
Transverse Acceleration	RMS about the mean	g
Vertical Acceleration	RMS about the mean	g
Roll Rate	RMS about the mean	^{o}/sec
Pitch Rate	RMS about the mean	^{o}/sec
Yaw Rate	RMS about the mean	^{o}/sec
Noise	Mean	dB(A)
Temperature	Mean	^{o}C

C. Subjective Response Forms

Passengers' ratings of ride comfort and trip acceptability are the primary dependent measures used for model development and validation. Comfort level was rated on a seven-point scale as follows:

Comfort Level	Comfort Scale
Very Comfortable	1
Comfortable	2
Somewhat Comfortable	3
Neutral	4
Somewhat Uncomfortable	5
Uncomfortable	6
Very Uncomfortable	7

Passengers rated the comfort of each segment of their trip using this scale. They were told to rate according to what they perceived as comfortable or uncomfortable. At the end of the trip, passengers were asked to rate the overall comfort of the trip using the same seven-point scale.

Each individual also rated the acceptability of the trip using the following five-point scale from Richards and Jacobson (1975):

> Considering the ride you have just rated, if you had a choice, would you:
>
> ______ Be eager to take other rides?
>
> ______ Take other rides without hesitation?

______ Take another ride, but with some hesitation?

______ Prefer not to take another ride?

______ Not take another ride?

The numerical values 1 through 5 were assigned to the answers for data analysis. This type of data is needed to determine what level of ride quality is acceptable to a majority of the passengers.

Questions on passenger reaction to seating, leg room and temperature were also included during both phases of the program. A five-point attitude rating scale was used in conjunction with a definitive statement about some aspect of the ride environment such as the following:

Your seat is comfortable:

Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
______	______	______	______	______

The subject indicates how strongly he agrees or disagrees with the statement by checking one answer for each statement.

The above described rating scales were arranged in a booklet given to each passenger at the beginning of the trip. Each segment and its associated comfort scale were identified by a letter code. Comfort scales for individual segments appeared at the beginning of the booklet; questions and scales dealing with overall comfort, acceptability of ride, and other features of the environment appeared on the last few pages of the booklet.

During Phase 2 of the program, when actual revenue vehicles were used, information was also collected on the characteristics of the passengers who volunteered to participate in the study. Such information included sex, household income, frequency of travel and purpose of trip. These data helped to ensure that the individuals used to validate the model were representative of the traveling public. A copy of the response booklet used in the validation studies is reproduced in Appendix A.

D. Subject/Passenger Selection

A number of riders were needed to participate as subjects during the Phase 1 data collection effort. Subjects were selected to be representative of the traveling public in terms of age, sex and usage of the transportation mode under study.

For the Phase 1 studies, subjects were solicited from local businesses, civic organizations and universities. Leaders of such groups were contacted, the purpose of the study explained and their cooperation sought well in advance of the date set for data collection. In an effort to select a representative sample of the public, subjects were drawn from many different groups. Advertising and travel agencies were employed prior to the Phase 2 studies to obtain passengers for the validation effort.

A total of 120 subjects were selected for Phase 1 of the bus study and 60 were selected for Phase 1 of the train study. For each part of the study, 60 riders were assigned to two matched groups of equal size. Each group was balanced in terms of passenger age, sex and riding experience. For their participation in the Phase 1 studies, remuneration of subjects was fixed at a rate of twenty dollars which was considered commensurate with their time and effort spent on the study as well as the inconvenience and cost involved in traveling to and from the departure site.

During Phase 2, actual passengers on regular scheduled vehicles were used to provide data for model validation and refinement. Solicitation of passengers on board the vehicle or immediately prior to departure was considered impractical. Instead, volunteer passengers, who normally use this service, were solicited well in advance of data collection. In this way, it was possible to determine how many passengers to accommodate and thereby be able to carry out the study without disturbing other passengers who did not wish to be involved. In the train validation study, the passengers rode in a rail car located next to the last car of the train. During the bus study, they rode in a reserved vehicle which followed the regular bus.

Experience has shown that some incentive must be given to regular passengers for volunteering to participate in a study of this sort; otherwise, sufficient numbers of riders will not be obtained to validate the model. For this reason, passengers were allowed to ride in the reserved vehicle without paying a fare during the Phase 2 validation studies.

E. Route Selection

Ride comfort and acceptability are significantly influenced by the external inputs to the vehicle. Among these inputs are variables associated with surface conditions, track type and vehicle speed. To ensure that the models would be based on a representative sample of the vehicle's ride environment, every effort was made to employ a wide range of these variables in the research design. To this end, bus routes and train track, employed in the Phase 1 effort, were carefully selected and pre-tested in advance of actual data collection. Roads with different types of surfaces and conditions of repair, in Hartford, Connecticut, were found and vehicle motion measured while traveling over them at typical vehicle speeds. Final selection of road segments for use in the Phase 1 studies were based on an examination of the recorded vehicle motion.

The track between New London, Connecticut and New York City was chosen for the train study because it contained welded and unwelded sections, switches and curves which produced a wide range of typical motions and noise.

During the Phase 2 validation effort, a high degree of control over external vehicle inputs was not possible since scheduled services over existing routes had to be used. However, it was possible to choose routes that, based on inspection, provided a typical range of vehicle motions. Both train and bus routes were pre-tested to ensure they provided a full range of typical vehicle motions for the Phase 2 validation studies.

For the train study, it was impossible to pre-select specific route segments for data collection due to the difficulty of predicting train speeds, and identifying segments using mile markers. For these reasons, the ride environment was sampled for approximately one minute at periodic intervals, at which times the passengers were asked to rate ride comfort. With this technique, many samples of the ride environment were taken rather than a limited number of carefully chosen ones as was done during the bus study. The route segments were found to provide a typical range of vehicle motions.

F. Data Collection Procedures

The first task during the data collection effort of both phases was to set up the motion recorder near the vehicle's point of percussion. At the same time, in Phase 1 data collection, the operator and crew members were briefed on the route to be followed, speeds to be maintained, temperature regulation and other items necessary to ensure that the ride environment was controlled in accordance with the plan.

Once subjects arrived at the departure site, response booklets were handed out and seats assigned in accordance with a pre-established scheme. A seating plan was necessary to determine the locations and distances of individual subjects from the vehicle's point of percussion. Subjects seated in the rear of the vehicle, for example, may have experienced more motion and rated the ride less comfortable than those seated elsewhere.

Once the subjects were seated, they were briefed on the procedures to be followed during data collection. This briefing contained simple instructions on how they should complete the rating scales and when they would be asked to do so. Following the briefing, questions were solicited from the subjects and answered before the start of the first segment.

The researcher alerted the subjects when the vehicle approached, entered and left the test segment. At the end of each segment, the subjects were instructed to rate the comfort of ride. The start and end of each segment were marked on the motion recorder tape. Noise, temperature and vehicle speed were also measured and recorded during each segment. In addition, the instrument operator recorded a verbal description of the ride environment during each segment. This record contained a description of any unusual circumstances, e.g., traffic conditions, sudden stops, violent maneuvers and weather conditions, that may have influenced the subjects' responses and would assist in the analysis of anomalous data.

A rest period of 20 minutes was given after a maximum of one hour of running time on board buses. This period was also used to change recorder tape, switch vehicles and assign new seats. In the Phase 1 train study, approximately one hour elapsed between trains in New London. During this time, passengers had lunch and rested before boarding for the return trip.

When the last segment was completed, the subjects were requested to indicate their comfort rating for the overall trip and the acceptability of ride. Response booklets were then collected and the subjects were paid for their participation in the study.

In Phase 2, essentially the same procedures as described above were used (except for those that follow). Operators were not requested to maintain control over their vehicle in accordance with a plan but allowed to operate as they normally would in regular service. Passengers were also not assigned seats but were permitted to sit wherever they desired within the reserved vehicle. Rest periods were also not given since trips typically lasted less than one hour and none are given in real life. Finally, passengers were not paid but allowed to ride in a reserved vehicle without paying a fare.

G. Data Reduction

The data gathered during both phases of the program were reduced and analyzed for use in model development. The data reduction effort consisted of two tasks. The first task involved the reduction of the subjective response data gathered by means of the rating scales. The second task was concerned with the reduction of the physical measures of the ride environment.

1. Subjective Response Data

Reduction of the subjective response data was accomplished in a three-step process. The responses were first scaled utilizing the techniques described above. The scaled responses were then tallied for each segment, experimental condition, and subject variable using a matrix based on the original research design. Once the cells in the matrix were filled and the tally completed, the frequencies for rows and columns were calculated and cross-checked for accuracy. The final step in the process was to compute the mean and standard deviation for each segment and variable using standard statistical techniques.

Histograms were also prepared using the reduced data to evaluate trends, to identify anomalies and to evaluate the sensitivity of the data to the variables included in the research design. Such techniques, however, were not necessary for model development.

2. Environmental Data

The environmental data consisted primarily of recordings of vehicle motion in six degrees of freedom--accelerations in the three linear directions and angular rates in the three rotational axes.

As illustrated in Figure II-3, the first step in the reduction process was to demultiplex the recorded signal using discriminators to extract the individual signals for each degree of freedom. Each signal was then filtered to remove high frequency noise using an analog computer. This resulted in a frequency range of 0 to 25 Hertz. The analog computer was also employed to produce differentiated signals for each degree of freedom. All signals were then converted to digital form by means of an analog-to-digital converter at a rate of 50 to 100 per second. As the final step in the process, the digitized signals were reduced into means, rms values, excedance values, and power spectra for use in model development, together with the reduced subjective response data.

Since all of the above procedures are standard ones, described in any text on the subject, they are not repeated here except for the differentiation of signals. A simple circuit that was used to differentiate signals is shown in Figure II-4, taken from Fairchild and Krovetz (1965). This circuit was tested and found to introduce approximately 5% error which was considered acceptable.

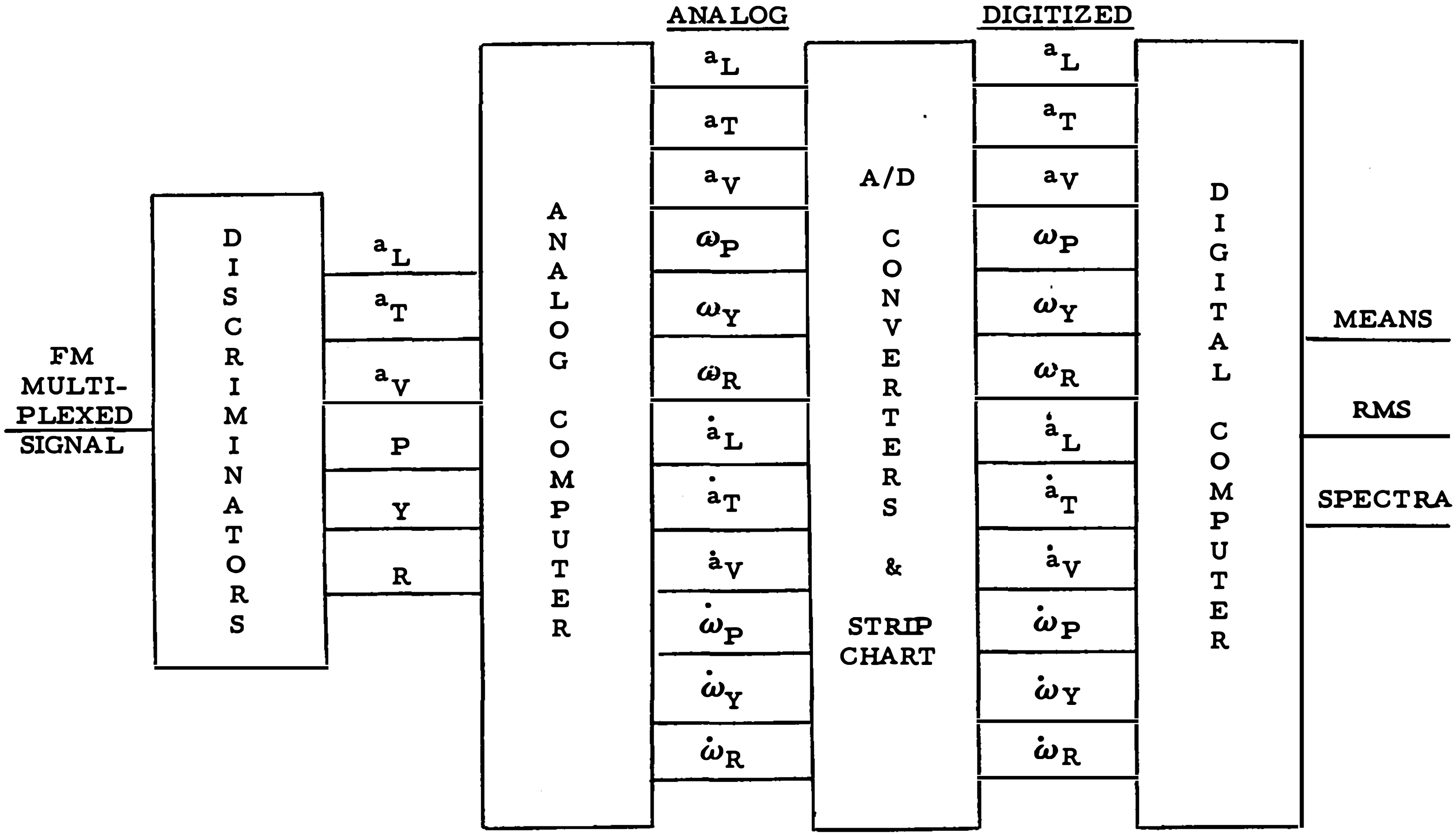

FIGURE II-3. SIGNAL PROCESSING SCHEMATIC.

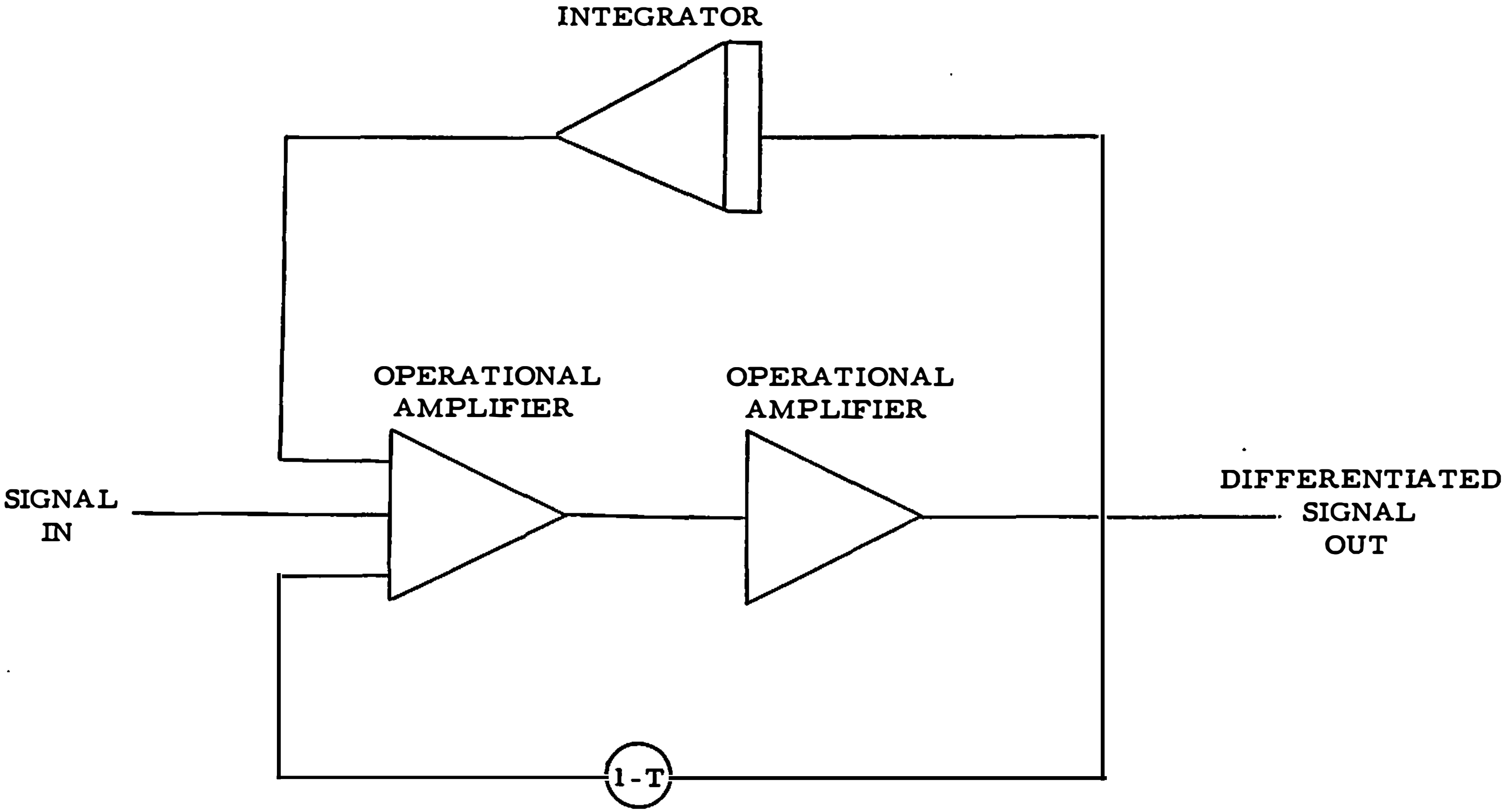

FIGURE II-4. DIFFERENTIATION CIRCUIT.

III. RESULTS OF THE BUS STUDY

The bus study was carried out in two phases. Phase 1 dealt with the collection of comfort responses from selected subjects under controlled field conditions and the development of quantitative model(s) able to predict those levels of vehicle motion considered both comfortable and acceptable to the majority of potential passengers. Phase 2 dealt with the validation of the model(s) utilizing additional comfort ratings obtained from volunteer passengers in regular scheduled bus service.

Phase 1 of the study was conducted in two parts. Part 1 involved the collection of data over straight/level roads and hills, and conditions of acceleration and deceleration. During Part 2, data were gathered while traveling on curves, both banked and unbanked. Two separate models were developed using these two sets of data as presented below.

A. Bus Model for Straight/Level Roads and Hills (Part 1)

Data for 52 different ride segments of straight roadways were collected during the initial part of the Phase 1 bus study. Thirty comfort ratings were obtained for each segment in addition to the environmental measures. The raw data can be found in Appendix B. The mean comfort rating for each segment is the dependent variable used in the following analyses.

Table II-2 shows a statistical summary of the data obtained in the bus study as well as comparable data from the train study and previous work with aircraft (Jacobson and Richards, 1977). The RMS values are equivalent to standard deviations of the motions observed in each ride segment. The means and standard deviations shown are based on variation in the motions encountered and not on central tendency. RMS values for the bus data display a relatively wide spread for all motion variables; the coefficient of variation exceeds 25% on all of them. Roll rate is the dominant motion variable for the bus data, having the largest mean and greatest range. The subjective responses had a mean value of 3.4, representing "moderately comfortable," with observed values ranging from 2.2 to 6.3.

Intercorrelations of the various physical measures and comfort ratings are shown in Table II-3. Temperature was eliminated from the set of physical variables because it did not show sufficient variation and thus could not correlate with subject responses. Since temperature levels were extremely restricted in this study, the correlation of temperature with comfort was necessarily low. Clearly, if temperature had varied widely, it would be expected to correlate with rated comfort.

TABLE 11-2. STATISTICAL COMPARISON OF BUS, TRAIN AND AIRPLANE MOTION.

Variable	Statistics	Bus Phase 1*	Train Phase 1*	Commercial Airplane
Subjective Response	mean	3.4**	2.9**	3.2**
	std. deviation	1.1	.8	.9
	range	2.2→6.3	1.7→4.8	2→6
Roll Rate (deg/sec)	mean	2.4	1.4	1.0
	std. deviation	.8	.3	.7
	range	1.1→4.6	.9→2.6	.11→3.6
Pitch Rate (deg/sec)	mean	2.1	.95	.3
	std. deviation	.5	.10	.25
	range	1.2→3.4	.76→1.1	.05→2.2
Yaw Rate (deg/sec)	mean	2.1	1.3	.26
	std. deviation	.6	.3	.37
	range	1.1→3.5	.8→2.7	.009→3.6
Longitudinal Acceleration (g)	mean	.044	.012	.014
	std. deviation	.015	.040	.009
	range	.017→.073	.007→.022	.001→.076
Transverse Acceleration (g)	mean	.075	.029	.014
	std. deviation	.028	.010	.012
	range	.031→.134	.009→.064	.001→.080
Vertical Acceleration (g)	mean	.082	.030	.044
	std. deviation	.027	.007	.031
	range	.036→.152	.018→.049	.008→.19
Noise (dB(A))	mean	75.8	70.4	87
	std. deviation	2.6	4.4	2.7
	range	70 → 83	62 → 82	81 → 94

* Both subject groups combined

** Somewhat comfortable.

TABLE II-3. CORRELATION COEFFICIENTS FOR BUS DATA FROM STRAIGHT/LEVEL ROADWAY STUDY (PART 1 OF PHASE 1).

Variable	Subject Response	RMS Roll	RMS Pitch	RMS Yaw	RMS Long. Accel.	RMS Trans. Accel.	RMS Vert. Accel.	Noise
Subject Response	1.00							
RMS Roll (deg/sec)	.76	1.00						
RMS Pitch (deg/sec)	.22	.57	1.00					
RMS Yaw (deg/sec)	.05	.39	.63	1.00				
RMS Long. Acceleration (g)	.48	.57	.50	.48	1.00			
RMS Trans. Acceleration (g)	.28	.59	.80	.77	.61	1.00		
RMS Vertical Acceleration (g)	.57	.71	.68	.60	.62	.77	1.00	
Noise	.07	.28	.47	.52	.25	.56	.51	1.00

The motion variables are highly intercorrelated. A principal components analysis of the correlation matrix for the six motion variables was done to assess the extent of colinearity. The first principal component accounts for 68.7% of the variance in the motion variables. Loadings on the first component vary from .76 for roll to .92 for transverse. Since the motion variables were so highly intercorrelated, the designer who controlled one of these variables would, in effect, control all of them. If he could reduce roll rate, the other motions would also be affected. The first three principal components account for 88.5% of the variance in the motion measures. A varimax rotation was done on the first three components: yaw, transverse and pitch load strongly on the first rotated component; roll and vertical on the second; and only longitudinal on the third.

Comfort ratings for the initial bus data correlate most strongly with roll rate (r = .76) and vertical acceleration (r = .56); thus, they relate to the second component above. A stepwise regression procedure was used to relate the environmental variables to rated comfort. Such a procedure would, of course, initially bring roll into the regression equation, then other variables which contribute independent information (predictability) regarding comfort. For the present data, insignificant gains in predictability result from variables other than roll. The equation:

$$C' = .87 + 1.05\omega_R \qquad (1)$$

$$\sigma = (.32)\ (.13)$$

yields an R of .76, thus 58% of the variance in comfort responses is accounted for by roll alone. The numbers in parentheses are standard errors (σ) for the corresponding coefficients.

The subjective responses given by passengers to any given ride segment showed some variability; indeed, it was not uncommon to see passenger responses at four or more comfort levels for any given segment. For example, a typical set of responses for nine ride segments is displayed in Table II-4. Notice that six different responses were registered by the passengers for the first road segment, from "very comfortable" to "uncomfortable."

The ride quality model shown in Equation (1) is an average passenger response model. It is based on the mean response from a group of passengers to the set of environmental stimuli. For any motion input, it can be used to predict the mean comfort response. The problem of variability in passenger response is more complex and will be dealt with in two ways. One way is to develop a model which specifies a predicted response distribution--a set of values and the predicted probability of occurrence of each. Such a distributive response model would permit assertions about the percent of passengers who would rate a given segment at a certain level or better. Such a model is presented in Section VI of this volume.

TABLE II-4. "TYPICAL" SUBJECTIVE RESPONSES IN BUS STUDY (PHASE 1) FOR SEGMENT NOS. 1 THROUGH 9.

Segment Number	Number of Passenger Responses						
	Very Comfortable 1	2	3	4	5	6	Very Uncomfortable 7
1	1	5	3	1	4	1	0
2	2	6	3	2	1	1	0
3	1	1	6	5	1	1	0
4	2	4	2	2	3	1	1
5	1	2	4	1	5	1	1
6	5	5	4	1	0	0	1
7	2	5	4	2	1	0	1
8	3	7	3	1	0	1	0
9	0	0	0	1	1	3	10

The second way to deal with passenger variability in comfort responses is to determine whether those responses are related to identifiable characteristics of the passengers (that is, to individual differences). The two groups of subjects used in this study were stratified in terms of age, sex and frequency of bus use. In Table II-5, separate comfort models are shown for the seven categories of riders. The regression equation for all subjects is also shown. In all eight equations, RMS roll rate is the dominant variable. The various groups of subjects may be compared in terms of their regression coefficients and the R^2 resulting from each equation. Comparing equations for different age groups, young riders are generally less satisfied with the bus ride, as evidenced by the large intercept constant, but are more tolerant of the roll motion; older riders are generally more satisfied with the bus ride but are more sensitive to the rolling motion. Within the male and female categories, the intercepts are significantly different, but the slopes are not. The males tend to be generally more intolerant of the ride than the women, but their response to the vehicle motions is approximately the same. Infrequent riders have a lower intercept but a higher slope coefficient than do frequent riders. The regression equation for infrequent riders accounts for more variance in comfort responses than does that for frequent riders.

The usual reason for stratifying the sample in this way is to improve the predictive validity of the regression equations. Equations constructed for the various subgroups will predict the reactions of the subgroup better than the overall regression equation will. In the present study, there were too few subjects in each of the subgroups to make much of the resulting equations. Thus, our discussion simply notes the trends in the data.

For a vehicle designer, the whole issue of disaggregation, or stratified subject groups, is academic. He must design to the aggregate or overall model; there is only one kind of vehicle which must be designed to the passenger population as a whole.

B. Field Validation of the Bus Model

During phase 2 of the bus study, field validation data were gathered while traveling over 20 segments of roadway used in scheduled commuter bus service. The number of passengers who participated and their characteristics are shown in Table II-6. Mean responses of the passengers were computed for each segment. Summary statistics on the motion and comfort measures are shown in Table II-7 and the intercorrelation matrix for these variables appears in Table II-8. Comparison of the bus statistics from Table II-2 with the values in Table II-7 shows that motions were less extreme in the validation segments than in the initial bus data gathered during Phase 1 above. The greatest problem is the restricted range on the roll rate: in the validation data, the range is only 1/3 of that in the original bus data; the coefficient of variation was 33% in the original sample and is only 20% in the validation sample. The range of comfort judgments is also restricted somewhat in the validation sample.

TABLE II-5. COMFORT MODELS USING BUS DATA FROM STRAIGHT/LEVEL ROADWAY (PART 1 OF PHASE 1).

Category of Passenger	Comfort Model	R^2	Level of Significance
Total Sample	$C = .87 + 1.05\omega_R$ $\sigma = (.32) \quad (.13)$	.58	<.001
Infrequent Riders	$C = .79 + 1.12\omega_R$ $\sigma = (.31) \quad (.12)$	.62	<.001
Frequent Riders	$C = .93 + .97\omega_R$ $\sigma = (.33) \quad (.13)$	.53	<.001
Ages 16-24	$C = 1.71 + .91\omega_R$ $\sigma = (.31) \quad (.12)$	.53	<.001
Ages 25-48	$C = .84 + 1.01\omega_R$ $\sigma = (.38) \quad (.15)$	.47	<.001
Ages 49 and older	$C = -.22 + 1.28\omega_R$ $\sigma = (.37) \quad (.14)$	.61	<.001
Males	$C = 1.25 + .99\omega_R$ $\sigma = (.31) \quad (.12)$	.56	<.001
Females	$C = .47 + 1.09\omega_R$ $\sigma = (.35) \quad (.14)$	.56	<.001

C = Mean comfort rating

ω_R = Roll rate (°/sec)

σ = Standard errors in ( )

Frequent = Daily or weekly use of bus

Infrequent = Less than weekly use of bus

TABLE II-6. PASSENGER CHARACTERISTICS IN BUS VALIDATION STUDY (PHASE 2).

Category	Characteristics	Number of Subjects	
Age	16 - 24	15	
	25 - 34	44	
	35 - 48	31	
	49 and older	23	
			113
Sex	Male	59	
	Female	54	
			113
Frequency of Ridership	Daily	101	
	Weekly	6	
	Monthly	3	
	Infrequent	3	
			113

TABLE II-7. STATISTICAL SUMMARY OF BUS VALIDATION DATA (PHASE 2) FOR STRAIGHT/LEVEL ROADWAYS.

Variable	Mean	Standard Deviation	Range
Subjective Response	3.2*	0.7	2.6 - 5.2
Roll Rate (deg/sec)	1.5	0.3	1.1 - 2.3
Pitch Rate (deg/sec)	1.5	0.5	1.0 - 2.8
Yaw Rate (deg/sec)	1.8	0.7	0.9 - 3.6
Longitudinal Acceleration (g)	.032	.014	.008 - .063
Transverse Acceleration (g)	.043	.015	.021 - .085
Vertical Acceleration (g)	.041	.011	.025 - .054
Noise (dB(A))	71	1.9	68 - 74

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*Somewhat comfortable.

TABLE II-8. CORRELATION COEFFICIENTS FOR BUS VALIDATION DATA (PHASE 2).

Variable	Subject Response	Roll	Pitch	Yaw	Long. Accel.	Trans. Accel.	Vert. Accel.	Noise
Subject Response	1.00							
Roll (deg/sec)	.69	1.00						
Pitch (deg/sec)	.76	.72	1.00					
Yaw (deg/sec)	.31	.12	.15	1.00				
Longitudinal Acceleration (g)	.11	.11	.04	.08	1.00			
Transverse Acceleration (g)	.53	.59	.49	.58	.28	1.00		
Vertical Acceleration (g)	.74	.79	.61	-.02	.57	.28	1.00	
Noise (dB(A))	.00	.26	-.03	-.23	-.44	.13	.31	1.00

A principal components analysis was done on the motion intercorrelations shown in Table II-8. The first component accounted for 50.3% of the variance in the motion measures. Three components accounted for 87.4% of the total variance. Component 1 had substantial loadings on roll, pitch, vertical and transverse acceleration; Component 2 was yaw; and Component 3 was longitudinal acceleration. The varimax rotated factor matrix differs from the principal components solution in that transverse acceleration loads highly on both Components 1 and 2 of the rotated space.

The first row of Table II-8 shows the correlations of rated comfort with the various physical variables. Judged comfort correlates highly with roll, pitch, vertical and, to a lesser extent, transverse acceleration. Clearly, comfort judgments are related to the first principal component of the motion variables. If a stepwise regression procedure was followed in the validation study, pitch would be the first, and only, variable to appear in the equation. However, pitch and roll are highly correlated, and roll is restricted in range in the validation data, so the effects of roll are attenuated.

A test of the degree to which the validation data fit the model may be obtained by using the model to predict comfort. The predicted comfort responses (CPR) and the actual comfort responses, gathered during the Phase 2 validation study, can then be correlated with each other. The size of the resulting correlation coefficient indicates the "goodness of the model." Comfort responses were predicted for each of the 29 validation segments using the formula:

$$\text{CPR} = .87 + 1.05\omega_R \qquad (2)$$

The correlation of CPR with mean rated comfort was .69 which is significant at $\alpha = .00002$. The standard error of estimate is .203 and r^2 is .47. This degree of correlation indicates that the validation data do validate the bus model.

C. Bus Model for Curved Roadway (Part 2)

The initial bus model was developed using data from straight/level roads and hills, and acceleration/deceleration conditions. Curved roadways are a special case of vehicle operation needing a separate modeling effort. Consequently, an additional experiment was conducted during Phase 1 using paid subjects. Data were collected from 50 passengers, similar in characteristics (e.g., age, sex and experience) to those used in the initial modeling effort. These data can be found in Appendix B. City buses traveled over curved roadways in the Hartford, Connecticut area. Both right- and left-hand curves were included, and a variety of road conditions were represented. Thirty-one road segments were involved. For each segment, both the mean and RMS values for each of the six degrees of freedom of motion were calculated, along with a mean comfort rating based on judgments from the 56 subjects.

Table II-9 contains summary statistics for each of the physical measures used in this study; subjective response statistics are also shown. Table II-10 presents the intercorrelations of these variables. The highest correlations with mean comfort ratings are found for mean yaw rate and mean transverse acceleration. RMS transverse acceleration is also strongly related to judged comfort. RMS vertical acceleration and RMS roll rate correlate about .50 with subjective response.

Stepwise multiple regression was used to develop various models for the data from the curved roadway experiment. Since transverse motions are dominant under curved roadway conditions, selective variable entry was used to bring them into the regression equation first. The following models resulted:

$$C' = 1.83 + 10.27\, m_T, \quad R^2 = .48 \qquad (3)$$

$$\sigma = (.28) \quad (2.00)$$

$$C' = 1.40 + 7.7 m_T + 8.25 a_T, \quad R^2 = .54 \qquad (4)$$

$$\sigma = (.34) \quad (2.29) \quad (4.08)$$

Additional variables did not significantly improve the predictive capacity of the model.

Thus, the model appropriate for curved roadway conditions differs from that developed for the straight roadway data. Whereas roll rate is important on a straight/level roadway, transverse acceleration is important on curves. Equation (4) reveals that, at a given speed, ride comfort diminishes with increasing rate of curvature on a turn (implying greater mean transverse acceleration) and with increasing "bounciness" in the transverse acceleration.

TABLE II-9. STATISTICAL SUMMARY OF BUS DATA FOR CURVED ROADWAY (PART 2 OF PHASE 1).

Variable	Mean	Standard Deviation	Range
Subjective Response	3.0*	0.8	2.0 - 4.9
Roll Rate (deg/sec)	2.9	.8	1.5 - 4.2
Pitch Rate (deg/sec)	2.6	.7	1.4 - 3.5
Yaw Rate (deg/sec)	5.1	1.5	2.3 - 7.4
Longitudinal Acceleration (g)	.036	.015	.021 - .086
Transverse Acceleration (g)	.092	.036	.036 - .167
Vertical Acceleration (g)	.055	.011	.037 - .081
Noise (db(A)) (deg/sec)	76.3	2.6	72 - 83
Mean Roll Rate** (deg/sec)	1.2	1.1	0.1 - 3.3
Mean Pitch Rate+ (deg sec)	0.1	1.4	-3.0 - 2.7
Mean Yaw Rate** (g)	8.1	3.0	1.4 - 12.9
Mean Longitudinal Acceleration++ (g)	.006	.028	-.030 - .077
Mean Transverse Acceleration** (g)	.128	.064	.031 - .248
Mean Vertical Acceleration** (g)	1.002	.021	.958 - 1.045

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* Somewhat comfortable

**These are the absolute values of the means in these cases.

\+ Positive pitch is arbitrarily defined as being when the front end is pitching upward.

++Positive longitudinal acceleration is arbitrarily defined as being in the reverse direction.

TABLE II-10. CORRELATION COEFFICIENTS FROM BUS STUDY ON CURVED ROADWAY (PART 2 OF PHASE 1).

Variable	Subject Response	Roll	Pitch	Yaw	Long. Accel.	Trans. Accel.	Vert. Accel.	dB(A)	Mean Roll	Mean Pitch	Mean Yaw	Mean Long. Accel.	Mean Trans. Accel.	Mean Vert. Accel.
Subject Response	1.00													
RMS Roll	.50	1.00												
RMS Pitch	.31	.94	1.00											
RMS Yaw	.35	.21	.12	1.00										
RMS Long. Accel.	.19	.46	.46	.55	1.00									
RMS Trns. Accel.	.60	.40	.31	.79	.48	1.00								
RMS Vert. Accel.	.52	.76	.74	-.02	.32	.39	1.00							
dB(A)	.55	.55	.51	.15	.41	.57	.69	1.00						
Mean Roll	.44	.54	.45	.26	.27	.43	.57	.50	1.00					
Mean Pitch	.21	.18	.12	-.08	.06	-.03	.12	.07	-.05	1.00				
Mean Yaw	.67	.65	.57	.50	.49	.59	.58	.51	.60	.17	1.00			
Mean Long. Accel.	.02	.13	.13	.08	.48	-.20	-.10	-.12	-.11	.56	.16	1.00		
Mean Trans. Accel.	.65	.64	.57	.30	.44	.56	.59	.62	.37	.28	.72	.13	1.00	
Mean Vert. Accel.	.26	.20	.13	-.01	.13	.10	.20	.17	-.02	.98	.22	.49	.37	1.00

IV. RESULTS OF THE TRAIN STUDY

The train study was also carried out in two phases. Phase 1 dealt with the collection of comfort responses from selected riders while traveling over track between Stamford and New London, Connecticut, and the development of ride quality model(s) based on these responses. During Phase 2, the model(s) were validated using data obtained from preselected volunteer passengers in regularly scheduled service.

A. Train Model

Thirty ratings of comfort were collected on all 79 ride segments in the train experiment. As in the bus analysis, the dependent variable is the mean comfort response based on the responses of two groups of 30 subjects each. The raw data can be found in Appendix C.

The train data are summarized in Tables II-11 and II-12. Table II-11 displays a statistical summary of the environmental data, including each variable's mean, standard deviation, and range for the 79 segments. Motion data, collected in the train study, displayed noticeably less variation than that collected in the bus study: coefficients of variation were 20% for roll and 11% for pitch with the others ranging from 23% to 35%.

Table II-12 displays the correlation coefficients for the train data. The noise level displays the highest correlation with the subject responses. Roll and transverse acceleration have correlations with comfort of .44 and .43, respectively.

A principal components analysis was done on the correlation matrix for the six motion variables for the initial train data. Three components accounted for 79% of the variance in motion measures, and four accounted for 91%. The first component had high loadings on roll, yaw and transverse acceleration, and the second on pitch and longitudinal acceleration. Vertical loaded about .50 on all of the first three components; its loading was negative on the second.

Since noise correlated most strongly with comfort and showed significant correlations with several motion variables, a second principal components analysis was done on the train data; the entire matrix shown in Table II-12 was used. Here, three components account for 69% of the variance, and only three have eigenvalues exceeding unity. Additional components are statistically justified, but they are usually marked by only a single variable. The first two principal components were interesting because both had respectable loadings for comfort. The first component is marked by roll, transverse acceleration and yaw; the second by noise and pitch. Thus, both

TABLE II-11. STATISTICAL SUMMARY OF TRAIN FIELD EXPERIMENTAL DATA.

Variable	Mean*	Standard Deviation**	Range
Subjective Response	2.9	.8	1.7 - 4.8
RMS Roll Rate (deg/sec)	1.4	.3	.9 - 2.6
RMS Pitch Rate (deg/sec)	.95	.10	.76 - 1.1
RMS Yaw Rate (deg/sec)	1.3	.3	.8 - 2.7
RMS Long. Acceleration (g)	.012	.004	.007 - .022
RMS Trans. Acceleration (g)	.029	.010	.009 - .064
RMS Vert. Acceleration (g)	.030	.007	.018 - .049
Noise (dB(A))	70.4	4.4	62 - 82
Temperature (°F, °C)	74, 23	4.8, 2.7	68 - 82, 20 - 28

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* The mean value of the RMS variables represents the average RMS values seen across all experimental segments.

** The standard deviation represents the dispersion of the individual RMS values from the mean defined above.

TABLE II-12. CORRELATION COEFFICIENTS FOR TRAIN FIELD EXPERIMENTAL DATA.

Variable	Subject Response	Roll	Pitch	Yaw	Long. Accel.	Trans. Accel.	Vert. Accel.	Noise	Temperature
Subject Response	1.00								
Roll (deg/sec)	.44	1.00							
Pitch (deg/sec)	.31	-.03	1.00						
Yaw (deg/sec)	.20	.62	-.14	1.00					
Longitudinal Acceleration	.43	.06	.18	.05	1.00				
Transverse Acceleration	.34	.56	-.18	.77	.07	1.00			
Vertical Acceleration	.08	.41	-.38	.18	-.05	.26	1.00		
Noise (dB(A))	.63	.15	.43	.05	.46	.04	-.13	1.00	
Temperature (^{o}F)	.24	-.04	-.06	-.03	.21	-.03	-.22	.27	1.00

motion and noise are necessary to account for judged comfort for the train data.

A stepwise regression solution yielded Equation (5) as a model for the Phase 1 train data. Noise, of course, entered the equation first, followed by roll. These two variables account for 52% of the variance in mean comfort responses.

$$C' = .73 + .10 \quad (dB(A) - 60) + .96\omega_R , \tag{5}$$

$$\sigma = (.96)\ (.01) \qquad\qquad (.21) .$$

The multiple correlation coefficient for this model is R = .71. Thus, both ground-based vehicles have roll rate as an important determinant of passenger comfort; for trains, comfort also depends on noise levels.

Table II-13 presents a set of train ride-quality models for different subcategories of subjects. Of particular interest is how the roll coefficients for the train models compare to those for the bus models.

The roll coefficient for the overall train model is .96 versus a coefficient of 1.05 for the bus model. However, the standard errors for the train and bus models are .21 and .13, respectively. Thus, the difference between the two coefficients is statistically insignificant. The similarity of the two coefficients suggests an individual's response to rolling motion does not depend on vehicle type.

The stratified roll coefficients from the train data are similar to those from the bus models. Coefficients from the two models for various groups of subjects are displayed below:

Passenger Category	Bus Roll Coefficient	Train Roll Coefficient
Total Sample	1.05	.96
Infrequent Riders	1.12	1.05
Frequent Riders	.97	.88
Ages 16 - 24	.91	.81
Ages 25 - 48	1.01	1.01
Ages 49 and Older	1.28	1.00
Males	.99	.86
Females	1.09	1.06

TABLE II-13. COMFORT MODELS FOR DIFFERENT PASSENGER CATEGORIES FROM TRAIN FIELD EXPERIMENT.

Category of Passenger	Comfort Model	R^2	Level of Significance
Total Sample	$C = .73 + .1(dB(A) - 60) + .96\,\omega_R$ $\sigma = (.96)\quad(.01)\quad(.21)$	.52	<.001
Infrequent Rider	$C = .54 + .08(dB(A) - 60) + 1.05\,\omega_R$ $\sigma = (.96)\quad(.01)\quad(.22)$	.48	<.001
Frequent Riders	$C = .30 + .11(dB(A) - 60) + .88\,\omega_R$ $\sigma = (1.06)\quad(.01)\quad(.24)$	.51	<.001
Ages 16 - 24	$C = .74 + .11(dB(A) - 60) + .81\,\omega_R$ $\sigma = (.94)\quad(.01)\quad(.21)$	.54	<.001
Ages 25 - 48	$C = .56 + .06(dB(A) - 60) + 1.01\,\omega_R$ $\sigma = (1.03)\quad(.01)\quad(.23)$	.37	<.001
Ages 49 and older	$C = .53 + .12(dB(A) - 60) + 1.00\,\omega_R$ $\sigma = (1.26)\quad(.02)\quad(.28)$	.46	<.001
Males	$C = .40 + .12(dB(A) - 60) + .86\,\omega_R$ $\sigma = (1.09)\quad(.02)\quad(.24)$	.50	<.001
Females	$C = .47 + .08(dB(A) - 60) + 1.06\,\omega_R$ $\sigma = (.92)\quad(.01)\quad(.21)$	.50	<.001

C = Mean comfort rating

ω_R = Roll rate (°/sec)

dB(A) = Noise level in dB(A)

σ = Standard errors in ( )

Infrequent = Less than weekly use of train

Frequent = Daily or weekly use of train

The coefficients for each category from the two vehicles are statistically indistinguishable. In addition, the coefficients display the same general trends within the different rider categories. In both the train and bus studies, infrequent riders have larger roll coefficients than frequent riders. Thus, infrequent riders are more sensitive to roll than are frequent riders; roll influences their comfort judgments to a greater extent. Older riders have larger roll coefficients than younger riders; and female riders have larger roll coefficients than male riders. Thus, similar trends in comfort response are apparent for both types of vehicle. The differences in reaction of the various types of passenger would probably be stable and significant with a larger sample of passengers.

The train model was compared to the bus model, developed for straight/ level roadways, because about 80% of the train data represent straight and level roadbed. The data represented a variety of different roadbed conditions, but, given the train routes from which data were obtained, hill and curve data could not be gathered separately.

B. Field Validation of the Train Model

The train validation data were limited; only 14 ride segments were obtained, and these showed an extremely limited range of noise levels. Two additional trips had to be aborted due to a power failure in one case, and excessive passenger drinking in the other, which made passenger judgments of minimal value. The validation data, reported below, were gathered while traveling over relatively good segments of track and from straight-level roadbed conditions between New Haven, Connecticut and New York City using volunteer passengers.

In deciding whether the model for the train data, based on the passenger sample, fits the model based on data gathered during Phase 1, we have two problems: 1) the small number of segments (N = 14) obtained for validation, and 2) the peculiar distribution of noise levels obtained in this sample.

In the Phase 1 data set, based on 79 segments, noise levels varied from 62 to 82 dB(A) with a mean of 70.4 and a standard deviation of 4.4. These data included segments in which the train doors were open. Such conditions are common on many trips. In the validation data of Phase 2, noise levels were limited in range from 66 - 71 dB(A) with a mean of 68.43 and a standard deviation (SD) of 1.9 since all doors were closed. The actual distribution was:

dB(A)	66	67	68	69	70	71	ALL
N	3	3	1	1	4	2	14

Thus, the effective range of the noise data in the validation sample was about 1/4 that in the original sample. Restricting the range of a variable used in a correlation matrix can drastically alter the pattern of correlations of that variable with others.

In the present case, the restricted range of noise levels did produce peculiar results. The correlations between roll, noise and comfort for the two data sets are:

Original Sample (Phase 1)	Validation Sample (Phase 2)
$r_{dB, \omega_R} = .15$	$r_{dB, \omega_R} = -.34$
$r_{dB, C} = .63$	$r_{dB, C} = -.24$
$r_{\omega_R, C} = .44$	$r_{\omega_R, C} = .54$

The negative correlations found in the validation study are surely spurious, effects of restricted range and the peculiar distribution of the noise variable. If we test the hypothesis that $\rho_{dB, \omega_R} = 0$, we cannot reject that hypothesis, even at $\alpha = .10$; similarly for $\rho_{dB, C} = 0$. Thus, the only meaningful results will involve the two variables whose range was closer to that encountered in the original study.

In the two data sets, the means and standard deviations for roll and comfort were:

	Original Sample (Phase 1)			Validation Sample (Phase 2)		
	$\overline{X}$	SD	Range	$\overline{X}$	SD	Range
Roll	1.4	.3	.9→2.6	1.4	.4	1.0→2.1
Comfort	2.9	.8	1.7→4.8	2.3	.8	1.5→3.9

Thus, these two variables have distributions which are similar in the two data sets. Note above that, for the original data, $r_{\omega_R, C} = .44$ and, for the validation data, $r_{\omega_R, C} = .54$. A test of the difference between these correlation coefficient yields a z value of .41 which would not be significant, even if $\alpha = .50$. Therefore, we accept the hypothesis that the relationship between comfort and roll does not differ between these two samples. Similar tests show that the correlation of noise with roll, and noise with comfort <u>do</u> differ significantly between the two samples.

The multiple regression equation for the initial train data (Phase 1) took the form:

$$C = .73 + .10\,(\mathrm{dB(A)} - 60) + .96\,\omega_R \qquad (6)$$

$$\sigma = (.96) \quad (.01) \qquad\qquad (.21)$$

The numbers in parentheses are the standard errors (σ) corresponding to each coefficient. This equation was used to predict the comfort responses (CPR) for the validation sample. The correlation of calculated CPR with mean rated comfort from the validation sample was .44, which yields an α value of .06. Given the small sample size (N = 14) involved in the validation, this level of significance indicates reasonable agreement between the above model and the validation data. With an increased sample size for the validation study, the correlation should be larger and more significant as was found in the bus study.

V. COMPOSITE RIDE-QUALITY MODELS

The models presented so far in this volume represent bus and train environments likely to be encountered in existing vehicles. For future bus and train designs, these models should be adequate for evaluating ride quality. However, for future vehicles which combine aspects of these two modes or which deviate significantly from both, other models might be better. Two models are now considered which are equations based on composite data sets: the first is for just ground-based vehicles; the second includes data from the air mode.

A. Composite Model for Ground-based Vehicles

The data from the Phase 1 bus and train studies were pooled to allow construction of a composite model for ground-based vehicles. There were 131 ride segments for which both physical and subjective data existed. The correlation matrix for this composite data set is shown in Table II-14. Roll has the strongest correlation with comfort (R = .63), while noise, vertical and lateral acceleration are moderately correlated with comfort.

A principal components analysis of the correlation matrix yielded only one eigenvalue greater than unity. The first principal component accounted for 71% of the total variance. The six motion variables had loadings between .85 and .94, noise loaded .70, and comfort .54. With three components, 90% of the variance was accounted for; these three components were rotated to a varimax solution. Rotated Component 1 is motion, 2 is comfort, and 3 is noise. Component 2 also involves roll and, to a lesser extent, noise, vertical and lateral acceleration.

Clearly, a composite model for these data will involve roll and noise in the prediction of comfort. A stepwise regression solution yields:

$$C' = 1.42 + .69\omega_R + .04 \quad (dB(A) - 60), \qquad (7)$$

$$\sigma = (.20) \quad (.10) \qquad (.02) .$$

This equation has a multiple R of .65, thus accounting for 42% of the variance in comfort judgments. As a general descriptive model for ground-based vehicles, this is acceptable.

B. Comparison with Air Mode

In previous papers (Jacobson and Richards, 1976 and 1977), models for predicting comfort judgments from motion variables were developed for aircraft. Several differences are apparent in the data for air versus ground

TABLE II-14. REGRESSION COEFFICIENTS BY MODE AND MOTION.

Vehicle Type	Roll	Vertical	Transverse	Noise
Bus	1.05 ± .13	16.6* ± 5.2	NA**	NA
Train	.96 ± .21	NA	28.6* ± 8.5	.10 ± .01
Airplane ($a_V \geq 1.6a_T$)	.76* ± NA	18.9 ± 1.0	12.1 ± .2	.19* ± .03
Airplane ($a_V < 1.6a_T$)	NA	1.6 ± .7	39.8 ± 8.6	.19 ± .03

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* Not an important variable for mode

**NA indicates a coefficient is either not available or was statistically meaningless vehicles. First, the spectral content of the three modes are different. The airplane motion is dominated by low-frequency components (i. e., <2hz) for roll rate, vertical and lateral acceleration. In contrast, the bus data, and to a lesser extent the train data, exhibit more high-frequency content. A second difference is the range of motion encountered for the three modes. Table II-2 indicates that there is less angular motion on the airplane than on the ground modes. In addition, higher noise levels were encountered on-board the aircraft.

Models of passenger comfort for the air mode emphasize vertical and transverse accelerations. The general model developed in Jacobson and Richards (1977) is:

$$C' = 17V + 17T + 2.14 \tag{8}$$

for data from three commuter planes and one helicopter. The ground-based models emphasize roll and noise. Note, in Table II-3 and Table II-8, that roll is correlated with both transverse and vertical accelerations. Noise levels (see Table II-2) vary substantially only for the train data. On planes, noise levels are unacceptable; passengers say that they are disturbed by the noise (see Richards and Jacobson, 1976). However, since noise levels are generally high across planes, they do not covary with comfort judgments to the extent that motion does. A model for planes employing both noise and motion was reported in Rudrapatna and Jacobson (1976):

$$C' = 2 + 17a_V + 17a_T + .1\,(dB(A) - 65) \tag{9}$$

If Equation (9) is used to predict comfort judgments for the bus/train composite data set, a correlation of .47 results, which is significant at $p \leq .01$. A model incorporating features of both planes and ground vehicles is:

$$C' = 1.0 + \omega_R + .1\,(dB(A) - 63) + 25T + 15V \tag{10}$$

When it is applied to the ground-based data, the correlation with observed comfort levels is .54.

Another possible composite model is:

$$C' = .5 + 17a_V + 17a_T + .1\,(dB(A) - 70) + .5\omega_R \tag{11}$$

It has a multiple R of .53. While these correlations are not as good as roll alone for the ground-based data, it is possible to predict comfort levels in ground-based vehicles using models developed in the air mode. This confirms the hypothesis that there are similarities in the way people react to to motion in these various vehicles. Given sufficiently extensive data sets, it should be possible to obtain general models of human reaction to motion independent of vehicle type.

It is important to realize that the coefficients for these models represent a compromise and that such models will not fit any of the other three existing data bases as well as the mode-specific equations that were developed earlier. However, in cases where the vehicle environment differs from any of the specific existing modes, the above models may provide useful guidance for estimating the ride quality or determining tradeoff benefits of a future vehicle.

The dominant factors influencing comfort judgments for the air mode are different from those for buses and trains. Vertical and transverse accelerations are dominant motions for planes; roll rate is dominant for ground-based vehicles. Table II-14 shows the similarities in response to these motion variables and noise for the three vehicles for which models have been developed. There are two rows for the air mode because a difference in comfort reaction is apparent depending on whether $a_V \geq 1.6\ a_T$ or not. Data for which $a_V \leq 1.6\ a_T$ has been gathered on simulators. In commercial vehicles, $a_V \geq 16\ a_T$.

VI. A DISTRIBUTED RESPONSE RIDE-QUALITY MODEL

Ride quality models predict overall (average) passenger response to vehicle motions, but additional assumptions are needed to characterize the distribution of responses among passengers. Investigators have long realized that a particular set of vehicle motions elicits different comfort responses from different individuals. For example, on a standardized scale of 1 - 7, from "very comfortable" to "very uncomfortable," it is not uncommon to observe four or more different passenger responses to a given set of vehicle motions. The distribution of passenger responses in the bus and train studies is shown in Appendix D.

If a response distribution can be estimated for a vehicle, then one may estimate the probability that, say, 90% of the passengers are "comfortable." The criterion level defining "comfortable" is set by the user of the model, but it will be a certain mean comfort rating. Conversely, if it is desired that a stated percentage of the population is to be comfortable, the model estimates the allowable motions level which would yield that level of comfort.

This analysis of the response distribution is based on the empirical bus and train data gathered during Phase 1 as presented in Sections III. A. and IV. A. The underlying model to be used is based on the binomial distribution.

A. Binomial Model

The binomial distribution is a reasonable choice in approximating a discrete probability density function such as the present response distribution. One can envision the mean comfort response as representing the response for the average individual; particular passengers, with particular individual traits, will vary in their response around this average. In other words, the vehicle motions and environment will lead the "average" subject to respond at the mean comfort level; individual passengers will respond "near" this mean level, but not necessarily exactly at that level. The binomial distribution may be defined over seven values and is governed by a two parameter probability density function (pdf). Before describing this distribution, however, it is useful to modify our passenger responses from a 1 - 7 scale to a 0 - 6 scale, a change which makes the scale more conformable to the binomial pdf:

Description	Original Comfort Rating	Modified Comfort Rating
Very Comfortable	1	0
Comfortable	2	1
Somewhat Comfortable	3	2
Neutral	4	3
Somewhat Uncomfortable	5	4
Uncomfortable	6	5
Very Uncomfortable	7	6

Given this change, the binomial pdf is defined as follows:

$$f_X(x) = \binom{n}{x} p^x (1-p)^{n-x}, \quad 0 \leq x \leq n \tag{12}$$

where n and p are the two parameters of the distribution. These two parameters are defined by the expectation, E(x), and variance, V(x), of the binomial pdf, where:

$$E(x) = np \tag{13}$$

and

$$V(x) = np\,(1 - p). \tag{14}$$

In the case of the passenger responses, the "n" parameter is equal to six, the maximum value in the modified response scale. Therefore, only one of the above equations will be used in estimating the second parameter "p", to be called the probability parameter. In particular, the equation for E(x) will be used. Note that because n is fixed, we have two equations and one unknown. If both the variance and mean are observed from empirical data, the p parameter is overspecified.

The following equation, which follows from Equation (13), may be used to estimate p as a function of an observed or estimated mean comfort value, $\bar{c}$, on the original comfort scale:

$$p = \frac{\bar{c} - 1}{6} \tag{15}$$

Having estimated p, the complete response distribution may be estimated using Equation (12). This equation, which defines the probabilities for the modified comfort scale, also estimates the probabilities on the original comfort scale:

$$P\,(\text{Comfort Rating} = c) = f_X\,(c - 1), \quad c = 1,\ 7, \tag{16}$$

or

$$P\,(\text{Comfort Rating} = c) = \binom{6}{c-1} \left[\frac{\bar{c} - 1}{6}\right]^{c-1} \left[1 - \frac{\bar{c} - 1}{6}\right]^{7-c} . \tag{17}$$

Where the leading term is the binomial coefficient and can be expressed in terms of factorials as:

$$\binom{6}{c-1} = \frac{6\,!}{(7 - c)\,!\,(c - 1)\,!}$$

The above probabilistic model of ride comfort is the basis for the estimates shown in the following two sections. In Section 1, below, the model is used with the empirical $\bar{c}$ as the primary input; Section 2, below, examines the case where $\bar{c}$ is estimated using a linear regression model of the form shown in Sections III. A. and IV. A., above.

1. Binomial Model Using Empirical Comfort Mean

This section examines the results of the binomial pdf model when the input to Equation (15) is the empirical mean comfort response. That is, the observed comfort responses for a sample segment are used to define the mean comfort value for that sample. This empirical $\bar{c}$ is then used in Equation (15) to estimate the probability parameter p.

In order to compare a theoretical pdf to an empirical pdf, a statistical "goodness of fit" test is required. The test to be used is the Kolmogorov-Smirnov one-sample test (Siegal, 1956). This is a non-parametric goodness of fit test which may be applied to problems with small sample sizes (in this case, 25 - 30). The critical Kolmogorov-Smirnov statistic, D, is defined as follows:

$$D = \max_{X} \left| F_e(x) - F_t(x) \right| \qquad (18)$$

where $F_e(x)$ = The empirical cumulative probability distribution function (Cdf) observed in the experiment; and

$F_t(x)$ = The theoretical cumulative probability distribution function to which the empirical Cdf is being compared.

The critical values for D depend on the sample size. For sample sizes 25 to 30 and a .05 level of significance, the critical value of the Kolmogorov-Smirnov statistic is .24. Thus, if $D > .24$ for a particular distribution, one rejects the hypothesis at a .05 level of significance that the observed empirical distribution is identical to the theoretical distribution.

Recall that the data collected in Phase 1 of the bus and train studies consist of 52 and 79 sets of comfort response distributions respectively. The objective is to fit a theoretical pdf to the response distribution. The goodness of fit statistic, D, is therefore defined for each sample segment. Rather than displaying this statistic for each segment individually, Table II-15 displays summary information on the two studies--the average D, the maximum D, and the minimum D values observed in the bus and train studies.

Note that in both the bus and train studies, the maximum D value observed in any particular sample is .20 and .22 respectively. Neither of these values would cause rejection of the null hypothesis that the binomial

TABLE II-15. KOLMOGOROV-SMIRNOV GOODNESS OF FIT STATISTICS (D) FOR BUS AND TRAIN EXPERIMENTS USING EMPIRICAL VALUES FOR THE MEAN COMFORT.

Bus Data	Average D	Maximum D	Minimum D
Binomial Model Using Empirical $\bar{c}$ *	.10	.20	.02
Train Data			
Binomial Model Using Empirical $\bar{c}$	.13	.22	.05

---

*The "empirical" $\bar{c}$ is the mean comfort rating observed in the actual experiment. This is distinguished from the "estimated" $\bar{c}$, which is estimated using a mathematical model of comfort versus ride motion and environmental variables.

pdf is the parent distribution underlying the observed response distribution. In fact, the degree of fit is generally very good. The average D value observed is .10 and .13, respectively, reflecting excellent fit between the observed data and the bionmial pdf. Further evidence of this good fit is seen in Table II-16 which displays the best fit, worst fit and an "average" fit for the binomial pdf as applied to the bus and train studies. The best fit is the sample ride segment in which the D statistic is smallest; the worst fit is the segment in which D is largest; and the average fit is a segment in which D is equal to the average value defined in Table II-15 (D = .10 for the bus and D = .13 for the train).

Finally, Figures II-5 and II-6 display the empirical data for the average fit segments and the binomial pdf approximations. Although there are discrepancies between the actual and theoretical frequencies within each comfort rating, the overall fit is clearly representative of the empirical data.

2. Binomial Model Using Estimated Comfort Mean

The previous section discussed the binomial pdf in the case where the input to Equation (15) is the observed mean comfort rating. This section examines the more interesting problem of estimating the response distribution when the actual mean comfort rating is unknown--i.e., when the mean comfort must be estimated as a function of the environmental and motion variables. In particular, the mean comfort level for a particular ride segment will be estimated using the ride quality models for buses and trains from Sections III.A. and IV.A.

Restating these equations:

$$C'_B = .87 + 1.05\omega_R \quad \underline{\text{BUS MODEL}}\,, \tag{19}$$

and

$$C'_T = .73 + .10\,(\text{dB(A)} - 60) + 96\omega_R \quad \text{TRAIN MODEL}\,, \tag{20}$$

where

dB(A) = A-weighted decibel reading, and

R = RMS roll rate.

Because these equations have inherent uncertainty in them, one expects the results to these equations, when input to a probability model, will yield less exact results than the results observed in Section 1, above. This is precisely what occurs.

TABLE II-16. BEST FIT, WORST FIT, AND "AVERAGE FIT" SAMPLES FOR BUS AND TRAIN EXPERIMENT USING BINOMIAL EMPIRICAL $\bar{c}$ MODEL.

Bus Experimental Results

	Frequency of Passenger Responses					
	"Average Fit"		Worst Fit		Best Fit	
Comfort Rating	Actual	Binomial Empirical	Actual	Binomial Empirical	Actual	Binomial Empirical
1	1	1.5	0	.0	6	6.3
2	8	5.7	1	.5	12	11.0
3	10	9.2	8	2.5	7	7.9
4	2	7.8	0	6.5	3	3.1
5	6	3.8	8	9.5	1	0.7
6	2	1.0	6	7.4	0	0.1
7	0	0.1	6	2.4	0	0.1

Train Experimental Results

	Frequency of Passenger Responses					
	"Average Fit"		Worst Fit		Best Fit	
Comfort Rating	Actual	Binomial Empirical	Actual	Binomial Empirical	Actual	Binomial Empirical
1	0	2.9	4	10.5	8	7.2
2	11	8.3	23	12.1	12	11.6
3	14	9.9	3	5.8	6	7.8
4	2	6.3	0	1.5	2	2.8
5	2	2.2	0	0.2	2	0.6
6	1	0.4	0	0.0	0	0.1
7	0	0.0	0	0.0	0	0.0

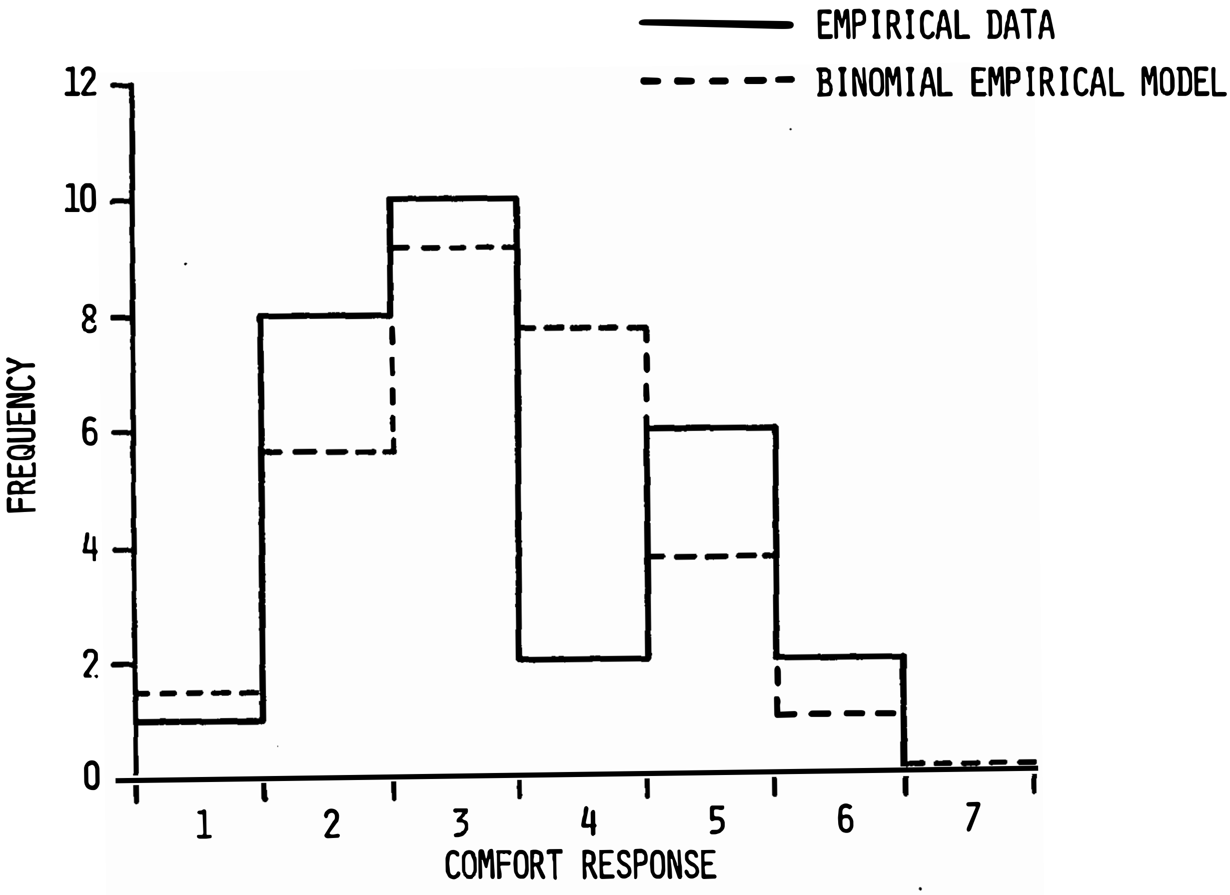

FIGURE II-5. BINOMIAL EMPIRICAL MODEL
FOR AN "AVERAGE" SAMPLE POINT IN THE PHASE 1 BUS STUDY.

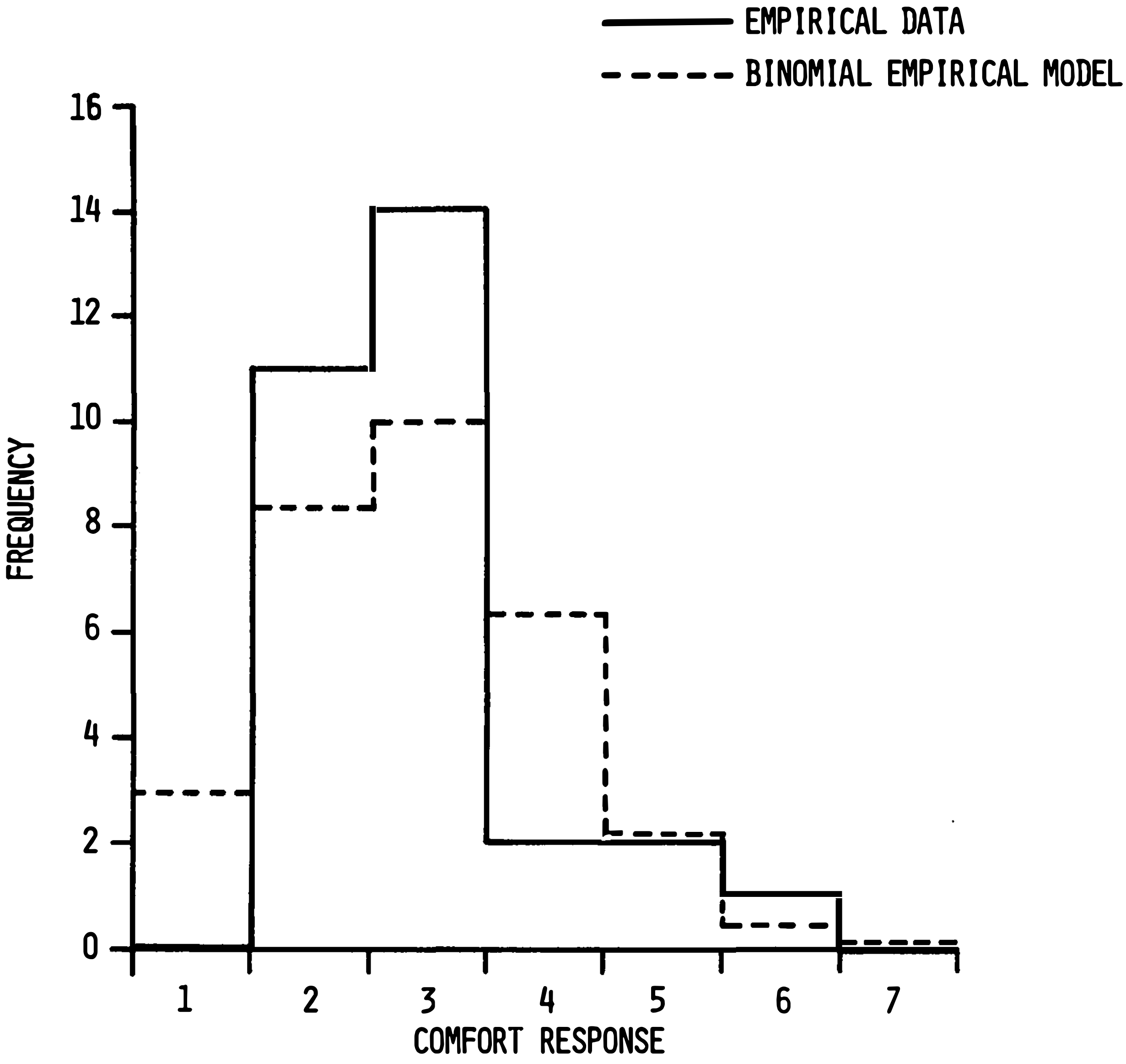

FIGURE II-6. BINOMIAL EMPIRICAL MODEL
FOR AN "AVERAGE" SAMPLE POINT IN THE PHASE 1 TRAIN STUDY.

Table II-17 displays the Kolmogorov-Smirnov statistics for the binomial pdf when the input is the estimated $\bar{c}$. The results in this case are noticeably worse than in Section 1. The average D statistic is .26 for both the bus and train studies, a value greater than the critical value of .24. In addition, very poor estimates were obtained on particular segments, with D statistics as large as .58 and .92, respectively, for the bus and train data. A comparison of the binomial pdf with the response distribution is displayed in Table II-18, again for the best fit, worst fit, and average fit cases. Although the best fit is acceptable, the worst fit case bears no real resemblance to the empirical data. The average fit is only marginally acceptable from a practical point of view and not acceptable statistically.

It should be noted that there is, as expected, high correlation between a good mean comfort estimate and a good response distribution estimate. For example, the worst case fit for the bus study occurs when the empirical mean comfort rating is 2.52 and the estimated mean comfort is 3.97, a 58% error. Similarly, the best case fit for the bus study occurs when the empirical mean comfort rating is 2.34 and the estimated mean comfort is 2.23, a 6% error. This is not surprising given the central role of the probability parameter p in the binomial pdf model.

B. Summary and Discussion

The fundamental result is that the binomial model is a statistically acceptable estimator of the comfort response distribution when the model parameter p is defined by the observed data. That is, given the mean of the passenger's comfort rating, then the binomial model may be used reliably to estimate the comfort response distribution.

A second important result is that the distribution model is not statistically acceptable when estimated parameters are used for the comfort mean. Generally, the "goodness of fit" of the estimated theoretical distributions is directly related to the reliability of the mean comfort estimate. If the estimated mean comfort is "near" the actual mean comfort level, the estimated distribution is a good approximation for the empirical distribution; if the estimated mean comfort is a poor estimate of the actual mean comfort, the estimated distribution is also a poor estimate of the empirical distribution. In other words, the reliability of the theoretical response distribution models is only as good as the reliability of the estimated mean comfort model.

Given that the probability distribution of the passenger responses depends only on the mean passenger response, one can generate the response distribution as a priori, as a function of $\bar{c}$. The more interesting issue, however, is related to the proportion of passengers who find a ride acceptable. For example, given that $\bar{c} = 3.4$, what proportion of the passengers find the ride "comfortable" or better? Table II-19 displays the information which addresses

TABLE II-17. KOLMOGOROV-SMIRNOV GOODNESS OF FIT STATISTICS (D) FOR BUS AND TRAIN EXPERIMENTS USING ESTIMATED VALUES FOR THE MEAN COMFORT.

	Average D	Maximum D	Minimum D
Bus Data			
Binomial Model Using Estimated $\bar{c}$*	.26	.58	.05
Train Data			
Binomial Model Using Estimated $\bar{c}$	.26	.92	.06

---

*The "estimated" $\bar{c}$ is estimated using a mathematical model of comfort versus ride motion and environmental variables. This is distinguished from the "empirical" $\bar{c}$, which is the mean comfort rating observed in the actual experiment.

TABLE II-18. BEST FIT, WORST FIT AND "AVERAGE FIT" SAMPLES FOR BUS AND TRAIN EXPERIMENT USING BINOMIAL ESTIMATED $\hat{c}$ MODEL.

Bus Experimental Results

Frequency of Passenger Responses

	"Average Fit"		Worst Fit		Best Fit	
Comfort Rating	Actual	Binomial Estimated	Actual	Binomial Estimated	Actual	Binomial Estimated
1	5	2.6	3	0.5	6	7.4
2	11	7.1	17	2.8	12	11.3
3	7	8.2	5	6.9	7	7.3
4	2	5.1	1	9.1	3	2.5
5	0	1.8	1	6.7	1	0.5
6	0	0.3	2	2.6	0	0.1
7	0	0.0	0	0.4	0	0.0

Train Experimental Results

Frequency of Passenger Responses

	"Average Fit"		Worst Fit		Best Fit	
Comfort Rating	Actual	Binomial Estimated	Actual	Binomial Estimated	Actual	Binomial Estimated
1	1	3.8	8	0.3	8	9.0
2	20	9.4	22	2.2	12	12.0
3	5	9.6	0	6.2	6	6.7
4	0	5.3	0	9.3	2	2.0
5	4	1.6	0	7.8	2	0.3
6	0	0.3	0	3.5	0	0.0
7	0	0.0	0	0.7	0	0.0

TABLE II-19. PROBABILITY DISTRIBUTION OF PASSENGER RESPONSES AS A FUNCTION OF MEAN COMFORT VALUES.

MEAN COMFORT	x ≤ 1	x ≤ 2	x ≤ 3	x ≤ 4	x ≤ 5	x ≤ 6	x ≤ 7
1.10	.90	1.00	1.00	1.00	1.00	1.00	1.00
1.20	.82	.98	1.00	1.00	1.00	1.00	1.00
1.30	.74	.97	1.00	1.00	1.00	1.00	1.00
1.40	.66	.94	.99	1.00	1.00	1.00	1.00
1.50	.59	.92	.99	1.00	1.00	1.00	1.00
1.60	.53	.89	.98	1.00	1.00	1.00	1.00
1.70	.48	.85	.98	1.00	1.00	1.00	1.00
1.80	.42	.81	.97	1.00	1.00	1.00	1.00
1.90	.38	.78	.95	.99	1.00	1.00	1.00
2.00	.33	.74	.94	.99	1.00	1.00	1.00
2.10	.30	.70	.92	.99	1.00	1.00	1.00
2.20	.26	.66	.90	.98	1.00	1.00	1.00
2.30	.23	.61	.88	.98	1.00	1.00	1.00
2.40	.20	.57	.86	.97	1.00	1.00	1.00
2.50	.18	.53	.83	.96	1.00	1.00	1.00
2.60	.16	.49	.80	.95	.99	1.00	1.00
2.70	.14	.46	.77	.94	.99	1.00	1.00
2.80	.12	.42	.74	.93	.99	1.00	1.00
2.90	.10	.38	.71	.92	.99	1.00	1.00
3.00	.09	.35	.68	.90	.98	1.00	1.00
3.10	.08	.32	.65	.88	.98	1.00	1.00
3.20	.06	.29	.61	.86	.97	1.00	1.00
3.30	.05	.26	.58	.84	.97	1.00	1.00
3.40	.05	.23	.54	.82	.96	1.00	1.00
3.50	.04	.21	.51	.80	.95	.99	1.00
3.60	.03	.19	.48	.77	.94	.99	1.00
3.70	.03	.16	.44	.74	.93	.99	1.00
3.80	.02	.14	.41	.72	.92	.99	1.00
3.90	.02	.13	.38	.69	.91	.99	1.00
4.00	.02	.11	.34	.66	.89	.98	1.00
4.10	.01	.09	.31	.62	.87	.98	1.00
4.20	.01	.08	.28	.59	.86	.98	1.00
4.30	.01	.07	.26	.56	.84	.97	1.00
4.40	.01	.06	.23	.52	.81	.97	1.00
4.50	.01	.05	.20	.49	.79	.96	1.00
4.60	.00	.04	.18	.46	.77	.95	1.00
4.70	.00	.03	.16	.42	.74	.95	1.00
4.80	.00	.03	.14	.39	.71	.94	1.00
4.90	.00	.02	.12	.35	.68	.92	1.00
5.00	.00	.02	.10	.32	.65	.91	1.00
5.10	.00	.01	.08	.29	.62	.90	1.00
5.20	.00	.01	.07	.26	.58	.88	1.00
5.30	.00	.01	.06	.23	.54	.86	1.00
5.40	.00	.01	.05	.20	.51	.84	1.00
5.50	.00	.00	.04	.17	.47	.82	1.00
5.60	.00	.00	.03	.14	.43	.80	1.00
5.70	.00	.00	.02	.12	.39	.77	1.00
5.80	.00	.00	.02	.10	.34	.74	1.00
5.90	.00	.00	.01	.08	.30	.70	1.00
6.00	.00	.00	.01	.06	.26	.67	1.00
6.10	.00	.00	.01	.05	.22	.62	1.00
6.20	.00	.00	.00	.03	.19	.58	1.00
6.30	.00	.00	.00	.02	.15	.52	1.00
6.40	.00	.00	.00	.02	.11	.47	1.00
6.50	.00	.00	.00	.01	.08	.41	1.00
6.60	.00	.00	.00	.01	.06	.34	1.00
6.70	.00	.00	.00	.00	.03	.26	1.00
6.80	.00	.00	.00	.00	.02	.18	1.00
6.90	.00	.00	.00	.00	.00	.10	1.00
7.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00

this question. This table displays the cumulative density function F(c) as a function of (or conditional on) the mean comfort rating.

Using the above example, one may read the following information from the table: 82% of the passengers find the ride "neutral" or better, 96% of the passengers find the ride "somewhat uncomfortable" or better, and 100% of the passengers find the ride "uncomfortable" or better. In other words, for $\bar{c} = 3.4$, no passengers, in general, will find the ride either very uncomfortable or uncomfortable.

The binomial probability model is applicable to the bus and train studies, but it is perhaps questionable whether the same type of model can be applied to other travel modes. In order to answer this question, the binomial model is applied to 40 segments of an airplane ride comfort study. This analysis, presented below, displays results consistent with those reported here: that the binomial model, using the empirical mean comfort $\bar{c}$ as input, is an excellent representation of the response distribution. In no case can the hypothesis be rejected that the binomial model is the parent distribution of the response distribution. This result is important because it suggests that the binomial model may be applied to ride comfort experiments in both ground <u>and</u> in air modes.

C. Verification of Binomial Model Using Airplance Comfort Data

The applicability of the binomial model to bus and train data was discussed above. The binomial model may also be applied to airplane ride quality data to verify these results. The data used here are extracted from a document prepared for NASA by Schoonover (1974). This document describes airplane ride quality experiments performed by the University of Virginia and by the Hampton Institute. The data used consists of 20 segments on "Flight No. 1" in the University of Virginia experiment and 20 segments on "Flight No. 2" in the Hampton Institute experiment. These two flights were chosen because of the substantial variation in mean comfort response among segments within each flight. The actual comfort responses used in the analysis are presented in Tables II-20 and II-21. Note that there are 10 subject responses for each experimental segment.

Using the Kolmogorov-Smirnov one-sample test, the following results are obtained:

Average D Statistic:	.14
Maximum D Statistic:	.30
Minimum D Statistic:	.02

The critical value of the Kolmogorov-Smirnov statistic for a sample of N = 10 and .05 level of significance is D = .41, a value not exceeded in any

TABLE II-20. COMFORT RESPONSES FROM UNIVERSITY OF VIRGINIA FLIGHT NO. 1 IN TIFS RIDE QUALITY PROGRAM.

Segment Number	Comfort Response							Mean Response
	1	2	3	4	5	6	7	
1	0	0	5	3	1	1	0	3.8
2	0	0	1	3	3	2	1	4.9
3	1	7	2	0	0	0	0	2.1
4	0	0	2	4	4	0	0	4.2
5	0	0	0	0	5	3	2	5.7
6	0	2	5	3	0	0	0	3.1
7	0	1	2	6	1	0	0	3.7
8	0	0	0	0	5	5	0	5.5
9	2	5	2	1	0	0	0	2.2
10	0	0	4	3	3	0	0	3.9
11	0	0	1	7	1	1	0	4.2
12	1	7	2	0	0	0	0	2.1
13	0	0	0	0	5	4	1	5.6
14	0	1	3	2	4	0	0	3.9
15	0	5	2	3	0	0	0	2.8
16	0	0	1	1	3	2	3	5.5
17	0	0	2	5	1	2	0	4.3
18	0	8	1	1	0	0	0	2.3
19	0	1	0	4	4	1	0	4.4
20	0	4	5	1	0	0	0	2.7

TABLE II-21. COMFORT RESPONSES FROM HAMPTON INSTITUTE FLIGHT NO. 2 IN TIFS RIDE QUALITY PROGRAM.

Segment Number	Comfort Response							Mean Response
	1	2	3	4	5	6	7	
1	0	7	1	1	0	1	0	2.7
2	6	4	0	0	0	0	0	1.4
3	1	2	3	1	3	0	0	3.3
4	5	4	1	0	0	0	0	1.6
5	0	2	2	3	2	1	0	3.8
6	7	2	0	0	1	0	0	1.6
7	0	1	0	0	3	0	6	5.9
8	2	6	0	0	1	1	0	2.5
9	0	3	0	2	3	0	2	4.3
10	2	6	1	1	0	0	0	2.1
11	3	3	1	2	1	0	0	2.5
12	0	0	1	0	2	4	3	5.8
13	4	4	0	2	0	0	0	2.0
14	3	4	0	2	1	0	0	2.4
15	0	0	1	2	4	1	2	5.1
16	4	4	1	1	0	0	0	1.9
17	0	0	1	1	2	2	4	5.7
18	4	3	1	2	0	0	0	2.1
19	6	3	1	0	0	0	0	1.5
20	0	2	2	3	2	1	0	3.8

of the 40 airplane experimental segments. The average D statistic over all 40 segments is .14, representing a generally excellent fit between the empirical data and the theoretical model.

Given the above statistics, one cannot reject the hypothesis at a .05 level of significance that the binomial pdf is the parent distribution for the observed airplane comfort responses. This conclusion is compatible with those above in which the binomial pdf is shown to exhibit a statistically "good" fit with the bus and train results.

VII. ALTERNATIVE RIDE QUALITY MODELS

In previous work with aircraft ride quality, multiple regression equations relating comfort response to RMS vehicle motions provided the best models (Jacobson and Richards, 1976 and 1977). Therefore, that type of model was tried first on the present data and found to be quite satisfactory. However, other types of ride quality models have been proposed. Four of these alternative models are examined here; they are an excedance model, a jerk/angular acceleration model, a time weighted comfort model, and the International Standards Organization (ISO) model.

A. Ride Quality Modeling Using Excedance Values

The motion data, collected in these studies, consisted of accelerations and angular velocities recorded for a specific period of time. Data of this type may be characterized in any of several ways: the mean values observed, the RMS about these means, the frequency ranges encountered, the probability density function of the observed values, etc. A measure of particular interest is the "excedance value," where the excedance value is defined as follows:

E_β = That value of a variable (say roll, ω_R) such that some percent in the sample lies within the range $\bar{\omega}_R \pm E_\beta$, that is within E_β units from $\bar{\omega}_R$.

For example, assume a particular segment has a roll rate histogram as follows:

Roll Rate	Probability
.4	.05
.8	.05
1.2	.30
1.6	.30
2.0	.10
2.4	.15
2.8	.05

For this particular segment, some excedance values for $\beta = .50, .70$ and $.90$ are as follows:

$$E_{.50} = 0.2, \quad E_{.70} = 0.4, \quad E_{.90} = 0.8 \qquad (21)$$

Suppose the observed sample varies about the mean within any segment and, for any ride motion, can be represented by the normal distribution. The mean of this normal distribution would be the observed mean of the segment data, and its standard deviation would be estimated by the RMS of the observed data. Six representative motion segments were examined statistically to test for normality. The Kolmogorov-Smirnov one sample test for goodness of fit was used with an $\alpha = .05$.

Of the six segments tested, five were not statistically different from the normal distribution and one was statistically different at a .05 level of significance. Thus, the normal distribution does seem to represent the vehicle motions within the various ride segments.

Assuming that the vehicle motions are normally distributed, then it is true that the excedance value for a segment is simply a linear function of the RMS value. In particular,

$$E_{\beta} = Z_{\beta} \text{ (RMS)} \tag{22}$$

where:

Z_{β} = That value of the unit normal N(0, 1) probability function such that β% of the density function lies in the region $0 \pm Z_{\beta}$, and

RMS = The RMS or standard deviation of the observed sample data within the segment.

For example, typical values for Z_{β}, obtained from the normal distribution table, are $Z_{.90} = 1.64$, $Z_{.95} = 1.96$, $Z_{.99} = 2.58$. Therefore, if the RMS roll rate for a particular segment was, say, $\omega_R = 2.5$, then the appropriate excedance value for = .95 is:

$$\begin{aligned} E_{.95} &= 1.96\ (2.5) \\ &= 4.90 \end{aligned} \tag{23}$$

Since the RMS rates used in RMS models are simply linear functions of the excedance values, or

$$\text{RMS} = \frac{1}{Z_{\beta}} E_{\beta}, \tag{24}$$

the RMS models developed above are as reasonable as any possible excedance value model. Therefore, if the true parameter of importance were the excedance values rather than the RMS values, then it is immaterial whether the regression analysis is performed on the excedance values or on the RMS values.

B. Jerk/Angular Acceleration Models

The regression models developed were based on linear accelerations and angular velocities. However, it is possible that the "jerk" measure, or the time derivative of the acceleration, is more important for passenger comfort than acceleration. Similarly, angular velocities might be less important than angular accelerations. To explore these possibilites, 25 segments of the initial bus data, gathered during Phase 1, were selected.

The original time traces of linear accelerations were differentiated to generate the RMS of the "jerk" measure; and, the angular velocities were differentiated to obtain the RMS angular accelerations for these segments. Appendix E.contains the raw data for these segments.

The subsequent analyses revealed that for a simple univariate regression, non-differentiated data could explain, for this subpopulation of the data, 80% of the variance in passenger responses whereas the differentiated data could only explain 61% of the variance. When a second term is added to the differentiated data, the proportion of variance explained increases to 75%, but is still not as good as the modeling undifferentiated data. When the two sets of data are both included as independent variables, the most important variable is the roll rate followed by longitudinal acceleration. A differentiated variable (pitch acceleration) comes into the stepwise regression third.

Thus, while the differentiated data can be used in ride quality modeling, the results are not as good as those using the undifferentiated data. In terms of simple (one or two variable) models, the undifferentiated model is significantly better. Given the additional time and expense required to differentiate the data, it does not appear to be a worthwhile procedure.

C. Time Weighted Average Comfort Model

This model attempts to relate the passenger's overall satisfaction with a trip to the subjective responses given during individual segments of the trip. Based on previous findings, Jacobson and Richards (1976), it was hypothesized that the ride quality toward the end of a trip would be more important than the ride quality earlier in the trip; i. e., the passenger weights his most recent experiences most heavily. To test this hypothesis, the passengers in the bus and train studies were asked to give subjective responses for both individual segments of roadway and the overall trip. The individual responses for the first, second, third and fourth quarter of the trip were then averaged to yield an average response for the first quarter of the trip, the second quarter of the trip, etc. These data are presented in Table II-22. These average values for the four quarters of the trip were used as the independent variables in a regression with the overall comfort ratings for the trip. If the hypothesis is true, then the most important variable is the average response for the last quarter of the trip.

TABLE II-22. DATA FOR TIME WEIGHTED COMFORT MODEL.

Trip Number	Mean Comfort First 1/4	Mean Comfort Second 1/4	Mean Comfort Third 1/4	Mean Comfort Fourth 1/4	Overall Trip Comfort
Bus #1	3.26	3.95	2.92	3.54	2.50
Bus #2	3.41	3.27	3.02	3.31	2.41
Bus #3	3.04	3.41	3.22	3.48	2.52
Train #1	2.57	2.99	2.88	2.37	1.97
Train #2	2.43	2.67	2.89	2.72	2.03
Train #3	2.57	2.89	2.94	2.29	2.10
Train #4	2.89	3.67	3.92	3.86	2.93

This analysis yields the following best univariate regression equation from the stepwise regression analysis:

$$C_o' = .76 + .52\, x_4 \quad R^2 = .88, \tag{25}$$

where

C_o' = Overall trip comfort rating, and

x_4 = Average comfort response for the last quarter of the trip.

Thus, it does appear that the most important determinant of the overall comfort response is the average comfort response for the last quarter of the trip. A more detailed analysis of the time dependence data may be found in Appendix F.

D. International Standards Organization Ride Comfort Model

The International Standards Organization (ISO), Technical Committee 108 on Mechanical Vibration and Shock has provided a set of guidelines for human exposure to linear accelerations (1969).

Since linear accelerations do not appear in the regression equations derived previously, there is no reason to believe that these guidelines are appropriate for the present data. However, for the sake of completeness, several segments of both bus and train data were analyzed according to the guidelines.

Figures II-7 and II-8 indicate the problem encountered with applying the ISO guidelines in both the vertical and transverse directions. All of the 1/3-octave-band RMS acceleration values fall well below the one-hour reduced comfort boundary for both the bus and train segment selected. The actual comfort ratings, however, indicate that the train segment was uncomfortable. Further, the bus segment should have been rated at least as poorly as the train, but this was not the case. The numbers in parentheses represent predicted comfort ratings based on the models developed in this study. Data from several other ride segments, shown in Appendix G, indicate the general lack of relationship between actual rated comfort and the ISO guidelines. These data support the claims that 1) ISO should incorporate angular rates into their guidelines and 2) the interaction of motion variables needs to be considered in stating guidelines.

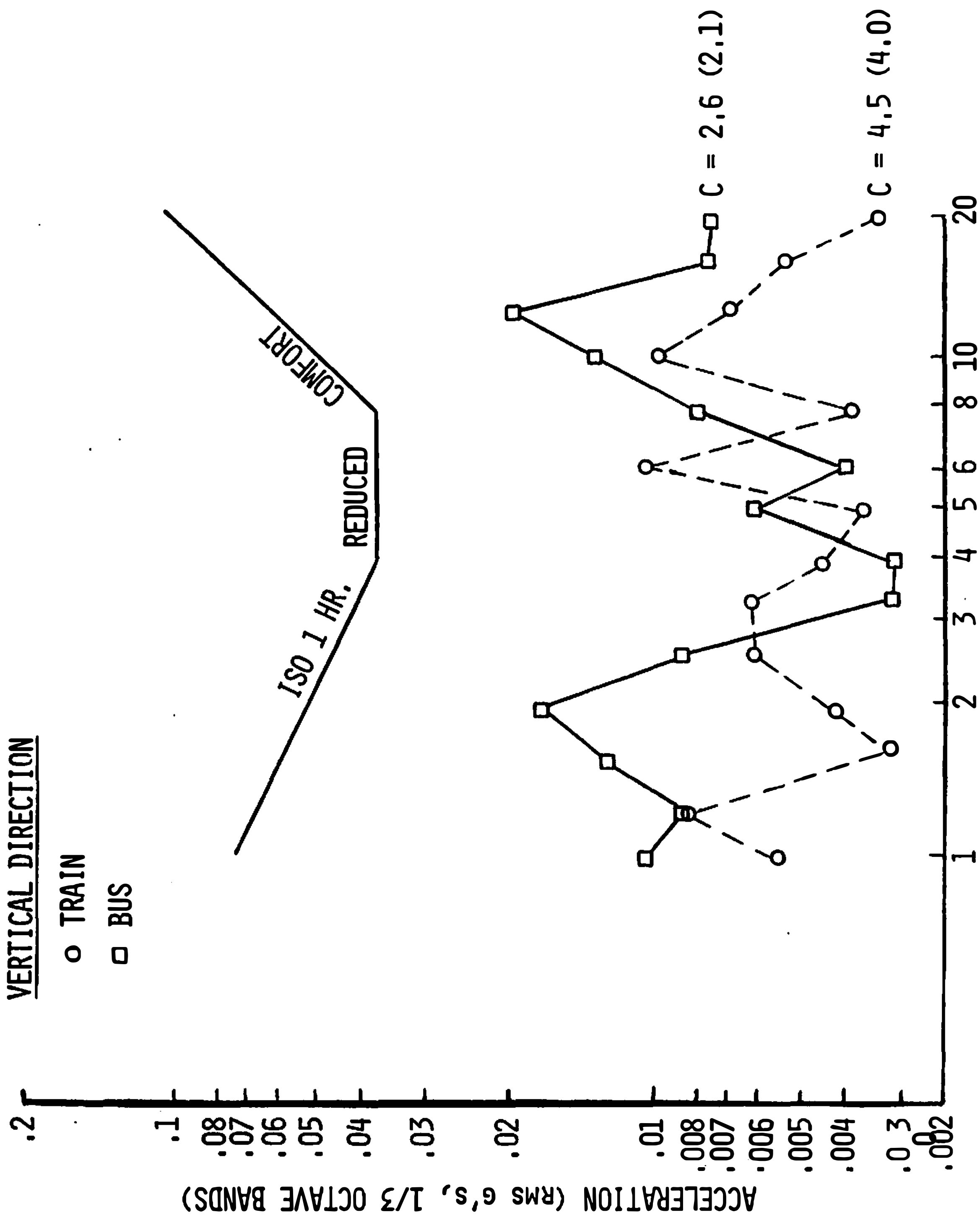

FIGURE II-7. COMPARISON OF ACTUAL RATED COMFORT WITH ISO GUIDELINES FOR VERTICAL DIRECTION.

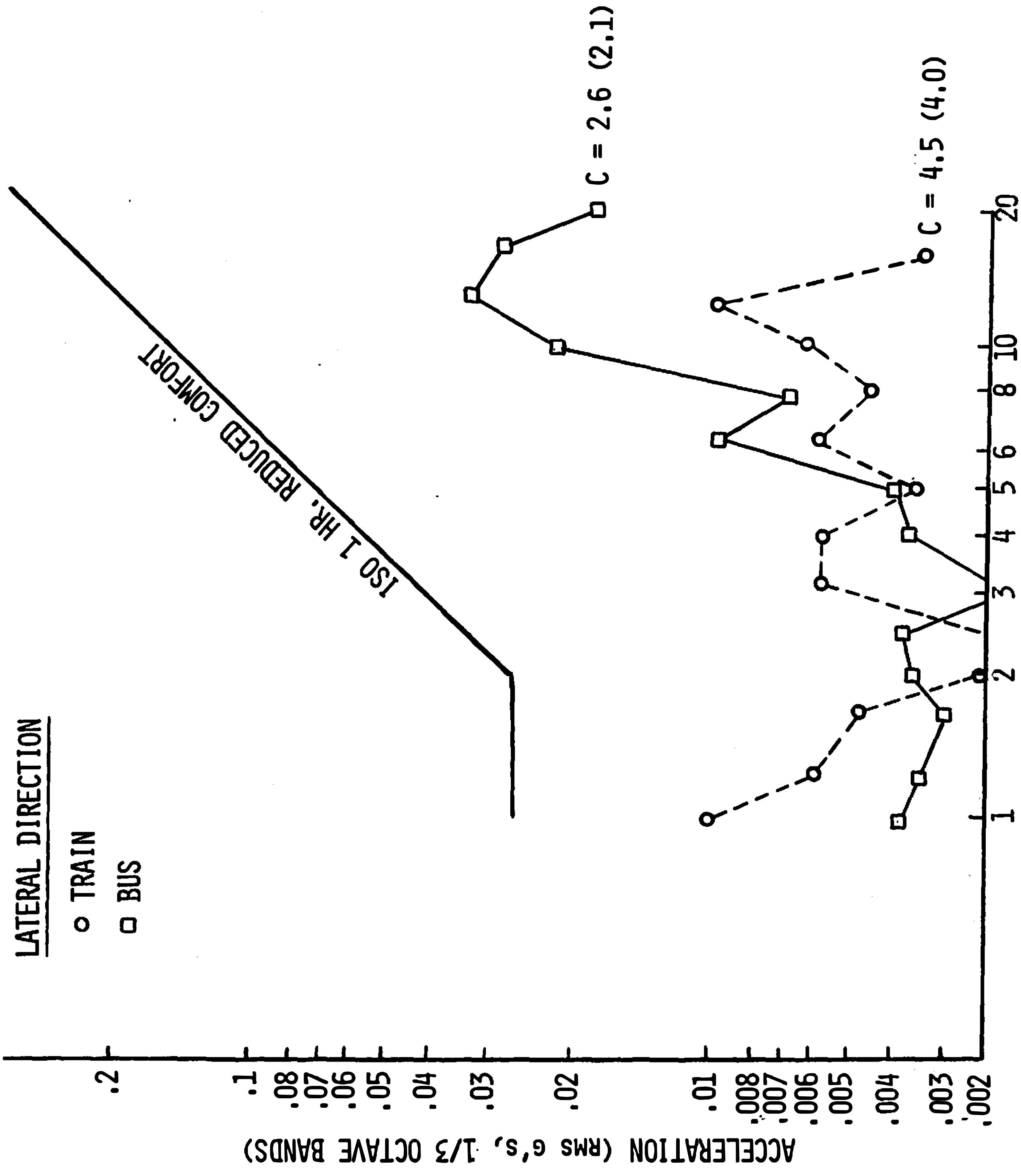

FIGURE II-8. COMPARISON OF ACTUAL RATED COMFORT WITH ISO GUIDELINES FOR LATERAL DIRECTION.

VIII. PRACTICAL APPLICATIONS OF RIDE-QUALITY MODELS

Ride-quality models may be used to evaluate the ride quality of existing or proposed vehicles and to write specifications for new transportation systems.[1] Each of these applications involves selecting the appropriate model, restricting the analysis to those variables within the model and utilizing the quantitative relationships to derive equal comfort zones. It is important to note that none of these applications presupposes the level of ride quality that is acceptable to the general public. The user must select the level of comfort deemed appropriate for the vehicle in question. Some guidance for doing this is provided by previous work (Jacobson and Richards, 1976) that has indicated a relationship between mean comfort level and perceived willingness to take another trip. Although this is not necessarily accurate for all modes and subpopulations or for actual prediction of return trips, it does serve to indicate when passengers might become reluctant to "take another trip" on the mode in question. This relationship is shown in Figure II-9.

A. Specifications for New Vehicles

Models may be used to determine the ride quality specifications for new vehicles. Such specifications may be determined by following the steps described below:

Select the desired mean comfort level.

Restrict the non-inclusive variables.

Apply appropriate comfort model.

Generate equicomfort contours.

Ensure new vehicle environment lies below generated equicomfort contours.

To illustrate this technique, it is applied to the specifications for a new light rail vehicle.

Select the desired mean comfort level. Based on passenger acceptance as shown in Figure II-9, a mean comfort level of C = 3.0 (somewhat comfortable as per scale on Page 10 of this volume) is chosen corresponding to approximately 90% of the population being satisfied with the ride. The user can choose any value desired.

Restrict non-inclusive variables. Since the model used contains only three of the motion variables and noise, all other variables which could cause comfort problems should be restricted to within the range for which the model holds.

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[1] Models presented in the document should not be used where vehicle motion is characterized by uncommon or infrequent shocks (high crest factor motions)

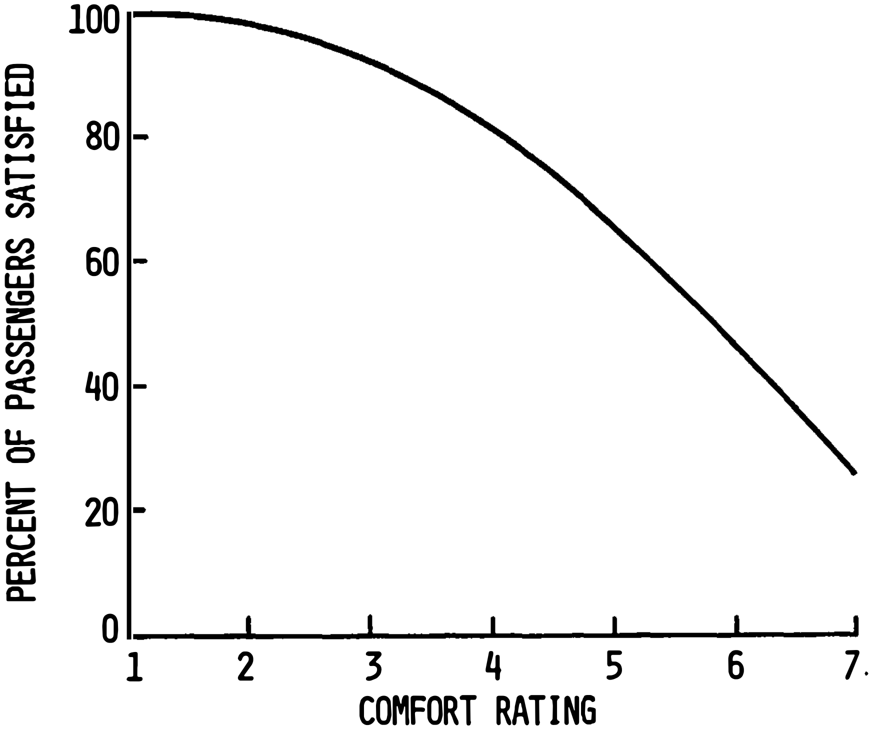


FIGURE II-9. PASSENGERS SATISFIED AS A FUNCTION OF COMFORT.

Thus:

$$\omega_P = 1.0 \text{ deg/sec rms}$$

$$\omega_Y = 2.5 \text{ deg/sec rms}$$

$$a_L = .02 \text{ g} \quad \text{rms}$$

Apply appropriate comfort model. Since the future light rail vehicle will exhibit characteristics which are similar to both trains and buses, the model considered appropriate is a composite model which gives comfort as:

$$C' = 1.0 + .5\omega_R + 0.1\,[\text{dB(A)}] + 17a_T + 17a_V \qquad (26)$$

Generate equicomfort contours. Selecting a noise level representing the desired level on the vehicle in question, e.g., 80 dB(A), allows the generation of surfaces of equal comfort in the remaining three motion dimensions. This is shown in Figure II-10. Changing the noise level to 75 dB(A), as illustrated in Figure II-11, changes the contour substantially upward. That is, lowering the noise level allows higher motion levels and maintains a given comfort rating.

Ensure new vehicle environment lies below generated equicomfort contours. Ensuring the design possesses vehicle motions, which do not exceed the values given for a prescribed railbed, will also ensure compliance with the chosen mean comfort rating. This requires the designer to meet a ride quality specification while still providing the freedom to trade one variable against another in achieving the desired level.

This, of course, does not assure adequate ride comfort for all possible combinations. However, it will give an adequate ride environment for all straight/level road and hill sections of the system. If there are a significant number of curves to be considered, the model for curves should be applied as above and be included as a second criterion to be met.

B. Evaluation of Existing Vehicles

To evaluate the ride quality of an existing vehicle, there are two alternative methods, depending on the data available. If sufficient data exist, taken aboard the vehicle of interest, to make a statistically meaningful prediction (no less than 25 separate measurements of at least 30-second duration over a variety of roadbeds), then the model(s) can be used directly. If not, an analytic process must be used to obtain motion data over the types of roadbeds likely to be encountered. The application described herein assumes the user has on hand the data needed to apply the appropriate model.

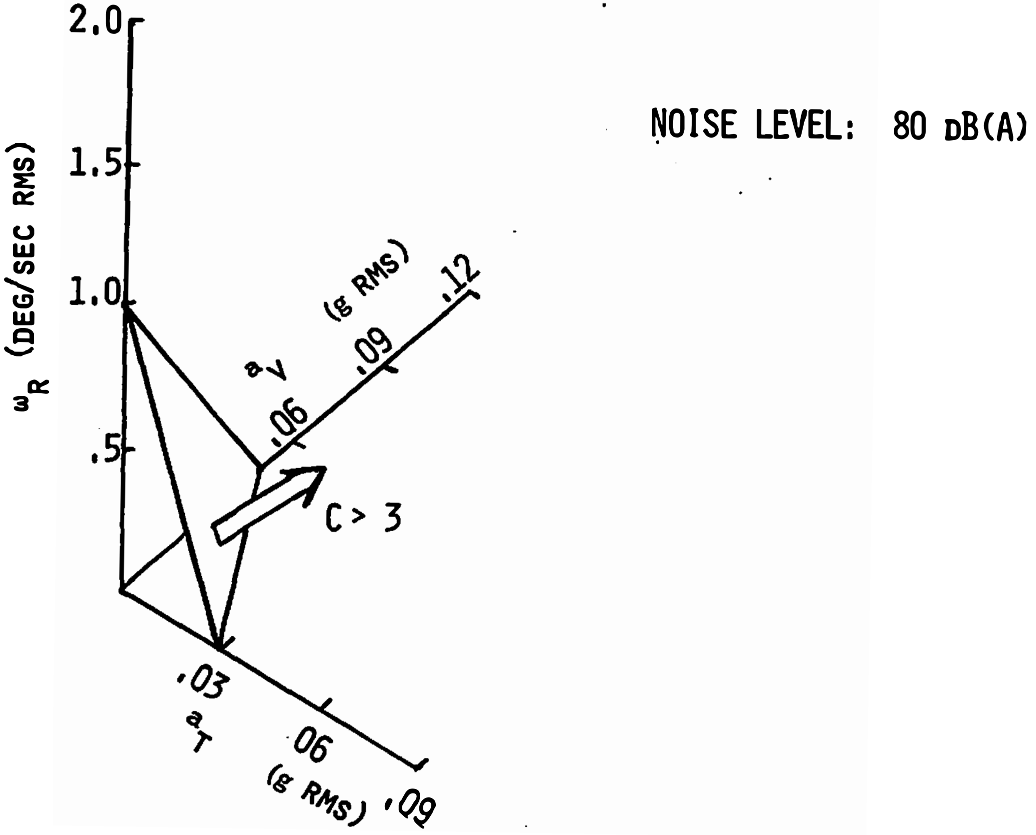
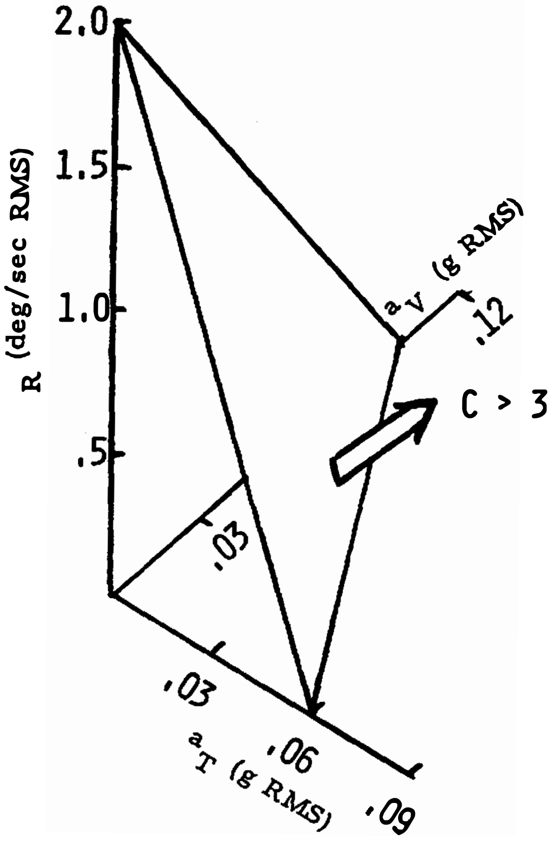


FIGURE II-10. EQUAL COMFORT SURFACE FOR 80 dB(A).



NOISE LEVEL: 75 dB(A)

FIGURE II-11. EQUAL COMFORT SURFACE FOR 75 dB(A).

The steps to be taken are:

Measure (or predict) existing ride environment.

Select appropriate model.

Check motion and noise variables to ensure model applicability.

Apply selected model(s).

Determine distribution about the mean.

Determine satisfaction level.

To illustrate this technique, it is applied to the evaluation of the ride environment of a bus.

Measure existing ride environment. It is assumed, in this case, that an instrumentation package has been placed on the vehicle and that at least 25 segments of the route in question have been analyzed. For each of the 25 segments, the data should include rms values of three linear accelerations and three angular rates with the means biased out and noise in dB(A). Each sample should contain between 30 and 60 seconds of ride environment.

Select the appropriate model. If the vehicle to be evaluated is a bus over straight/level roads or hills, then the appropriate equation gives the mean comfort rating as:

$$C' = .87 + 1.05\omega_R \qquad (27)$$

If curves are to be evaluated as well, then the appropriate equation for curves must also be selected.

Check motion and noise variables. The next step in the process involves examining the ranges of the measured variables. This determines whether the equation is being used over the range for which it was derived or not. If not, the confidence in the results are seriously reduced. For the case of the bus, these ranges are (for straight/level roads or hills):

	ω_R(°/s)	ω_P(°/s)	ω_Y(°/s)	a_L(g's)	a_T(g's)	a_V(g's)	dB(A)
Min	1.1	1.2	1.1	.017	.031	.036	70
Max	4.6	3.6	3.5	.073	.134	.152	83

The user should assess the degree to which the variables, for the data being analyzed, meet these minimum and maximum ranges. Assuming that the data satisfy this requirement, continue with the next step.

Apply selected model. The selected model is applied for each segment. That is, the value of the rms roll rate (mean biased out) is used to determine a mean comfort rating for each segment. For example, if a segment has an rms roll rate of 2 deg/sec, the computed mean comfort rating would be C = 2.97.

Determine distribution about the mean. The distribution about the mean for each comfort rating can be found by using a distributive model such as:

$$P\,(\text{Comfort Rating} = c) = \binom{6}{c-1}\left[\frac{\bar{c}-1}{6}\right]^{c-1}\left[1-\frac{\bar{c}-1}{6}\right]^{7-c} . \quad (28)$$

For the example segment of the previous step, this reduces to

$$P\,(\text{Comfort Rating} = c) = \frac{6!}{(7-c)\,!\,(c-1)!}\left[\frac{1.97}{6}\right]^{c-1}\left[1-\frac{1.97}{6}\right]^{7-c} . \quad (29)$$

which gives the following distribution of responses for the seven comfort ratings. This distribution indicates that although the mean comfort rating for the segment is 2.97, there are 31% of the respondees who can be expected to give a rating of 4 or worse.

Comfort Rating	% Responses
1	9
2	27
3	33
4	21
5	8
6	2
7	0

Determine satisfaction level. Another method of evaluation involves determining the percentage of passengers satisfied for the given mean rating. From Figure II-8, 92% of the passengers will be satisfied for a comfort rating of 2.97. The difference between this calculation and the one above for comfort is accounted for by recognizing that, although uncomfortable, a passenger may still be satisfied if the "other" benefits of the system outweigh comfort.

After each segment has been evaluated, the composite for the entire route can be determined.

C. Evaluation of Proposed New Travel Modes

In considering the ride quality of proposed new travel modes (e. g., magnetic levitated vehicle, air cushion vehicles and automated guideway vehicles), it is necessary to use caution in applying a mode specific model. These vehicles will not always have ride characteristics similar to a conventional mode, e. g., bus, train and aircraft. In many cases, they may have ride characteristics similar to portions of several conventional modes. If the ride environment differs significantly from any single existing mode, it is recommended that a composite model such as the following be used:

$$C' = 1.0 + .5\omega_R + 0.1\,[dB(A) - 65] + 17a_T + 17a_V \qquad (30)$$

The procedure to be followed for the actual evaluation parallels that given above.

Analytically predict the expected ride environment.

Select the appropriate model(s).

Determine the range of validity of the model.

Apply the selected model to determine mean comfort levels.

Determine distribution of responses about mean comfort levels.

Determine passenger satisfaction level.

The only difference between this application and the previous one for an existing mode are: in general, experimental ride environment data will not be available so that the motion and noise environment will have to be analytically determined, and the selection of the appropriate model will require a significant degree of judgment. In reference to the latter, some guidance is provided here.

There are three major areas to examine before determining the appropriateness of a mode specific versus a composite model. These are: dominant motions, correlations between motion variables, and spectral content of motion variables.

First, regarding dominant motions, each mode is dominated by one or more motion/noise variables. For the bus mode, it is the roll rate; for the train, roll rate and noise level; and for the air mode, vertical acceleration, lateral acceleration and noise level. Should the new mode have ranges of the environmental variables exceeding those given in the table of minimums and maximums shown in Section VIII. B., it is possible for one or more of those variables to become the determinant of ride quality. In those cases where no model exists, the user is advised to apply a composite model for best results.

Next, an analysis of the correlation between motion variables should be carried out to determine the amount of interdependence. Finally, the spectra of the major degrees of freedom of the motion variables should be compared with the spectra for each of the existing modes. If the spectra are significantly different from those for existing modes, then a composite model should be used.

Once these comparisons have been made and the user determines that a composite model is the appropriate one, the steps given in Section VIII. B. should be followed, replacing the mode specific model with a composite model.

IX. SUMMARY AND CONCLUSIONS

This volume of the report has shown the statistical characteristics of physical environments encountered by passengers in three types of vehicles, the structure of the correlations between the environmental variables, and the relationships of environmental variables to passenger comfort. The regression models indicate how people in buses, trains and planes integrate physical information to arrive at comfort judgments. The models tell us which variables were important and how to use them for evaluating comfort. Such models are descriptive and are limited to the range of motions actually encountered in the trip situations, but the ride characteristics were varied over the range of values likely to be encountered during normal operation of these kinds of vehicles. Thus, we have confidence they can be applied to trains and buses in most situations that will occur.

Passengers are clearly influenced by the dominant input mode on each type of vehicle; comfort judgments correlate most strongly with those factors that vary most. For ground-based vehicles, roll rate was the dominant motion and passenger comfort judgments were strongly related to it. In the air mode, the linear accelerations, vertical and transverse, were most important. But the correlation matrices and their principal components indicate that there are similarities in the motion characteristics of these vehicles, and suggest that unified comfort models are feasible, given more extensive data. Such general models are needed to specify standards for exposure to environmental inputs and to specify criteria for the design of new vehicles or the assessment of existing ones.

Passenger comfort is, of course, determined by other factors in addition to motion and noise. Aircraft data clearly show the influence of seat characteristics: good seat design can compensate for a basically poor motion spectrum; conversely, poor seats can lower passenger comfort in good motion environments. A complete comfort model would involve both motion and seat variables, as well as other physical factors such as pressure and temperature.

Some systematic variance in comfort judgments was due to individual differences between passengers; such differences were expected and the pasenger characteristics used here did prove to be important. These differences are interesting to psychologists, but are not of major concern to the design engineer. The engineer must design a single system to accommodate the "average" user. While other variables clearly influence comfort, it is important to keep in mind how well comfort judgments are explained with the several physical predictors assessed in this research.

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APPENDIX A.

SAMPLE SUBJECTIVE RESPONSE BOOKLET

DUNLAP AND ASSOCIATES, INC.
and
UNIVERSITY OF VIRGINIA

IN AN EFFORT TO IMPROVE PUBLIC TRANSPORTATION, YOU ARE INVITED TO PARTICIPATE IN A RESEARCH STUDY. THE STUDY CONCERNS PASSENGER REACTIONS TO THE QUALITY OF RIDE AND OTHER FEATURES OF THE SERVICE. IF YOU ARE WILLING TO TAKE PART IN THIS STUDY, PLEASE COMPLETE THE QUESTIONNAIRE.

<u>You need not answer any question that offends you.</u>

1. Age: ___16-24 ___25-34 ___35-48 ___49 and up

2. Male_____ Female_____

3. Approximate household income (before taxes):

____under $10,000 ____$20,000 - $29,999

____$10,000 - $19,999 ____$30,000 or more

4. Are you a licensed automobile driver? ___Yes ___No

5. If you had wished, could you have used a car for this trip? ____Yes ____No

6. How often do you use this type of transportation?

____Daily ____Weekly ____Monthly ____Seldom

7. What is the purpose of your trip?

____Commuting ____Company Business

____Personal Business ____Pleasure

YOU ARE REQUESTED TO RATE THE QUALITY OF RIDE DURING THE PORTIONS OF YOUR TRIP INDICATED BELOW. USE A SINGLE CHECK MARK TO INDICATE YOUR RATING ON EACH COMFORT SCALE, AS APPROPRIATE.

Segment A

____Very Comfortable

____Comfortable

____Somewhat Comfortable

____Neutral

____Somewhat Uncomfortable

____Uncomfortable

____Very Uncomfortable

Segment B

____Very Comfortable

____Comfortable

____Somewhat Comfortable

____Neutral

____Somewhat Uncomfortable

____Uncomfortable

____Very Uncomfortable

Segment C

_____Very Comfortable
_____Comfortable
_____Somewhat Comfortable
_____Neutral
_____Somewhat Uncomfortable
_____Uncomfortable
_____Very Uncomfortable

Segment D

_____Very Comfortable
_____Comfortable
_____Somewhat Comfortable
_____Neutral
_____Somewhat Uncomfortable
_____Uncomfortable
_____Very Uncomfortable

Segment E

_____Very Comfortable
_____Comfortable
_____Somewhat Comfortable
_____Neutral
_____Somewhat Uncomfortable
_____Uncomfortable
_____Very Uncomfortable

Segment F

____Very Comfortable
____Comfortable
____Somewhat Comfortable
____Neutral
____Somewhat Uncomfortable
____Uncomfortable
____Very Uncomfortable

Segment G

____Very Comfortable
____Comfortable
____Somewhat Comfortable
____Neutral
____Somewhat Uncomfortable
____Uncomfortable
____Very Uncomfortable

Segment H

____Very Comfortable
____Comfortable
____Somewhat Comfortable
____Neutral
____Somewhat Uncomfortable
____Uncomfortable
____Very Uncomfortable

Segment I

____Very Comfortable

____Comfortable

____Somewhat Comfortable

____Neutral

____Somewhat Uncomfortable

____Uncomfortable

____Very Uncomfortable

Segment J

____Very Comfortable

____Comfortable

____Somewhat Comfortable

____Neutral

____Somewhat Uncomfortable

____Uncomfortable

____Very Uncomfortable

Segment K

____Very Comfortable

____Comfortable

____Somewhat Comfortable

____Neutral

____Somewhat Uncomfortable

____Uncomfortable

____Very Uncomfortable

Segment L

____Very Comfortable
____Comfortable
____Somewhat Comfortable
____Neutral
____Somewhat Uncomfortable
____Uncomfortable
____Very Uncomfortable

Segment M

____Very Comfortable
____Comfortable
____Somewhat Comfortable
____Neutral
____Somewhat Uncomfortable
____Uncomfortable
____Very Uncomfortable

Segment N

____Very Comfortable
____Comfortable
____Somewhat Comfortable
____Neutral
____Somewhat Uncomfortable
____Uncomfortable
____Very Uncomfortable

NOW THAT YOU HAVE RATED THE QUALITY OF RIDE DURING SEPARATE PORTIONS OF YOUR TRIP, PLEASE GIVE A SINGLE RATING OF RIDE QUALITY FOR THE OVERALL TRIP.

8. The ride during this trip was:

____Very Comfortable

____Comfortable

____Somewhat Comfortable

____Neutral

____Somewhat Uncomfortable

____Uncomfortable

____Very Uncomfortable

YOU HAVE JUST RATED QUALITY OF RIDE. NEXT, PLEASE INDICATE HOW STRONGLY YOU AGREE OR DISAGREE WITH EACH STATEMENT ABOUT OTHER FEATURES OF THE TRIP. CHECK ONLY ONE ANSWER FOR EACH STATEMENT BELOW.

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
9. Seat is comfortable:	____	____	____	____	____
10. Leg room is adequate:	____	____	____	____	____
11. Temperature is right:	____	____	____	____	____

12. Considering the ride you have just rated, if you had a choice, would you:

____ Be eager to take other rides?

____ Take other rides without hesitation?

____ Take another ride, but with some hesitation?

____ Prefer not to take another ride?

____ Not take another ride?

13. If we could significantly improve the service, how much more, if anything, would you be willing to pay per trip for each of the following, or any other improvement? (Please insert dollars, cents or zeros in the appropriate spaces.)

____ More frequent service

____ Improved cleanliness

____ Greater dependability (on timeness)

____ Faster service

____ Greater ride comfort

Other improvements (list)

____ ____________________

____ ____________________

____ ____________________

14. If the fare were increased commensurate with the improvement(s) indicated above, how certain are you that you would continue to use this service?

0% 50% 100%

(Mark the scale, as appropriate)

THANK YOU FOR YOUR HELP

APPENDIX B.

COMFORT RATINGS AND ENVIRONMENTAL MEASURES COLLECTED DURING PHASES 1 AND 2 OF BUS STUDY

TABLE B-1. SUBJECTIVE RESPONSE DATA FROM BUS STUDY FOR STRAIGHT/LEVEL ROADWAYS (PART 1 OF PHASE 1).

Segment Number	All Riders	Male Riders	Female Riders	Young Riders	Middle Age Riders	Older Riders	Frequent Riders	In-Frequent Riders
1	3.31	3.57	3.07	4.20	3.20	2.44	3.28	3.33
2	2.62	2.93	2.33	3.60	2.40	1.78	2.43	2.00
3	3.41	3.71	3.13	3.80	3.60	2.76	3.36	3.47
4	3.24	3.78	2.73	4.00	3.60	2.00	3.00	3.47
5	3.72	4.07	3.40	4.50	3.80	2.78	3.50	3.93
6	2.38	2.71	2.07	3.40	2.40	1.22	2.43	2.33
7	2.96	3.26	2.67	3.90	3.20	1.67	3.00	2.93
8	2.24	2.50	2.00	2.90	2.30	1.44	2.07	2.40
9	6.28	6.21	6.33	6.60	6.50	5.67	6.07	6.47
10	5.90	5.93	5.87	5.91	5.90	6.00	5.80	6.00
11	2.57	2.60	2.53	3.00	2.80	1.78	2.47	2.67
12	3.07	3.40	2.73	3.54	3.30	2.11	2.93	3.20
13	2.60	3.06	2.20	3.36	2.70	1.33	2.53	2.67
14	3.43	3.93	2.93	4.00	3.40	2.56	3.40	3.47
15	3.50	4.13	2.87	3.73	3.70	2.67	3.40	3.60
16	3.50	4.07	2.93	4.36	3.60	2.33	3.40	3.60
17	2.47	2.73	2.20	3.36	2.30	1.56	2.40	2.53
18	4.67	4.53	3.60	5.00	3.70	3.33	3.87	4.27
19	3.26	3.14	3.45	3.68	2.00	3.78	3.27	3.28
20	3.12	2.93	3.36	3.12	2.30	3.78	3.54	2.73
21	6.20	6.43	5.91	6.50	5.62	6.44	5.91	6.43
22	5.28	5.36	5.10	5.50	5.36	5.00	4.73	5.71
23	2.24	2.28	2.18	2.00	2.25	2.44	1.91	2.50
24	2.92	2.66	3.00	3.75	2.25	2.78	2.45	3.23
25	2.32	2.57	2.00	3.12	1.62	2.22	2.03	2.69
26	4.96	5.20	4.71	5.10	4.89	4.90	4.67	5.28
27	2.48	2.80	2.14	2.60	1.89	2.70	2.60	2.36
28	2.79	2.90	2.14	3.30	2.33	2.70	2.53	3.07
29	3.27	3.93	2.67	3.80	3.11	2.90	2.93	3.64
30	2.31	2.76	1.67	2.60	1.70	2.30	2.13	2.50
31	3.21	3.57	1.93	3.40	2.89	3.30	3.07	3.36
32	3.34	3.50	2.87	3.60	2.89	3.50	3.27	3.48
33	3.21	3.36	3.07	3.70	3.11	2.60	3.00	3.43
34	2.52	2.71	2.33	3.10	2.00	2.40	2.33	2.71
35	2.45	2.71	2.20	3.20	1.67	2.40	2.47	2.43
36	2.17	2.50	1.87	2.40	1.78	2.30	2.13	2.21
37	6.10	6.14	6.07	6.10	6.11	6.10	6.00	6.21
38	2.59	2.79	2.47	3.27	2.56	1.70	2.40	2.78
39	3.48	3.71	3.27	4.36	3.56	2.33	3.53	3.43
40	3.62	3.86	3.40	4.27	3.67	2.78	3.67	3.57
41	3.66	4.00	3.33	4.09	4.11	2.67	3.73	3.57
42	2.62	2.71	2.53	3.27	2.44	1.78	2.60	2.64
43	4.03	4.14	3.93	4.45	4.00	3.56	4.00	4.07
44	3.10	3.26	2.93	3.45	3.11	2.56	2.93	3.20
45	2.48	2.93	2.07	3.00	2.67	1.67	2.53	2.43
46	3.34	3.71	3.00	4.18	3.33	2.33	3.33	3.36
47	3.28	3.78	2.80	3.91	3.22	2.56	3.07	3.50
48	3.76	4.21	3.33	4.45	3.44	3.22	3.60	3.93
49	2.31	2.50	2.13	3.09	2.67	1.33	2.13	2.50
50	2.96	3.36	2.60	3.73	3.33	1.67	3.33	2.57
51	2.34	2.57	2.13	2.73	2.67	1.56	2.33	2.30
52	6.31	6.21	6.40	6.36	6.11	6.44	6.13	6.43

TABLE B-2. RIDE ENVIRONMENT DATA FROM BUS STUDY FOR STRAIGHT/LEVEL ROADWAYS (PART 1 OF PHASE 1).

Segment Number	Roll Rate	Pitch Rate	Yaw Rate	Long. Accel.	Trans. Accel.	Vert. Accel.	Noise	Temp. (°F)
1	2.53	2.32	2.51	.05	.09	.08	77.00	65.00
2	2.70	2.46	3.53	.05	.10	.11	77.00	70.00
3	2.59	2.44	2.46	.05	.09	.10	77.00	74.00
4	2.48	2.10	2.43	.07	.06	.08	77.00	74.00
5	2.81	2.64	2.62	.05	.10	.13	77.00	74.00
6	2.29	2.17	2.39	.04	.07	.09	79.00	74.00
7	2.36	2.47	2.71	.05	.05	.10	78.00	74.00
8	2.10	2.05	2.07	.04	.07	.07	75.00	73.00
9	4.33	3.62	3.15	.07	.13	.15	78.00	72.00
10	3.46	2.90	2.07	.09	.13	.14	80.00	72.00
11	1.96	1.83	1.52	.07	.07	.06	75.00	72.00
12	2.67	2.59	2.67	.05	.11	.11	79.00	66.00
13	2.36	2.28	2.39	.05	.11	.09	83.00	68.00
14	2.25	2.15	2.27	.05	.10	.10	82.00	71.00
15	2.50	2.06	2.14	.06	.06	.07	78.00	72.00
16	2.42	2.39	2.22	.04	.09	.10	78.00	71.00
17	1.97	1.91	3.15	.04	.08	.07	77.00	70.00
18	2.33	2.16	2.23	.06	.09	.10	74.00	70.00
19	2.33	3.44	2.53	.04	.06	.10	76.00	68.00
20	2.84	2.60	2.61	.05	.06	.05	72.00	68.00
21	4.66	2.43	2.44	.06	.10	.14	77.00	68.00
22	3.41	2.04	2.14	.05	.07	.10	74.00	69.00
23	1.92	1.92	1.45	.04	.06	.06	70.00	68.00
24	2.44	2.79	2.33	.04	.11	.03	74.00	70.00
25	1.91	2.01	1.91	.03	.06	.06	74.00	70.00
26	3.75	2.42	2.52	.06	.09	.10	77.00	70.00
27	2.25	2.12	2.10	.05	.08	.07	72.00	71.00
28	2.42	2.40	2.36	.05	.10	.10	76.00	70.00
29	2.55	2.36	2.25	.06	.08	.09	76.00	72.00
30	2.19	2.60	3.05	.05	.05	.09	76.00	72.00
31	2.24	2.25	2.01	.04	.05	.09	74.00	72.00
32	3.19	2.25	2.14	.04	.07	.09	79.00	72.00
33	2.31	2.21	2.21	.05	.06	.11	73.00	72.00
34	2.97	2.72	2.73	.03	.13	.09	79.00	72.00
35	2.25	2.12	2.37	.04	.11	.09	79.00	72.00
36	2.04	1.96	1.61	.06	.07	.06	73.00	71.00
37	4.55	2.16	2.06	.05	.09	.11	75.00	70.00
38	1.21	1.20	1.14	.02	.03	.04	75.00	72.00
39	1.27	1.32	1.21	.03	.04	.06	73.00	73.00
40	2.36	1.45	1.50	.02	.04	.05	73.00	73.00
41	1.57	1.65	1.04	.02	.05	.08	73.00	74.00
42	1.12	1.20	2.66	.02	.05	.04	76.00	73.00
43	1.62	1.38	1.14	.04	.04	.06	72.00	72.00
44	1.61	1.34	1.24	.05	.04	.05	72.00	75.00
45	1.43	1.45	2.75	.03	.05	.05	74.00	75.00
46	2.03	2.13	1.34	.02	.05	.09	75.00	74.00
47	2.44	1.66	1.46	.02	.03	.07	75.00	74.00
48	1.33	1.45	2.41	.03	.05	.06	76.00	75.00
49	2.32	2.36	1.32	.02	.04	.04	76.00	74.00
50	1.44	2.67	1.76	.02	.05	.06	77.00	75.00
51	1.26	1.39	1.14	.03	.02	.04	74.00	74.00
52	4.22	1.42	1.45	.06	.06	.03	73.00	75.00

TABLE B-3. SUBJECTIVE RESPONSE DATA FROM BUS VALIDATION STUDY (PHASE 2).

Segment Number	All Riders	Male Riders	Female Riders
1	2.67	3.12	2.00
2	3.18	3.81	2.27
3	3.92	4.56	3.00
4	3.67	4.38	2.64
5	2.85	3.12	2.45
6	2.74	2.75	2.73
7	3.78	4.25	3.09
8	4.50	4.62	4.41
9	2.80	2.69	2.88
10	2.77	2.77	2.76
11	3.20	3.38	3.06
12	2.83	2.69	2.94
13	3.63	3.54	3.70
14	3.71	3.46	3.93
15	3.27	3.69	2.78
16	2.77	2.88	2.64
17	2.60	2.62	2.57
18	2.47	2.75	2.14
19	3.03	3.38	2.64
20	2.57	2.88	2.21
21	3.30	3.56	3.00
22	5.20	5.31	5.07
23	4.07	4.21	3.92
24	2.69	2.86	2.50
25	2.23	2.28	2.17
26	3.08	2.93	3.25
27	2.81	2.78	2.83
28	3.42	3.64	3.17
29	2.67	3.00	2.27

TABLE B-4. RIDE ENVIRONMENT DATA FROM BUS VALIDATION STUDY (PHASE 2).

	Segment	Roll	Pitch	Yaw	a_L	a_T	a_V	dB	Temp.	Response
Day 1 AM	1	1.839	1.684	2.103	.033	.064	.043	72	72	2.67
	2	1.680	1.444	1.480	.011	.037	.045	72	73	3.18
	3	1.678	1.729	2.545	.045	.057	.064	72	73	3.92
	4	1.897	1.628	1.677	.019	.060	.054	72	72	3.67
	5	1.654	1.506	1.191	.027	.035	.049	74	74	2.85
	6	1.674	1.347	1.898	.027	.059	.040	74	73	2.74
	7	1.664	1.344	1.151	.045	.046	.054	73	74	3.78
Day 1 PM	1	1.768	2.358	1.917	.030	.053	.050	70	76	4.50
	2	1.559	1.901	1.153	.032	.039	.042	73	79	2.80
	3	1.252	1.245	.870	.029	.029	.035	71	79	2.77
	4	1.297	1.426	2.693	.010	.029	.025	70	79	3.20
	5	1.461	1.371	1.869	.011	.040	.029	74	79	2.83
	6	1.480	2.480	1.120	.034	.035	.039	69	79	3.63
	7	1.491	2.272	2.168	.017	.063	.046	70	79	3.71
Day 2 AM	1	1.229	1.042	.909	.040	.026	.047	70	72	3.27
	2	1.349	1.207	2.012	.039	.026	.028	67	68	2.77
	3	1.245	1.230	2.197	.030	.051	.028	70	68	2.60
	4	1.411	1.350	1.272	.024	.021	.033	71	67	2.47
	5	1.550	1.461	1.089	.063	.034	.036	68	68	3.03
	6	1.462	1.190	2.101	.063	.048	.035	68	68	2.57
	7	1.658	1.514	1.042	.029	.029	.041	71	69	3.30
	8	2.254	2.799	3.143	.050	.085	.066	71	70	5.20
Day 2 PM	1	1.911	2.229	2.716	.039	.049	.050	70	76	4.07
	2	1.372	1.282	1.053	.025	.029	.039	72	79	2.69
	3	1.312	1.292	1.136	.027	.024	.033	70	80	2.23
	4	1.204	.983	2.620	.008	.029	.026	72	80	3.08
	5	1.163	.986	3.633	.044	.052	.027	68	78	2.81
	6	1.568	1.439	1.275	.024	.037	.046	73	76	3.42
	7	1.138	.952	1.990	.051	.057	.033	72	75	2.67

TABLE B-5. SUBJECTIVE RESPONSE DATA FROM BUS STUDY FOR CURVED ROADWAY (PART 2 OF PHASE 1).

Segment Number	Young Riders	Middle Age Riders	Old Riders	Frequent Riders	Infrequent Riders	Male Riders	Female Riders	All Riders
1	2.69	3.11	2.22	2.77	2.71	2.77	2.71	2.74
2	2.56	2.44	2.67	2.46	2.64	2.59	2.57	2.56
3	2.22	3.22	3.08	3.00	2.64	3.00	2.64	2.81
4	2.11	2.44	2.33	2.38	2.21	2.15	2.43	2.30
5	1.84	2.33	2.33	2.38	2.00	1.92	2.43	2.18
6	2.33	2.56	2.22	2.46	2.20	2.15	2.57	2.37
7	2.11	2.00	2.00	2.23	1.86	2.08	2.00	2.04
8	2.56	2.67	2.22	2.69	2.28	2.69	2.28	2.48
9	3.56	3.89	3.33	3.69	3.50	3.46	3.71	3.59
10	3.67	3.67	3.44	3.46	3.71	3.65	3.36	3.59
11	2.99	3.22	2.78	3.15	2.78	3.08	2.86	2.96
12	2.00	2.33	1.89	2.15	2.08	2.08	2.07	2.07
13	3.44	3.56	2.78	3.36	3.14	3.77	2.76	3.26
14	1.89	2.44	1.85	2.15	2.00	2.08	2.07	2.07
15	2.11	2.00	2.00	2.00	2.17	2.15	1.93	2.04
16	2.56	2.56	2.33	2.77	2.36	2.77	2.36	2.56
17	3.20	3.00	2.56	3.00	2.88	3.00	2.87	2.93
18	3.20	2.70	2.67	2.92	2.81	3.07	2.67	2.86
19	2.90	2.60	2.89	2.92	2.69	3.00	2.60	2.79
20	3.80	3.60	2.78	3.23	3.06	3.21	3.07	3.14
21	4.20	3.10	2.44	3.77	3.30	4.00	3.07	3.55
22	2.50	2.10	2.33	2.61	2.06	2.36	2.27	2.31
23	4.50	3.60	4.11	4.23	3.94	4.07	4.07	4.07
24	5.20	4.60	4.75	5.15	4.75	4.90	5.00	4.93
25	4.80	4.40	3.22	4.15	4.19	4.00	4.33	4.17
26	4.80	4.30	4.00	4.62	4.44	4.57	4.47	4.52
27	3.10	3.40	2.33	3.08	2.80	2.71	3.07	2.97
28	3.80	3.80	3.44	3.69	3.69	3.20	4.07	3.69
29	4.50	4.00	3.56	4.00	4.31	4.07	4.53	4.17
30	2.70	3.00	2.56	2.85	2.69	2.57	3.93	2.76
31	3.40	3.50	2.44	3.54	2.81	3.36	2.93	3.14

TABLE B-6. RIDE ENVIRONMENT DATA FROM BUS STUDY FOR CURVED ROADWAY (PART 2 OF PHASE 1).

Segment Number	Noise	Roll Rate	Pitch Rate	Yaw Rate	Long. Accel.	Trans. Accel.	Vert. Accel.
1	72.00	1.97	1.42	7.14	.04	.10	.04
2	76.00	1.50	1.72	2.25	.02	.05	.06
3	75.00	2.02	1.97	6.66	.03	.12	.05
4	73.00	1.61	1.70	5.04	.03	.09	.04
5	73.00	1.97	1.96	7.50	.05	.09	.04
6	76.00	1.95	1.89	4.01	.03	.08	.04
7	77.00	1.51	1.36	3.62	.02	.07	.05
8	75.00	2.33	1.86	3.30	.02	.06	.05
9	73.00	2.34	1.98	5.02	.03	.08	.05
10	73.00	3.06	2.19	3.33	.02	.05	.05
11	73.00	2.90	2.69	4.11	.03	.05	.05
12	74.00	2.79	2.72	3.82	.03	.05	.05
13	77.00	2.26	2.66	4.56	.02	.07	.05
14	75.00	2.76	2.82	3.44	.03	.04	.04
15	74.00	2.62	2.53	4.30	.02	.04	.05
16	74.00	3.43	3.20	4.46	.04	.07	.06
17	76.00	3.01	2.46	6.67	.06	.10	.05
18	80.00	3.39	3.29	5.75	.03	.08	.07
19	77.00	3.58	3.14	7.07	.05	.16	.06
20	78.00	3.45	3.19	8.48	.09	.14	.06
21	77.00	3.45	3.29	5.05	.04	.12	.08
22	79.00	3.66	3.30	4.57	.05	.10	.07
23	78.00	4.20	3.54	5.37	.04	.11	.08
24	83.00	3.50	2.61	6.79	.04	.17	.06
25	79.00	3.64	3.06	4.80	.04	.11	.08
26	80.00	3.39	2.76	7.39	.04	.16	.06
27	77.00	3.74	3.52	4.64	.03	.09	.06
28	76.00	2.96	2.60	6.08	.03	.11	.06
29	76.00	3.13	2.91	5.51	.03	.12	.06
30	76.00	3.88	3.25	6.03	.02	.11	.06
31	80.00	3.68	3.42	4.21	.06	.08	.06

TABLE B-7. RIDE ENVIRONMENTAL DATA MEANS FROM BUS STUDY FOR CURVED ROADWAY (PART 2 OF PHASE 1).

Segment Number	Mean Roll Rate	Mean Pitch Rate	Mean Yaw Rate	Mean Long. Accel.	Mean Trans. Accel.	Mean Vert. Accel.
1	.17	-.43	7.85	.00	.06	1.00
2	.39	-.79	6.20	-.01	.03	.99
3	.11	-.31	8.85	-.01	.07	1.00
4	.60	.73	4.52	-.01	.09	1.01
5	.47	.19	7.04	.05	.14	1.00
6	.22	.23	4.41	-.02	.11	1.01
7	.83	-.79	1.37	-.01	.10	.99
8	.44	.39	5.67	.01	.13	1.01
9	.10	-.14	6.51	.00	.12	1.00
10	.37	.33	4.47	.02	.07	1.00
11	.23	-.29	5.46	.01	.06	.99
12	.72	.77	7.27	.02	.09	1.01
13	.25	.45	7.69	.02	.07	1.00
14	.41	.57	6.09	.02	.04	1.00
15	1.24	1.41	4.96	.04	.03	1.01
16	2.38	2.37	10.72	.07	.14	1.03
17	3.21	-2.96	9.09	-.02	.08	.96
18	3.18	-2.81	6.97	-.03	.09	.96
19	1.89	-1.96	7.70	-.02	.08	.97
20	.65	.25	9.81	.08	.16	1.01
21	1.23	1.12	10.25	-.01	.22	1.02
22	.53	.57	6.39	-.01	.14	1.01
23	2.04	1.57	11.80	.02	.24	1.03
24	2.11	1.08	12.90	.00	.25	1.02
25	3.27	2.72	12.47	.02	.22	1.05
26	3.32	2.62	12.14	.01	.17	1.04
27	.24	.49	7.46	-.02	.16	1.01
28	2.65	-2.27	12.89	-.02	.17	.97
29	.82	-.83	8.41	-.01	.20	.99
30	1.83	-1.78	11.74	-.03	.18	.97
31	1.02	.35	12.46	.06	.24	1.01

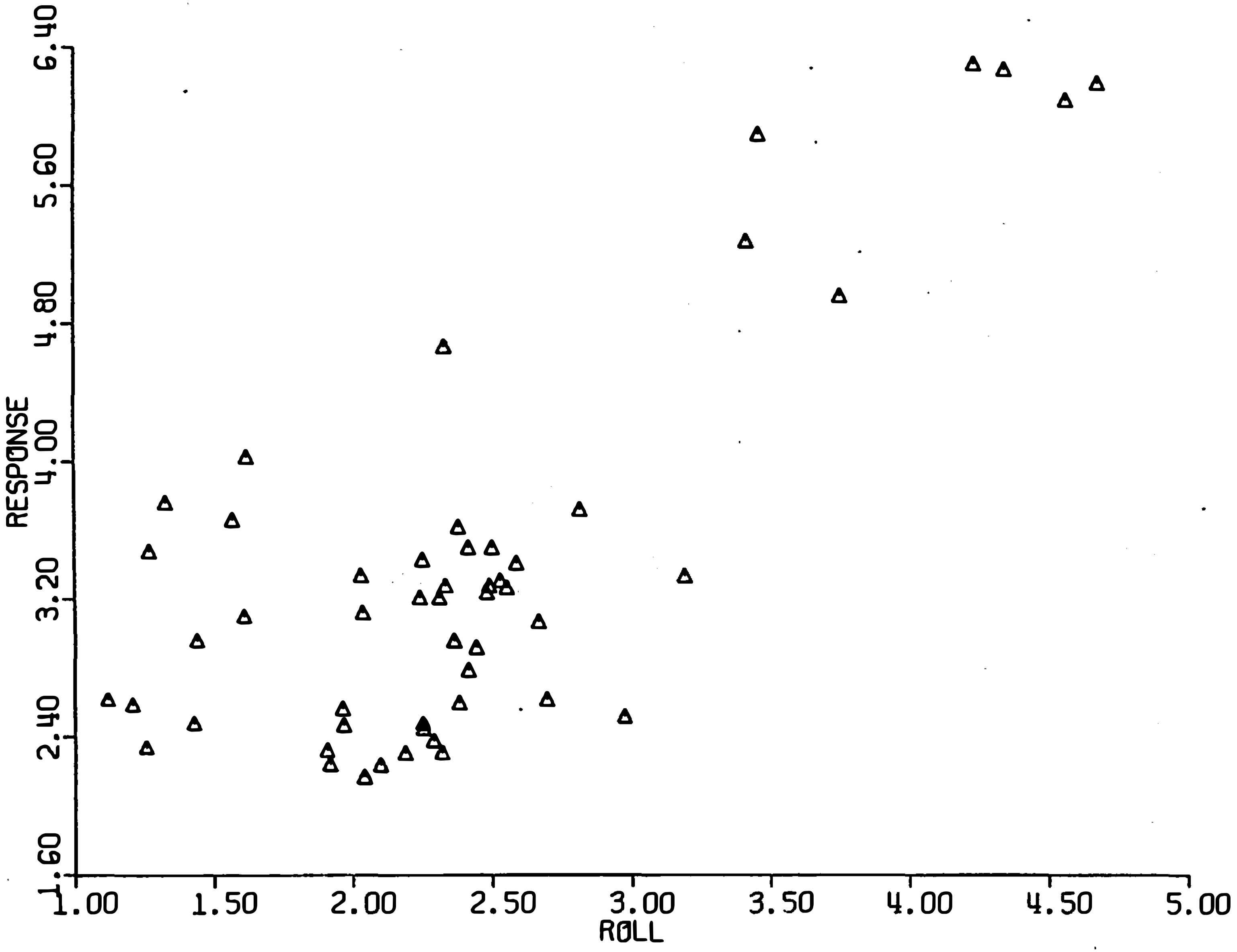

FIGURE B-1. COMFORT RESPONSES VERSUS RMS ROLL RATE FOR STRAIGHT/LEVEL ROADWAY (PART 1 OF PHASE 1).

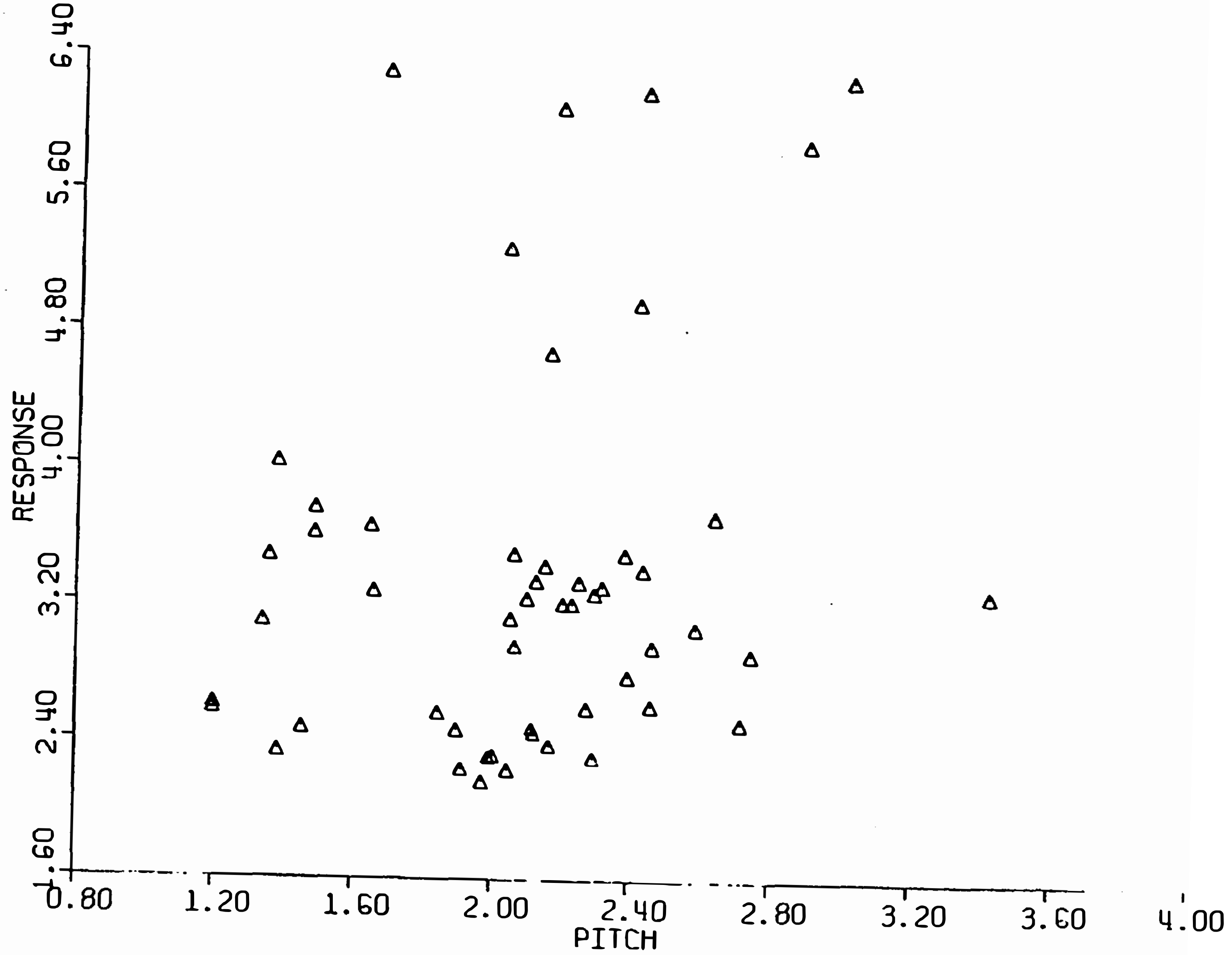

FIGURE B-2. COMFORT RESPONSES VERSUS RMS PITCH RATE FOR STRAIGHT/LEVEL ROADWAY (PART I OF PHASE I).

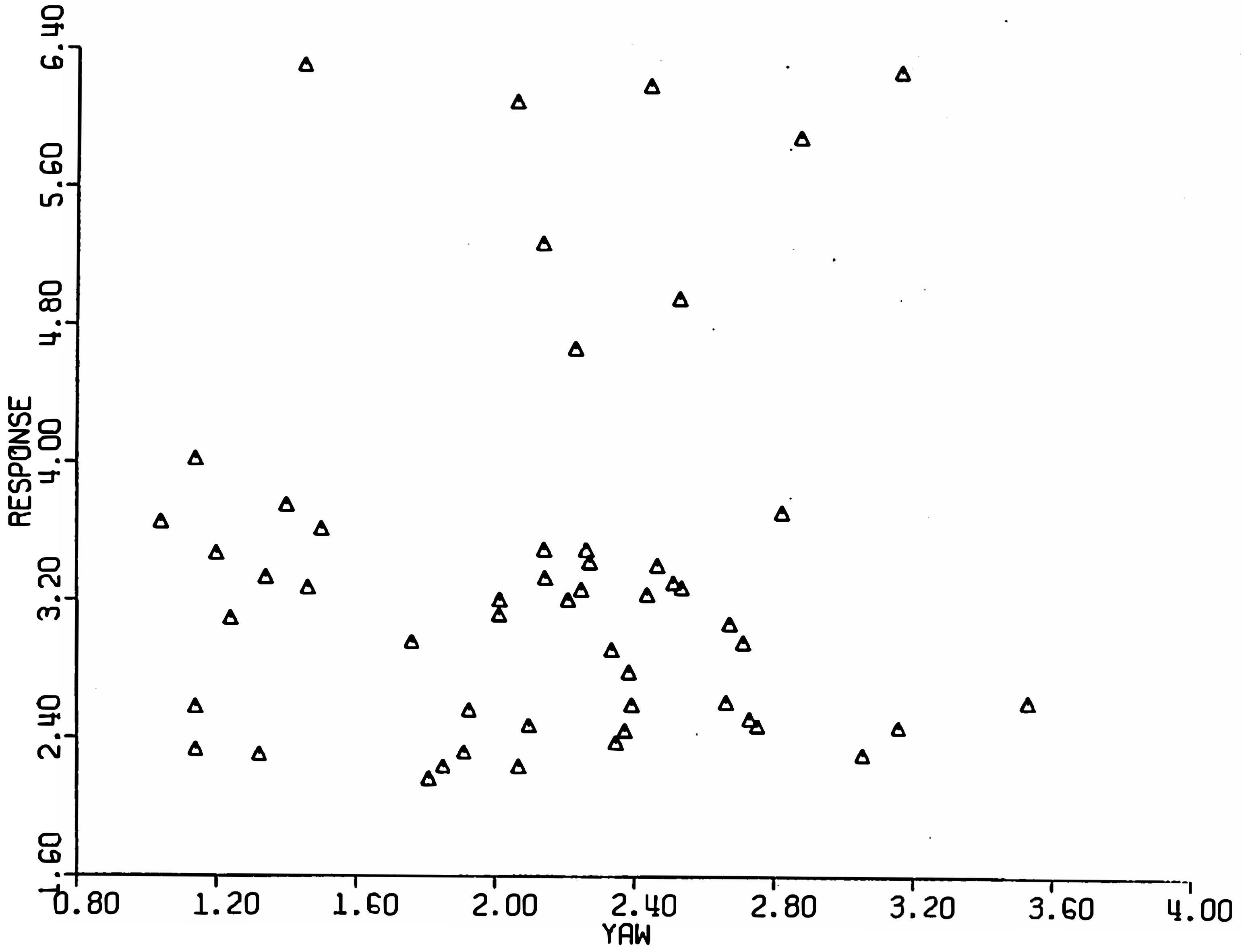

FIGURE B-3. COMFORT RESPONSES VERSUS RMS YAW RATE FOR STRAIGHT/LEVEL ROADWAY (PART 1 OF PHASE 2).

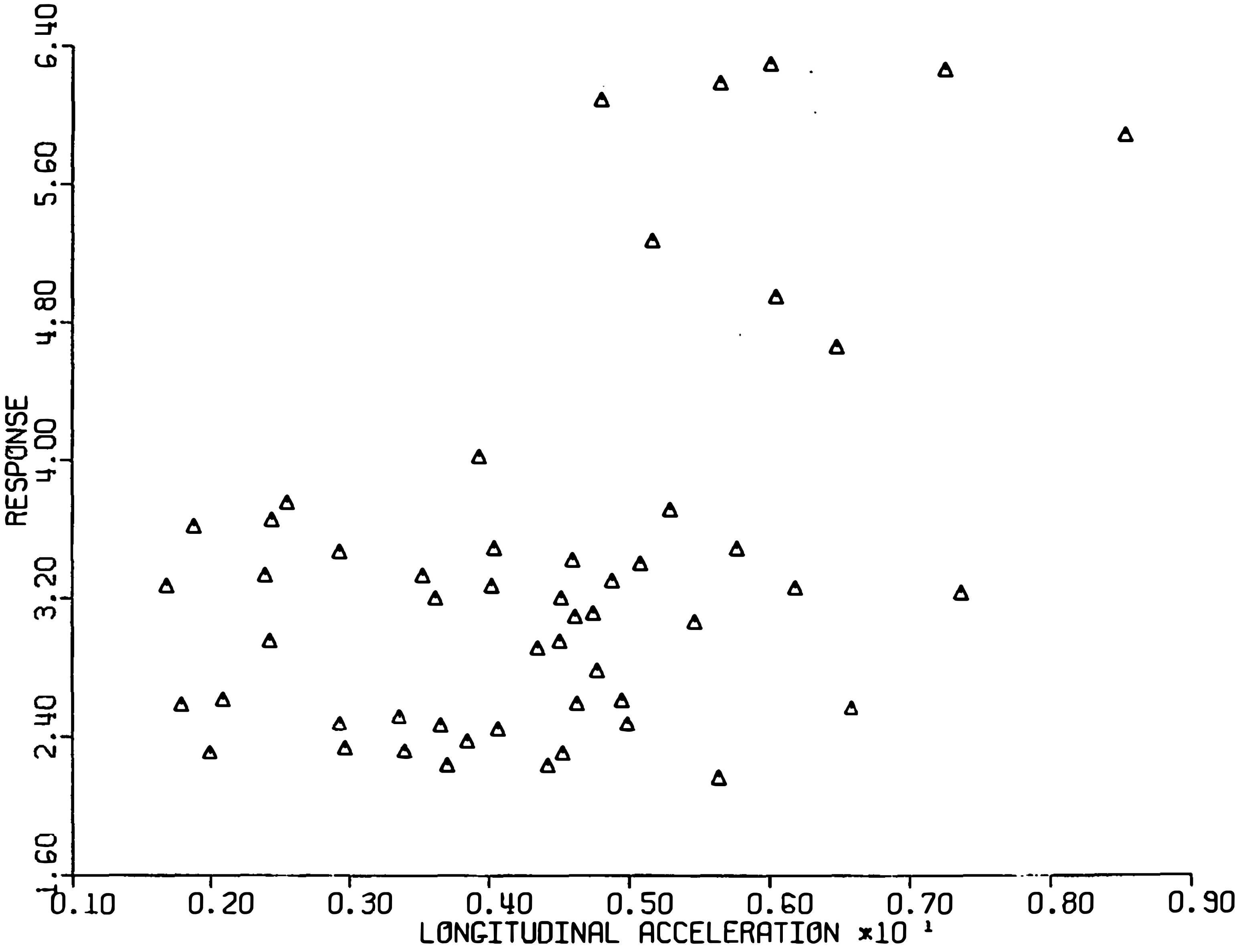

FIGURE B-4. COMFORT RESPONSES VERSUS RMS LONGITUDINAL ACCELERATION FOR STRAIGHT/LEVEL ROADWAY (PART 1 OF PHASE 1).

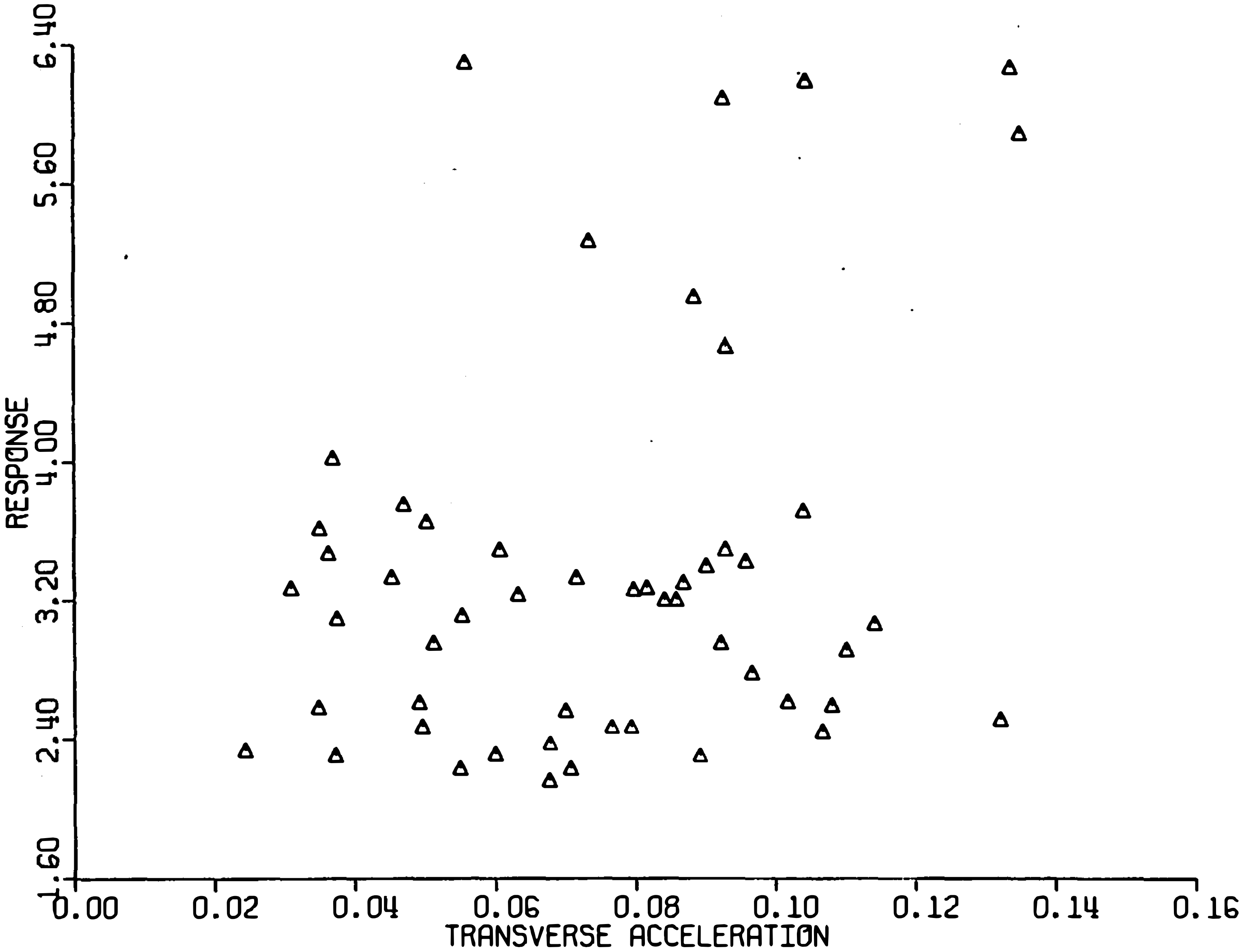

FIGURE B-5. COMFORT RESPONSES VERSUS RMS TRANSVERSE ACCELERATION FOR STRAIGHT/LEVEL ROADWAY (PART 1 OF PHASE 1).

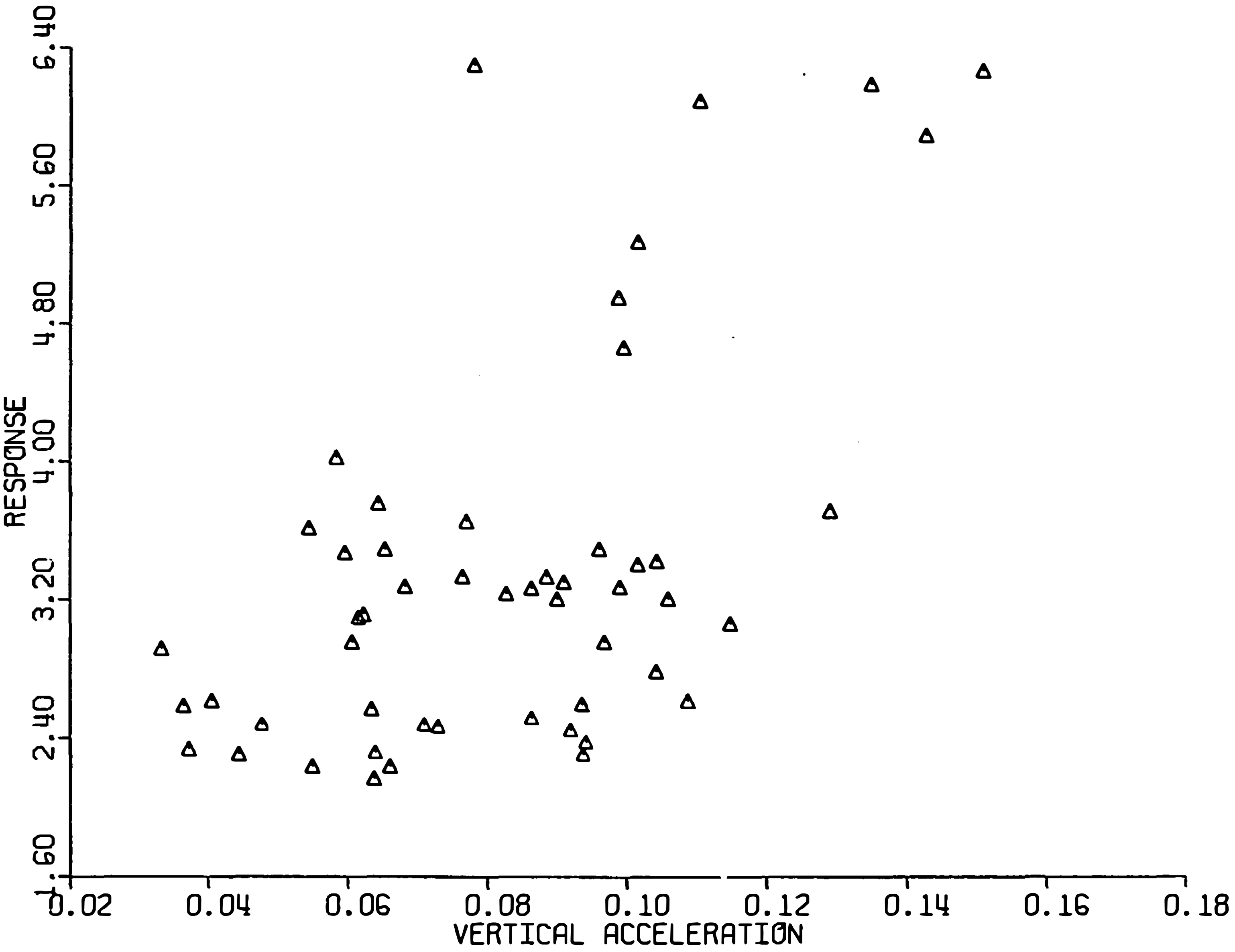

FIGURE B-6. COMFORT RESPONSES VERSUS RMS VERTICAL ACCELERATION FOR STRAIGHT/LEVEL ROADWAY (PART 1 OF PHASE 1).

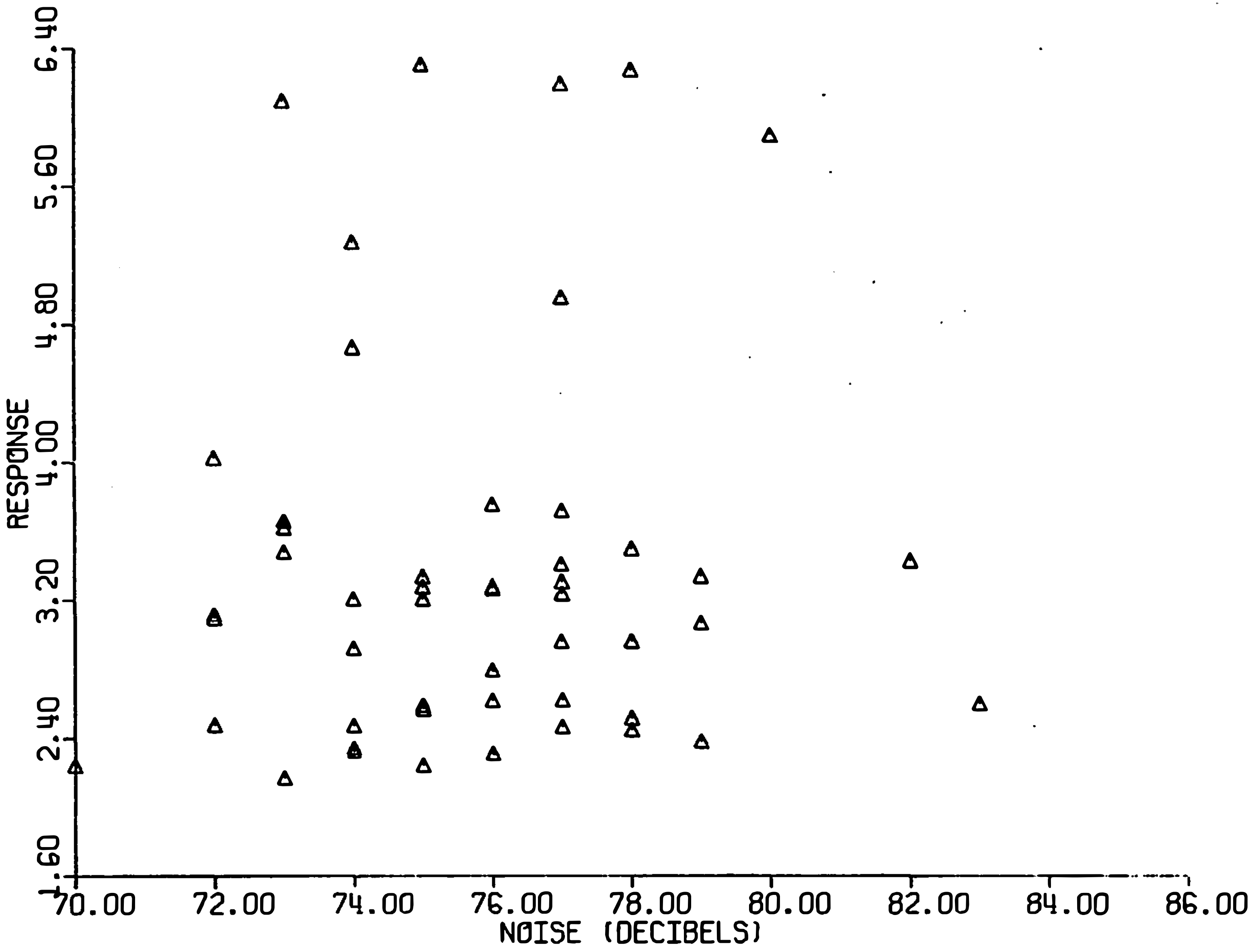

FIGURE B-7. COMFORT RESPONSES VERSUS NOISE (dB(A)) FOR STRAIGHT/LEVEL ROADWAY (PART 1 OF PHASE 1).

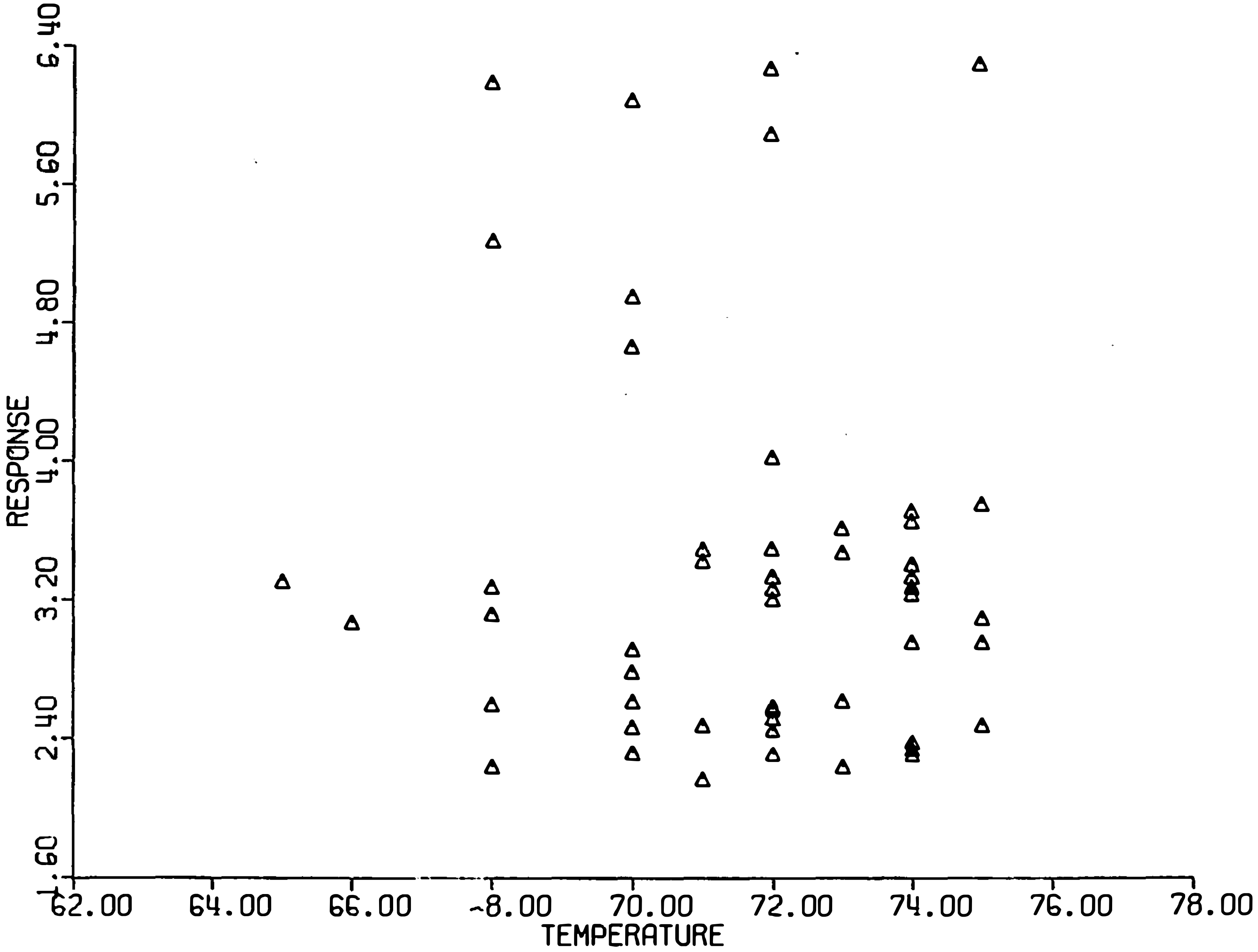

FIGURE B-8. COMFORT RESPONSES VERSUS TEMPERATURE (°F) FOR STRAIGHT/LEVEL ROADWAY (PART 1 OF PHASE 1).

APPENDIX C.

COMFORT RATINGS AND ENVIRONMENTAL MEASURES COLLECTED DURING PHASES 1 AND 2 OF TRAIN STUDY.

TABLE C-1. SUBJECTIVE RESPONSE DATA FROM TRAIN STUDY (PHASE 1).

Segment Number	All Riders	Male Riders	Female Riders	Young Riders	Middle Age Riders	Older Riders	Frequent Riders	In-frequent Riders
1	2.28	2.21	2.19	1.20	2.30	2.10	2.13	2.26
2	2.16	1.93	2.38	2.20	2.10	2.20	2.06	2.27
3	2.97	2.78	3.12	3.00	2.80	3.10	3.00	2.93
4	2.80	2.78	2.81	2.70	3.10	2.60	2.93	2.67
5	2.70	2.50	2.88	2.50	3.00	2.60	2.47	2.93
6	3.83	3.35	4.25	3.70	4.00	3.80	3.53	4.13
7	2.80	2.86	2.75	2.70	2.60	2.90	2.53	3.07
8	3.53	3.50	3.56	3.30	3.60	3.70	3.13	3.93
9	2.57	2.50	2.62	2.30	2.50	2.90	2.07	3.07
10	2.20	2.28	2.12	2.10	2.30	2.20	2.13	2.27
11	2.93	2.93	2.94	2.60	3.20	3.00	2.73	3.13
12	2.17	2.28	2.06	2.20	2.30	2.00	2.00	2.33
13	2.83	2.86	2.81	2.80	3.00	2.70	2.67	3.00
14	3.43	3.67	3.31	3.10	3.70	3.50	3.07	3.80
15	3.03	2.93	3.12	3.30	2.80	3.00	2.87	3.20
16	2.87	3.00	2.75	2.90	2.70	3.00	2.47	3.27
17	2.47	2.50	2.44	2.30	2.60	2.50	2.20	2.73
18	2.16	2.07	2.25	2.20	1.90	2.40	1.87	2.47
19	1.97	2.00	1.94	2.00	1.80	2.10	2.06	1.87
20	3.40	3.71	4.06	3.80	4.20	3.70	3.60	4.20
21	1.73	1.76	1.69	1.80	1.90	1.50	1.67	1.80
22	1.67	1.43	1.85	1.90	1.70	1.40	1.60	1.73
23	2.47	2.14	2.31	2.40	2.40	1.90	2.40	2.07
24	2.37	2.43	2.31	2.30	2.40	2.40	2.47	2.27
25	2.90	3.07	2.75	2.80	2.90	3.00	2.87	2.93
26	2.63	2.86	2.44	2.50	2.80	2.60	2.73	2.53
27	2.70	2.78	2.62	2.50	3.00	2.60	2.67	2.73
28	2.50	2.57	2.44	2.40	2.30	2.50	2.27	2.73
29	2.63	2.57	2.65	2.20	3.00	2.70	2.47	2.80
30	3.20	3.14	3.25	2.70	3.90	3.10	2.93	3.46
31	2.26	2.21	2.31	2.00	2.50	2.80	2.13	2.40
32	2.77	2.71	2.61	2.30	3.30	2.70	2.47	3.06
33	3.33	3.36	3.31	3.10	3.60	3.30	3.07	3.60
34	2.87	3.07	2.69	2.40	3.10	3.10	2.47	3.27
35	2.83	2.93	2.75	2.40	3.40	2.70	2.60	3.07
36	2.37	2.57	2.19	1.90	2.70	2.50	2.20	2.53
37	2.90	2.93	2.86	2.60	2.80	3.30	2.53	3.27
38	2.93	2.93	2.94	2.80	3.00	3.00	2.97	3.00
39	2.57	2.78	2.30	2.40	2.90	2.40	2.40	2.73
40	2.40	2.64	2.19	2.50	2.50	2.20	2.27	2.53
41	2.17	2.33	2.00	2.50	1.80	2.20	1.87	2.47
42	2.56	2.53	2.53	2.60	2.50	2.50	2.47	2.60
43	2.73	2.93	2.53	2.80	2.40	3.00	2.53	2.93
44	3.03	3.20	2.87	3.20	2.50	3.40	2.80	3.27
45	4.33	4.33	4.33	4.10	3.90	5.00	4.33	4.33
46	2.43	2.47	2.40	2.30	2.40	2.60	2.13	2.73
47	3.23	3.20	3.27	3.20	2.40	4.10	3.13	3.33
48	1.97	1.87	2.07	2.00	1.80	2.10	1.73	2.20
49	2.50	2.73	2.27	2.30	2.40	2.80	2.33	2.67
50	2.50	2.53	2.47	2.40	2.20	2.90	2.33	2.67
51	2.60	2.53	2.67	3.10	2.10	2.60	2.33	2.87
52	2.20	2.07	2.33	2.10	1.80	2.70	2.13	2.27
53	3.80	4.00	3.60	3.70	3.60	4.10	3.80	3.80
54	3.60	3.60	3.60	3.30	3.20	4.50	3.53	3.67

TABLE C-1. SUBJECTIVE RESPONSE DATA FROM TRAIN STUDY (PHASE 1) (Continued).

Segment Number	All Riders	Male Riders	Female Riders	Young Riders	Middle Age Riders	Older Riders	Frequent Riders	In-frequent Riders
55	2.67	2.60	2.73	2.50	2.40	3.10	2.40	2.93
56	2.33	2.53	2.13	2.50	2.20	2.30	2.33	2.33
57	2.20	2.47	1.98	2.00	2.40	2.20	2.40	2.00
58	2.37	2.60	2.13	2.60	2.10	2.40	2.40	2.33
59	1.87	1.93	1.60	1.80	1.70	2.10	1.87	1.87
60	2.83	2.93	2.73	3.30	2.80	2.40	2.93	2.67
61	3.20	3.67	2.73	2.70	3.60	3.30	3.27	3.13
62	2.60	2.80	2.40	2.60	2.50	2.50	2.53	2.67
63	2.57	2.67	2.47	2.50	2.40	2.30	2.67	2.47
64	3.27	3.60	2.97	3.10	3.10	3.60	3.40	3.13
65	3.77	4.13	3.40	3.50	3.70	4.10	3.93	3.60
66	4.60	5.07	4.13	4.40	4.40	5.00	4.87	4.33
67	4.20	4.53	3.87	4.00	3.00	5.00	4.33	4.06
66	2.97	3.07	2.87	3.50	2.40	3.00	3.00	2.93
69	2.80	3.00	2.60	3.30	2.50	2.50	2.73	2.86
70	2.27	2.33	2.20	2.20	2.10	2.50	2.27	2.27
71	3.37	3.80	2.98	3.30	2.90	3.90	3.40	3.33
72	4.43	4.87	4.00	4.40	3.80	5.10	4.40	4.47
73	4.30	5.14	4.47	4.80	4.40	5.20	4.93	4.67
74	4.77	5.13	4.40	4.00	4.30	5.20	5.00	4.53
75	2.87	3.13	2.80	3.20	2.40	3.00	2.87	2.87
76	4.63	4.73	4.50	4.80	4.00	5.10	4.53	4.73
77	4.50	4.73	4.27	4.40	4.00	5.10	4.67	4.33
78	2.93	3.13	2.73	3.50	2.30	3.00	2.87	3.00
79	4.36	4.07	4.07	4.40	3.70	5.00	4.73	4.00

TABLE C-2. RIDE ENVIRONMENT DATA FROM TRAIN STUDY (PHASE 1).

Segment Number	Roll Rate	Pitch Rate	Yaw Rate	Long. Accel.	Trans. Accel.	Vert. Accel.	Noise	Temp. (°F)
1	1.51	0.00	1.19	.01	.05	.05	70.00	72.00
2	1.37	0.00	1.34	.01	.03	.03	68.00	72.00
3	1.68	0.00	1.24	.01	.03	.03	69.00	72.00
4	.95	0.00	.78	.02	.01	.04	69.00	72.00
5	1.51	0.00	1.48	.01	.04	.04	69.00	70.00
6	1.82	0.00	1.42	.02	.03	.04	79.00	70.00
7	1.20	0.00	1.22	.01	.03	.03	72.00	69.00
8	1.60	0.00	1.44	.02	.03	.04	69.00	68.00
9	1.15	0.00	1.34	.01	.03	.03	66.00	70.00
10	1.36	0.00	.57	.01	.02	.05	65.00	71.00
11	1.53	0.00	1.76	.01	.04	.04	66.00	71.00
12	1.37	0.00	1.58	.01	.03	.04	65.00	72.00
13	1.89	0.00	1.21	.01	.03	.03	67.00	73.00
14	1.49	0.00	1.09	.01	.02	.04	69.00	73.00
15	1.39	0.00	1.25	.01	.03	.04	71.00	73.00
16	1.38	0.00	1.35	.01	.04	.03	68.00	72.00
17	1.76	0.00	1.33	.01	.04	.05	72.00	73.00
18	1.56	0.00	1.45	.01	.02	.04	65.00	74.00
19	1.09	0.00	1.32	.01	.02	.03	65.00	75.00
20	2.55	0.00	2.71	.01	.06	.04	70.00	75.00
21	1.15	0.00	1.55	.01	.03	.02	64.00	76.00
22	.92	0.00	.81	.01	.01	.02	64.00	76.00
23	1.23	0.00	1.57	.01	.04	.02	71.00	77.00
24	1.80	0.00	1.20	.01	.03	.03	65.00	77.00
25	1.14	0.00	1.23	.01	.04	.03	72.00	78.00
26	1.16	0.00	1.24	.01	.03	.03	68.00	77.00
27	1.19	0.00	1.68	.01	.05	.03	70.00	77.00
28	1.00	0.00	.90	.02	.03	.03	71.00	78.00
29	1.17	0.00	1.75	.02	.04	.03	71.00	78.00
30	1.10	0.00	.90	.01	.02	.03	63.00	78.00
31	1.62	0.00	1.36	.01	.04	.02	62.00	79.00
32	1.24	0.00	.97	.01	.02	.03	64.00	79.00
33	1.49	0.00	1.16	.01	.03	.04	72.00	79.00
34	1.22	0.00	1.20	.01	.03	.03	71.00	79.00
35	1.47	0.00	1.25	.01	.03	.03	69.00	79.00
36	1.12	0.00	1.32	.01	.03	.03	67.00	79.00
37	1.60	1.20	1.19	.01	.02	.03	67.00	79.00
38	1.41	1.00	1.16	.01	.03	.04	69.00	79.00
39	1.30	.98	1.14	.01	.03	.03	68.00	80.00
40	1.74	0.00	1.76	.02	.03	.03	71.00	80.00
41	1.06	.87	1.12	.01	.03	.02	70.00	70.00
42	1.16	.89	1.14	.01	.02	.02	74.00	70.00
43	1.16	.92	.97	.01	.01	.03	75.00	69.00
44	1.50	1.00	1.54	.01	.04	.03	70.00	68.00
45	1.81	1.01	1.64	.02	.04	.03	74.00	60.00
46	1.21	.96	1.05	.01	.02	.03	70.00	68.00
47	1.53	.90	1.64	.02	.03	.03	74.00	68.00
48	1.05	.83	.88	.02	.01	.02	68.00	68.00
49	1.49	.91	1.53	.01	.03	.03	66.00	60.00
50	1.40	.91	.95	.01	.03	.05	65.00	69.00
51	1.40	1.04	1.24	.01	.02	.03	68.00	69.00
52	1.25	.98	1.13	.01	.02	.03	68.00	68.00
53	1.67	.96	1.53	.01	.06	.03	71.00	68.00
54	1.34	.99	1.09	.01	.03	.03	69.00	69.00

TABLE C-2. RIDE ENVIRONMENT DATA FROM TRAIN STUDY (PHASE 1) (Continued).

Segment Number	Roll Rate	Pitch Rate	Yaw Rate	Long. Accel.	Trans. Accel.	Vert. Accel.	Noise	Temp. (°F)
55	1.43	1.01	1.13	.01	.03	.03	69.00	68.00
56	1.39	.93	.91	.01	.03	.03	65.00	68.00
57	.99	.92	1.42	.01	.04	.03	64.00	68.00
58	1.50	.99	1.55	.01	.03	.03	74.00	69.00
59	1.00	.84	1.03	.01	.02	.03	66.00	68.00
60	1.24	.91	1.05	.01	.02	.03	71.00	76.00
61	1.44	.96	1.28	.02	.03	.03	76.00	76.00
62	1.17	.91	.98	.01	.02	.03	74.00	76.00
63	1.38	1.01	1.25	.01	.02	.02	70.00	77.00
64	1.58	1.07	1.48	.01	.03	.03	73.00	77.00
65	1.17	.89	1.08	.02	.02	.02	76.00	76.00
66	1.25	1.06	1.18	.02	.03	.02	78.00	81.00
67	.97	.76	.80	.02	.02	.02	79.00	80.00
68	1.29	.77	1.64	.01	.02	.03	73.00	82.00
69	1.50	1.12	1.35	.01	.03	.03	84.00	80.00
70	1.18	1.06	1.08	.01	.01	.02	77.00	80.00
71	1.29	1.00	1.00	.01	.02	.03	73.00	80.00
72	1.64	.74	.80	.01	.03	.03	77.00	80.00
73	1.92	1.02	1.54	.01	.04	.03	75.00	80.00
74	1.84	1.04	1.76	.03	.05	.04	75.00	81.00
75	1.19	.89	1.30	.01	.04	.02	70.00	78.00
76	1.50	.98	1.14	.01	.03	.03	77.00	78.00
77	1.56	1.03	1.63	.01	.04	.03	77.00	78.00
78	1.00	.78	.87	.01	.02	.02	73.00	78.00
79	1.56	.95	1.27	.01	.03	.03	78.00	79.00

TABLE C-3. SUBJECTIVE RESPONSE DATA FROM TRAIN VALIDATION EXPERIMENT

Segment Number	All Riders	Male Riders	Female Riders
1	3.92	3.81	3.97
2	2.79	2.88	2.76
3	2.37	2.75	2.18
4	3.37	3.00	3.54
5	1.80	1.88	1.76
6	1.63	1.81	1.54
7	1.65	2.19	1.39
8	1.55	1.69	1.48
9	1.49	1.69	1.39
10	2,51	2.38	2.58
11	1.77	1.62	1.85
12	1.57	1.62	1.54
13	2.67	2.94	2.54
14	2.61	2.62	2.61

TABLE C-4. RIDE ENVIRONMENT DATA FROM TRAIN VALIDATION STUDY (PHASE 2) (AMTRAK, NEW HAVEN TO NEW YORK CITY).

Segment	Roll Rate °/s rms	Pitch Rate °/s rms	Yaw Rate °/s rms	Long. Accel. g's rms	Trans. Accel. g's rms	Vert. Accel. g's rms	Noise dB(A)	Temp. °C	$\bar{C}$
1	2.014	1.679	1.758	.014	.025	.035	67	23.3	3.92
2	1.159	.988	1.199	.010	.022	.023	69	24.4	2.8
3	1.357	1.312	0.895	.012	.032	.031	70	25	2.37
4	1.160	.712	1.556	.011	.038	.024	70	25	3.38
5	1.211	.887	1.157	.012	.021	.023	67	25	1.6
6	1.094	.838	1.119	.023	.020	.022	66	25	1.63
7	1.009	.890	1.015	.007	.041	.019	67	25	1.65
8	1.127	.927	.974	.007	.031	.018	71	25	1.55
9	1.010	.922	.914	.006	.009	.017	71	25	1.49
10	1.401	1.378	1.416	.009	.012	.023	66	25	2.51
11	1.411	1.335	1.367	.013	.012	.023	70	25	1.78
12	1.532	1.470	1.687	.010	.018	.025	70	25	1.57
13	1.718	1.654	1.697	.012	.022	.028	66	25	2.67
14	1.783	1.718	1.755	.012	.017	.030	68	25	2.61

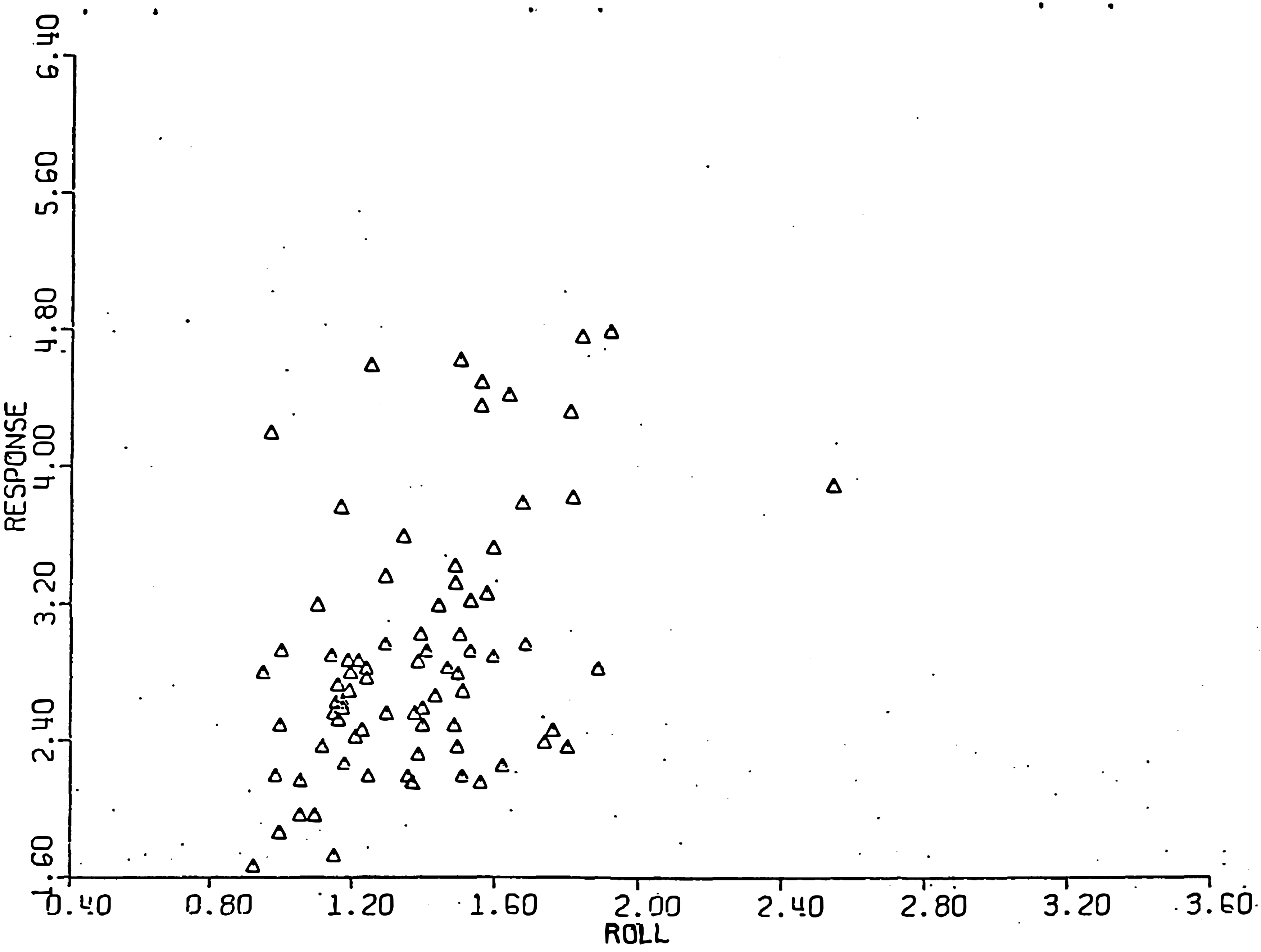

FIGURE C-1. COMFORT RESPONSES VERSUS RMS ROLL RATE FOR TRAIN STUDY (PHASE 1).

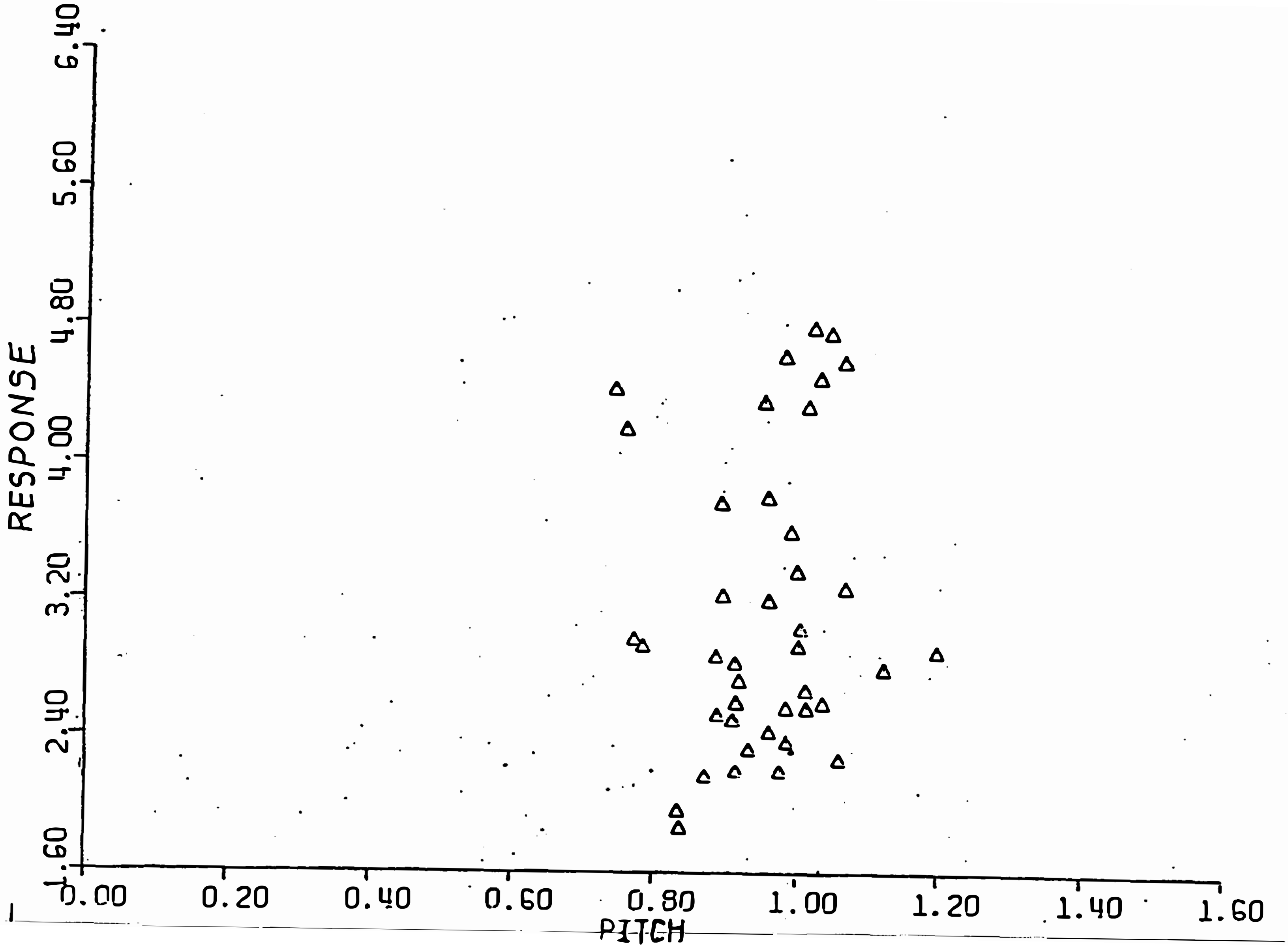

FIGURE C-2. COMFORT RESPONSES VERSUS RMS PITCH RATE FOR TRAIN STUDY (PHASE 1).

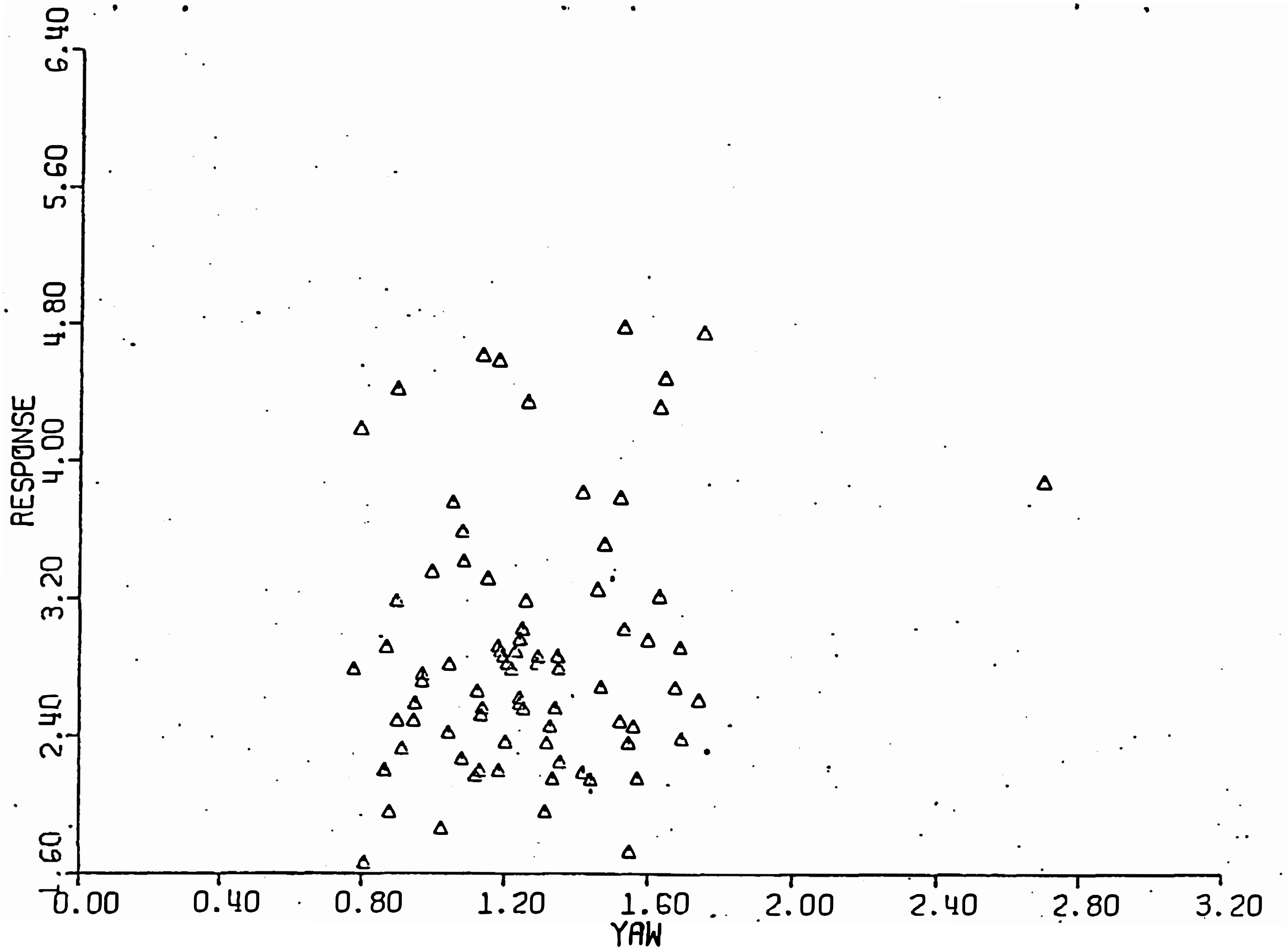

FIGURE C-3. COMFORT RESPONSES VERSUS RMS YAW RATE FOR TRAIN STUDY (PHASE 1).

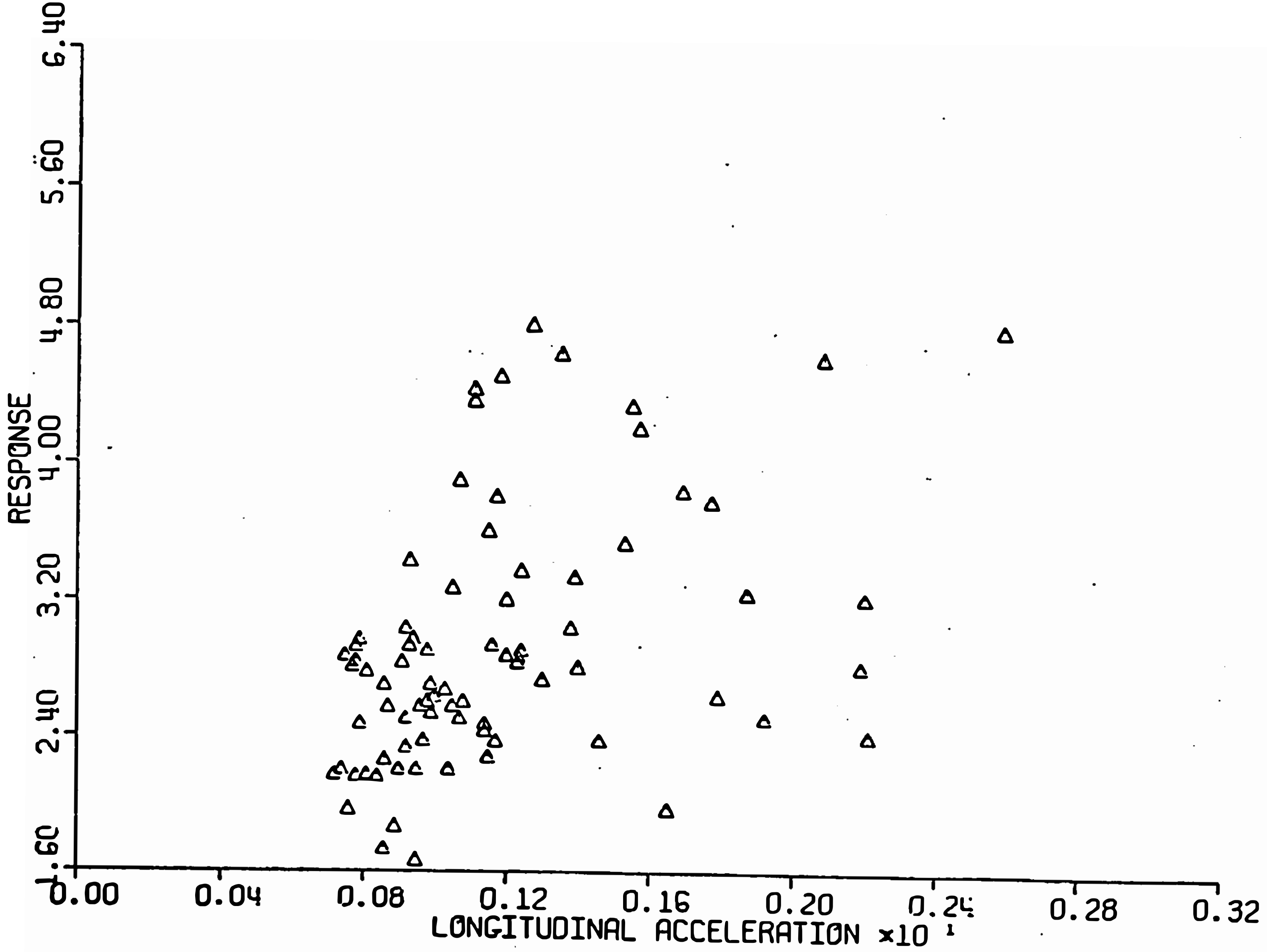

FIGURE C-4. COMFORT RESPONSES VERSUS RMS LONGITUDINAL ACCELERATION FOR TRAIN STUDY (PHASE 1).

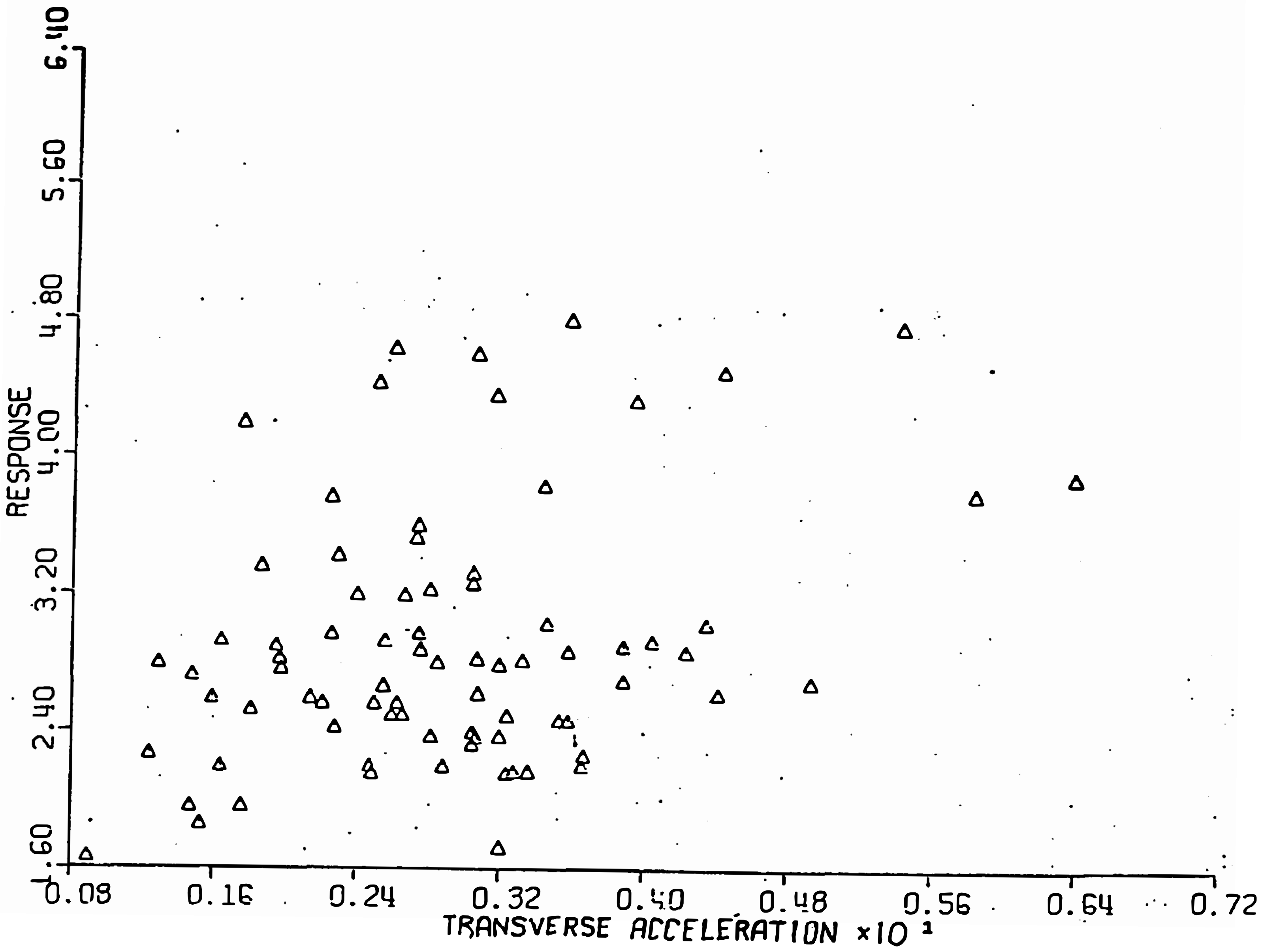

FIGURE C-5. COMFORT RESPONSES VERSUS RMS TRANSVERSE ACCELERATION FOR TRAIN STUDY (PHASE 1).

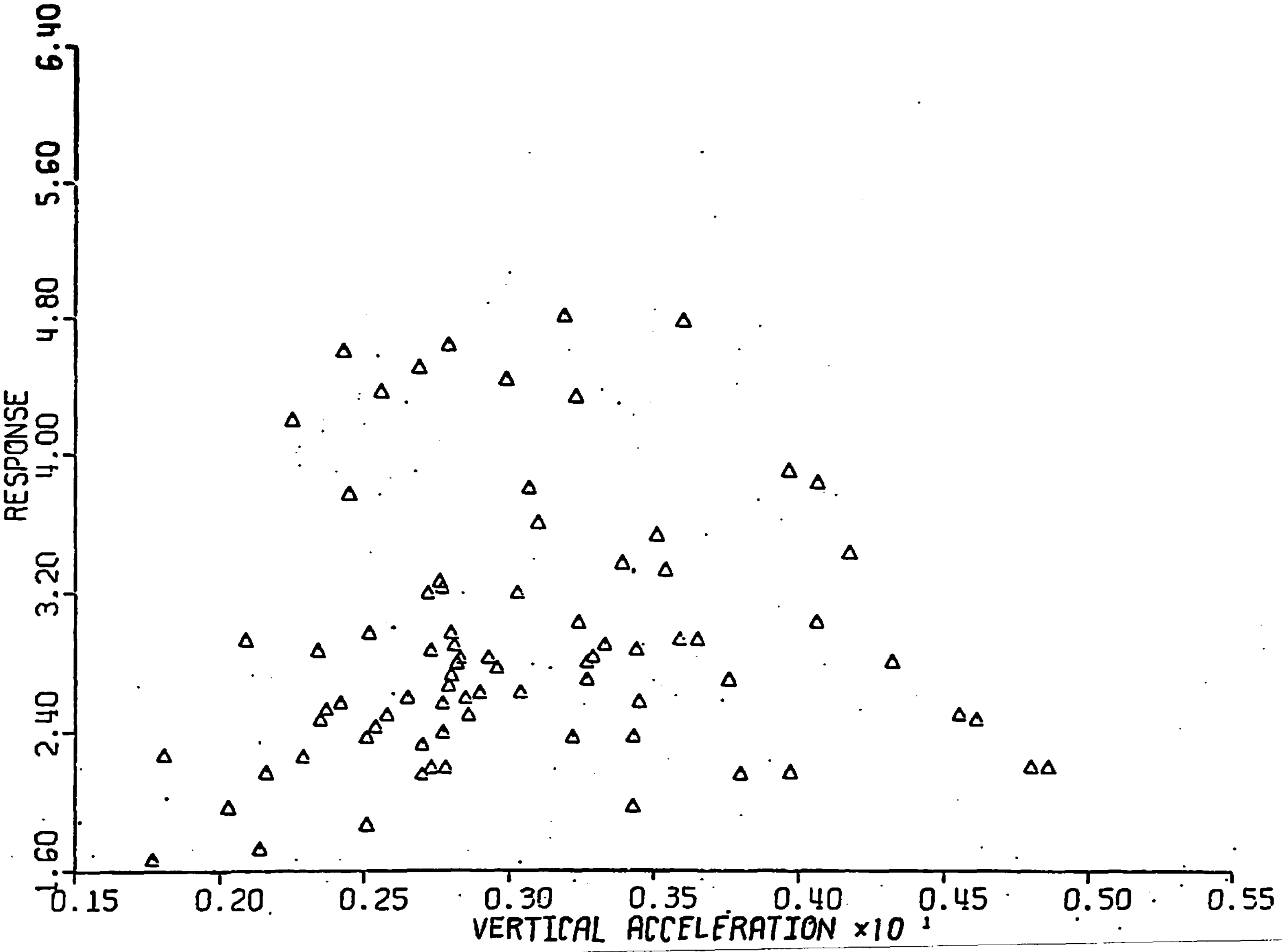

FIGURE C-6. COMFORT RESPONSES VERSUS RMS VERTICAL ACCELERATION FOR TRAIN STUDY (PHASE 1).

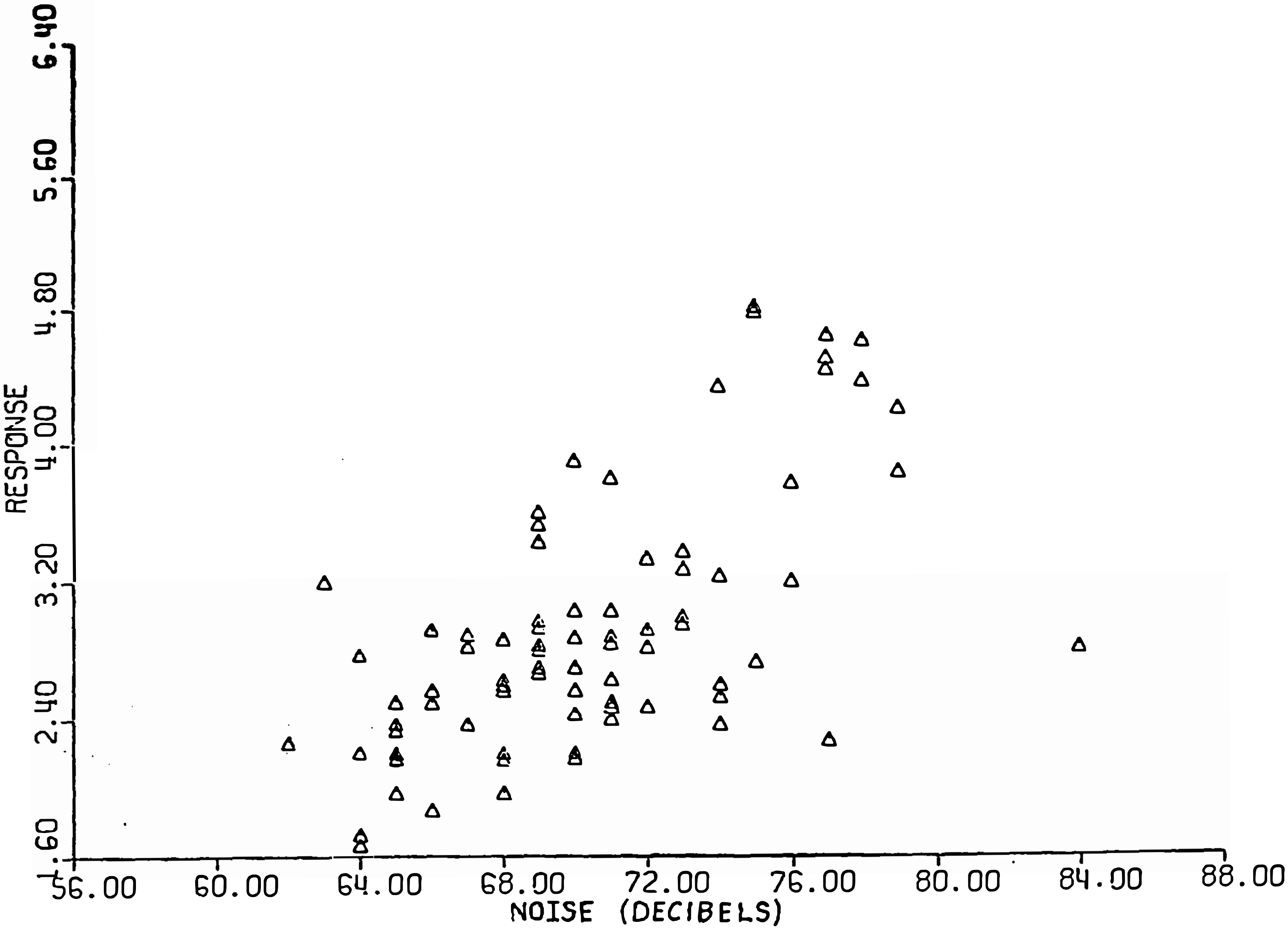

FIGURE C-7. COMFORT RESPONSES VERSUS NOISE (dB(A)) FOR TRAIN STUDY (PHASE 1).

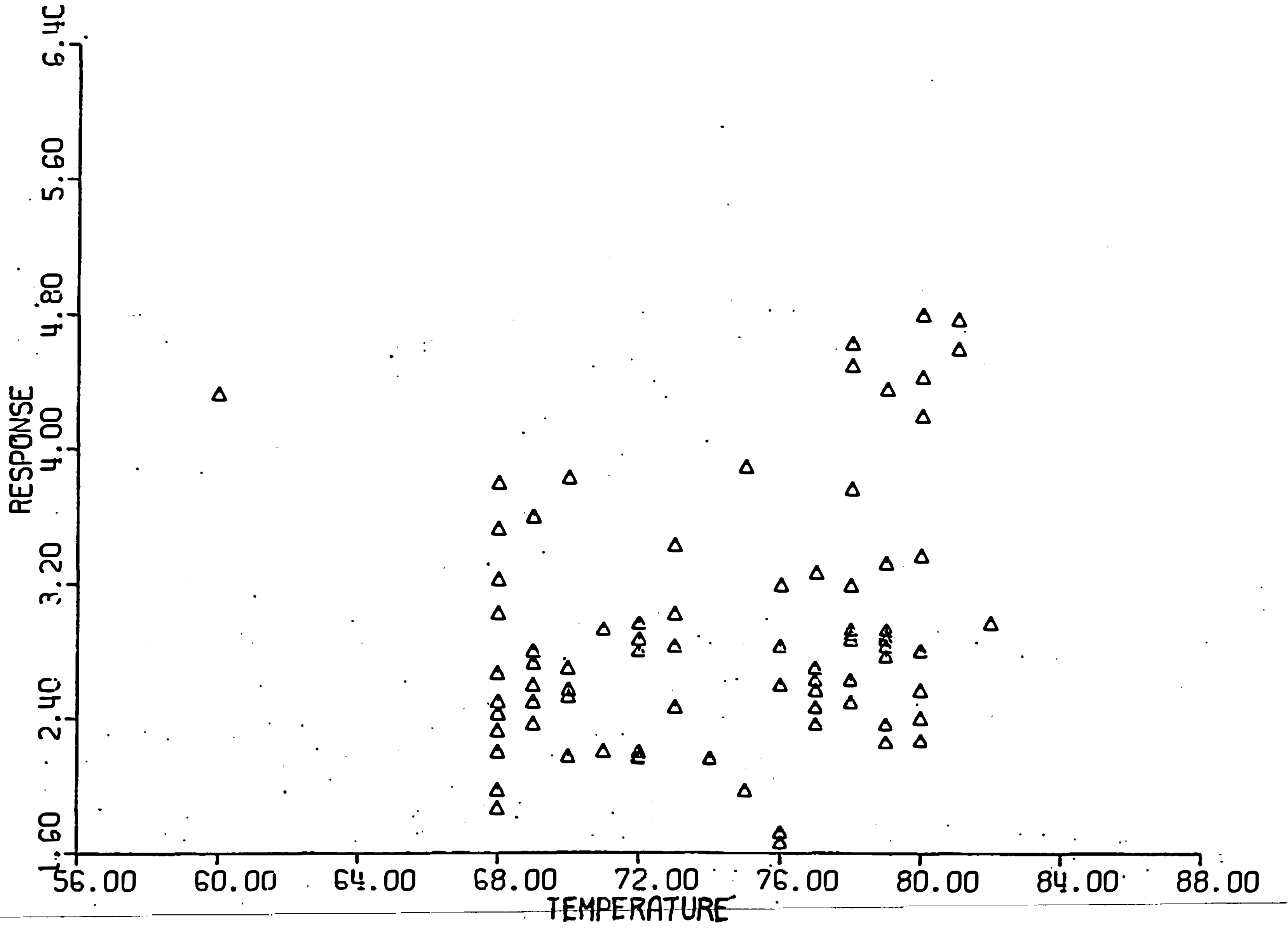

FIGURE C-8. COMFORT RESPONSES VERSUS TEMPERATURE FOR TRAIN STUDY (PHASE 1).

APPENDIX D.

DISTRIBUTION OF PASSENGER RESPONSES IN THE BUS AND TRAIN STUDIES (PHASE 1).

TABLE D-1. COMFORT RESPONSES IN BUS STUDY (PHASE1).

	Comfort Responses						
Segment	Comfortable					Uncomfortable	
Number	1	2	3	4	5	6	7
1	2	8	8	2	8	1	0
2	4	2	7	4	1	1	0
3	3	2	11	7	5	1	0
4	4	5	10	3	5	1	1
5	3	3	8	4	8	2	1
6	8	11	5	3	1	0	1
7	4	8	7	7	2	0	1
8	6	15	5	2	0	1	0
9	0	0	2	1	2	6	18
10	0	0	1	2	6	11	12
11	4	14	7	3	1	1	0
12	5	4	11	6	3	0	1
13	6	11	7	3	2	0	1
14	2	4	11	7	5	0	1
15	1	9	6	6	5	2	1
16	2	4	11	6	5	1	1
17	6	10	11	2	0	0	1
18	3	1	9	3	7	6	1
19	4	6	7	0	4	3	1
20	3	6	10	1	2	2	1
21	0	1	0	1	4	4	15
22	0	2	2	1	6	10	4
23	5	11	7	2	0	0	0
24	2	9	9	1	2	2	0
25	5	11	6	2	1	0	0
26	0	1	8	0	8	6	6
27	6	13	5	1	3	1	0
28	1	17	4	3	4	0	0
29	1	9	9	4	4	1	1
30	5	16	5	1	1	1	0
31	2	16	5	2	2	2	0
32	1	8	10	2	6	2	0
33	0	12	7	4	4	2	0
34	3	17	5	1	1	2	0
35	4	16	5	2	1	0	1
36	6	15	6	1	1	0	0
37	0	0	1	1	6	7	14
38	3	15	4	6	0	1	0
39	1	7	8	3	10	0	0
40	1	3	11	5	9	0	0
41	1	5	9	5	6	3	0
42	5	11	6	4	3	0	0
43	1	2	9	3	1	3	0
44	4	7	6	6	6	0	0
45	7	10	6	3	3	0	0
46	1	8	9	5	4	1	1
47	0	9	9	6	4	1	0
48	0	7	7	5	7	2	1
49	8	10	7	2	2	0	0
50	4	8	8	4	4	1	0
51	6	12	7	3	1	0	0
52	0	0	1	2	2	6	18

TABLE D-2. COMFORT RESPONSES IN TRAIN STUDY (PHASE1).

	Comfort Responses						
	Comfortable					Uncomfortable	
	1	2	3	4	5	6	7
Sat. a.m.	4	16	10	0	0	0	0
	4	19	6	0	1	0	0
	0	12	12	1	5	0	0
	1	11	14	1	3	0	0
	0	15	11	2	2	0	0
	0	7	7	3	10	3	0
	2	10	13	2	3	0	0
	1	8	9	1	8	3	0
	2	16	8	1	3	0	0
	3	19	7	1	0	0	0
	0	11	14	2	2	1	0
	6	15	8	0	1	0	0
	0	14	11	1	4	0	0
	0	11	7	1	10	1	0
	0	11	11	4	4	0	0
	0	13	11	3	3	0	0
	2	17	7	3	1	0	0
	3	21	5	0	1	0	0
	4	23	3	0	0	0	0
Sat. p.m.	8	22	0	0	0	0	0
	11	18	1	0	0	0	0
	4	19	5	0	2	0	0
	2	20	5	1	2	0	0
	3	10	10	2	4	1	0
	1	16	9	1	3	0	0
	2	13	11	0	4	0	0
	2	17	8	0	3	0	0
	1	15	11	0	3	0	0
	1	11	7	4	6	1	0
	8	12	6	2	2	0	0
	2	14	9	1	2	2	0
	1	10	8	3	5	3	0
	3	10	10	2	5	0	0
	3	11	10	1	4	1	0
	5	16	5	2	1	1	0
	2	15	4	4	3	2	0
	1	14	8	0	7	0	0
	3	13	11	0	3	0	0
	3	16	8	2	1	0	0

TABLE D-2. COMFORT RESPONSES IN TRAIN STUDY (PHASE 1). (Cont'd)

	Comfort Responses						
	Comfortable					Uncomfortable	
	1	2	3	4	5	6	7
Sun. a.m.	4	19	6	0	1	0	0
	1	20	5	0	4	0	0
	2	15	8	0	4	1	0
	0	13	9	2	6	0	0
	0	5	8	1	7	6	3
	3	17	7	0	3	0	0
	0	13	7	1	8	1	0
	6	21	1	2	0	0	0
	1	18	8	1	2	0	0
	0	20	7	1	2	0	0
	3	15	7	1	4	0	0
	6	14	9	0	1	0	0
	1	6	6	4	11	2	0
	0	8	9	2	9	2	0
	1	15	9	3	2	0	0
	3	16	10	0	1	0	0
	2	18	8	1	1	0	0
	5	18	4	2	1	0	0
	9	16	5	0	0	0	0
	0	12	12	1	4	1	0
Sun. p.m.	0	12	15	1	1	0	1
	0	20	6	1	3	0	0
	0	10	11	2	5	2	0
	0	10	6	1	7	6	0
	0	4	5	1	10	9	1
	0	6	7	1	8	7	1
	0	13	11	2	2	2	0
	1	13	11	2	2	1	0
	5	13	11	1	0	0	0
	0	9	12	1	6	1	1
	0	5	4	2	13	4	2
	0	3	1	4	14	7	1
	0	2	5	1	14	6	2
	0	13	12	1	4	0	0
	0	4	2	3	13	8	0
	0	4	4	5	9	6	2
	0	15	10	0	2	3	0
	0	6	4	1	12	6	1

APPENDIX E.

RMS JERK AND ANGULAR ACCELERATIONS FOR 25 ROAD SEGMENTS FROM BUS STUDY (PART 1 OF PHASE 1)

TABLE E-1. RMS JERK AND ANGULAR ACCELERATIONS FOR 25 ROAD SEGMENTS FROM BUS STUDY (PART 1 OF PHASE 1).

$\frac{\omega'_R (^\circ/sec^2)}{10}$	$\frac{\omega'_P (^\circ/sec^2)}{10}$	$\frac{a'_L (g/sec)}{10}$	$\frac{a'_T (g/sec)}{10}$	$\frac{a'_V (g/sec)}{10}$
3.645	2.149	.065	.162	.155
3.774	2.227	.079	.198	.198
3.647	2.157	.073	.182	.173
3.097	1.994	.047	.105	.120
3.945	2.220	.093	.207	.224
3.348	2.139	.060	.134	.162
3.473	2.238	.072	.172	.181
3.087	2.045	.055	.133	.124
4.997	2.972	.137	.259	.283
4.576	2.688	.125	.269	.262
2.924	1.901	.051	.140	.116
4.132	2.414	.093	.232	.221
3.874	2.376	.077	.234	.179
3.782	2.338	.082	.189	.202
2.900	1.942	.045	.113	.113
3.538	2.250	.073	.191	.174
2.786	1.785	.051	.139	.137
3.483	2.240	.089	.184	.189
3.557	3.396	.060	.157	.199
2.759	2.743	.043	.109	.123
4.127	3.380	.106	.210	.258
3.564	3.020	.071	.160	.191
2.761	2.671	.040	.116	.105
3.647	3.294	.069	.206	.205
2.679	2.580	.046	.120	.122

APPENDIX F.

TIME DEPENDENCE AND TEMPORAL INFORMATION INTEGRATION

This Appendix summarizes results of an analysis designed to assess two types of time effects in the five data sets discussed in this volume:

Bus field data (Phase 1, Part 1)

Bus validation data (Phase 2)

Bus curve data (Phase 1, Part 2)

Train field data (Phase 1)

Train validation data (Phase 2).

In all cases, respondents provided comfort judgments for selected ride segments during the trip and an overall comfort judgment for the entire trip. The number of segments rated varied from 7 for the bus validation data to 25 for the bus curve data, and the time spent in the vehicle by a subject ranged from 3/4 of an hour to 2 hours. Subjects in the bus and train field studies made two-way trips, while riders in the other three conditions provided ratings only on a one-way trip. A seven-point comfort scale was used throughout: a rating of one indicated that the subject found the ride "very comfortable," and a rating of seven indicated that the ride was "very uncomfortable."

The first question of interest is whether comfort judgments depend on time; in particular, do people become more uncomfortable solely as a function of the amount of time they have spent in a motion environment? The second question concerns how people put together their judgments about individual segments of a trip to arrive at an overall comfort rating for the entire trip. How does the way a passenger feels about the total trip depend on his reactions to its subparts?

Each of the five data sets will be discussed separately with attention to the issues of both time dependence and information integration. Then, the consistent conclusions from the five data sets will be reviewed.

Bus Field Data

On each run, ratings were obtained for nine segments and the overall trip. There were two groups of subjects (A and B) who rode on both good and bad buses in both of two directions. For each group-bus combination, a particular route was covered in one direction, then the same route was covered in the opposite direction; thus, the same segments were rated early in first run and late in the return run, and vice versa.

Table F-1 shows the ratings for the various segments of each trip, arrayed in the order in which they were experienced. There is no consistent trend for comfort ratings to increase (comfort to become worse) as a function of time into the trip. In Table F-2, the same data are presented such that the mean ratings are arrayed by the identity of the segments. The segment labels represent particular portions of the route covered. The time sequence in which those portions were covered is shown by the arrows in the table. Inspection of Table F-2 reveals that only for Segments A and I are there discrepancies in ratings depending on whether the segment occurred at the beginning or end of a trip. In these two cases, ratings are worse if the segment is rated at the end of a trip than if it is rated at the beginning. The most likely explanation of this result is that there are real differences for Segments A and I in the ride on the two sides of the road. The major reason for not attributing these differences to time dependence is that similar differences in the same direction are not found for Segments B, C, G, and H.

The second type of analysis was performed to determine how subjects integrate their ratings of trip segments to arrive at an overall comfort rating for the trip. Correlations of the ratings given for each segment with the overall ratings are also shown in Table F-1. The lowest correlations are for the first and final segments, which happen to be those segments with very poor comfort ratings. In making their overall trip rating, subjects seem to ignore these extreme segments. Means were taken for the ratings given during each third of the trip. Correlations of these mean ratings with overall ratings are shown in Table F-3. The correlations in most rows do not differ by much, but, in all but one row, the highest correlation is from the last two-thirds of the trip, with four of the eight bus trips having the best simple correlations between the last third of the trip and the overall ratings. The correlations taken over all trips and all subjects are shown in the last row of Table F-3. Ratings for the middle and last third of the trip correlate slightly better with the overall ratings than those from the first third.

Bus Validation Data

With the bus validation data, no strong test of the time dependence was possible. There are no repeated or highly similar segments. The mean ratings for the segments for each group of subjects are shown in Table F-4, and there is no trend of steadily worsening comfort ratings as a function of time. Here, segment numbers correspond to the order of experiencing each segment, and the segments rated by each of the four groups were different.

Correlations of mean comfort ratings for trip segments with the overall comfort ratings are shown in Table F-5. For the three combined groups, there is a slight tendency for later ratings to correlate best with the overall trip rating. For Group 4, the correlation of Segment 8 with overall trip comfort was quite low and Segment 8 was rated most uncomfortable. This supports the claim from the previous section that subjects ignore extremely bad segments in making their overall ratings.

Bus Data for Curved Routes

Twenty-five ride segments were rated in this study. Mean ratings for each segment for Groups A and B are shown in Table F-6. Again, equivalent segments were not run, either within or between groups, but no overall decline in comfort is apparent as a function of time. Recall that a decline in comfort would be indicated by an increasing mean comfort rating (greater than 4 means uncomfortable).

Table F-7 shows correlations of mean ratings for each fifth of the trip and overall ratings. The pattern of correlations differs for the two groups with Group A showing the best correlations for the final trip segments and Group B the best for the earliest segments. For all subjects combined, later trip segments do seem to influence the overall trip rating slightly more than earlier segments.

Train Field Data

Two groups of subjects had participated in the train study. Each group rated 20 ride segments in each two directions. Mean ratings by segment and the overall rating are shown in Table F-8. Again, a general decrease in rated comfort is not obvious. The decline evidenced by Group B in its initial run is not repeated by the other group. Correlations of mean ratings for each quarter of the trip with the overall trip ratings over all groups reveals that the initial quarter of the trip is least related to overall comfort (r's = .33, .48, .45, .48 for the four quarters, respectively).

Train Validation Data

Fourteen ride segments were rated by 49 subjects. The mean ratings show no general trend toward worsening comfort ratings with time. When the total trip was divided into three subparts (of 4, 5, and 5 segments respectively), the correlations of mean ratings with overall ratings are .49, .27, and .53, respectively.

Further Tests of Time Dependence

When the experiments reported here were designed, road segments were selected to represent different levels of ride quality (according to the judgment of the experimenters). However, this judgment was a global one and was not determined by values in any particular dimension of motion. Having found that roll rate is the dominant motion variable in our ride quality models, we can now ask several post hoc questions of our data.

Suppose we had done a factorial experiment varying roll rate over three levels and time over four levels with comfort response as the dependent variable. Ideally, such an experiment would be designed so that levels of roll are equally spaced along that continuum, and similarly for time intervals.

Using the bus field data, levels of roll and time were selected so that each cell of a factorial design table would contain at least one mean comfort rating. The resulting mean comfort judgments are shown in Table F-9a. Each of these means is based on data from the same 30 subjects (Group A). Table F-9a seems to show an interaction of time and roll level in determining comfort ratings. A curve drawn for the high roll data would be inverted from that for the low roll data, but both would appear quadratic in form. Thus, it would seem that: 1) time has an influence on comfort judgments, but that 2) the influence is different depending on the level of roll. However, when we look at the actual observed roll levels associated with each cell of the table (see Table F-9b), we see that the two most extreme mean comfort ratings are very discrepant in terms of roll rate from any of the other points. Thus, time and roll are confounded in this data; no rigorous test of time dependence is possible. However, Figure F-1, which shows comfort as a function of roll and time period (1 through 4), would suggest that roll rate alone is sufficient to account for the obtained mean ratings.

The train data were more extensive, and the rated segments were distributed over a longer time span. Here much tighter intervals were obtained for the categories based on roll rate, and it was possible to fill all the cells in the data table for both groups of subjects. The data from both groups were averaged cell by cell to provide the means shown at the top of Table F-10. Figure F-2 shows comfort response as a function of time and roll rate. Only for the most extreme roll rate (ω_{R_3}) is there an upward trend in rated comfort as a function of time. But when the data for the two groups are separated, (also in Table F-10), one group shows worse comfort ratings for the last two time periods, while the other group does not.

If all of the data from the train experiment are forced into this analysis, in spite of the resulting vastly discrepant sample sizes in the various cells, the means shown at the bottom of Table F-10 (labeled R_1, R_2 and R_3) result. Again, only for the most extreme roll rate category (R_3) is there any possibility of comfort decreasing as a function of time.

These analyses suggest that comfort ratings depend on the motion environment a person experiences, not on the amount of time spent in that environment.

Information Integration Models

Several models were tried for predicting overall comfort response based on individual ride segments: 1) a simple average of the ratings for the segments of a trip; 2) the stepwise regression model based on segments or subparts of the trip; and 3) a weighted average in which later segments have greater weights than earlier ones. In particular, the weighting function proposed by Jacobson and Richards (1976) was used:

$$W(I) = I^{0.75},$$

and the predicted mean comfort response was given by:

$$C'_W = \frac{\sum_{I=1}^{n} C(I)\ W(I)}{\sum_{I=1}^{n} W(I)}$$

where I = response segment number, C = segment comfort rating. The correlation coefficients obtained for these three models are shown in Table F-11 for each of the data sets. In all cases, the equal weighting composite (simple mean) does as well as anything. There are some slight increases in predictability for the best regression models, but not enough to have any practical consequences. The regression models usually do involve ride segments from later in the trip and larger weights are associated with them than with the earlier segments.

TABLE F-1. MEAN COMFORT RATINGS FOR RIDE SEGMENTS BY GROUP, BUS AND DIRECTION (SEGMENTS ARE ORDERED AS EXPERIENCED DURING A TRIP).*

			Segment Number									
Group	Bus	Direction	1	2	3	4	5	6	7	8	9	Overall
A	Good	CW	3.1	2.5	3.3	3.3	3.8	2.5	3.0	2.4	6.3	2.5
A	Good	CCW	6.2	2.6	3.3	2.6	3.5	3.6	3.7	2.6	4.0	2.4
A	Bad	CW	3.3	2.6	3.4	3.2	3.7	2.4	3.0	2.2	6.3	2.4
A	Bad	CCW	5.9	2.6	3.1	2.6	3.4	3.4	3.4	2.4	4.0	2.5
B	Good	CW	4.0	3.0	3.9	3.6	4.1	3.0	3.3	3.1	6.2	2.7
B	Good	CCW	5.3	2.2	2.9	2.3	3.2	3.2	3.7	2.3	4.1	2.5
B	Bad	CW	3.3	2.3	3.2	3.3	3.2	2.5	2.4	2.2	6.1	2.4
B	Bad	CCW	5.0	2.5	2.8	2.5	3.6	3.6	4.0	2.6	4.3	2.5
Mean segment rating over all groups			4.5	2.5	3.2	2.9	3.6	3.0	3.3	2.5	5.2	2.5
r_{o,s_i}			.26	.56	.54	.52	.52	.48	.55	.57	.31	

*Data are from Bus Field Study (Phase 1, Part 1)

TABLE F-2. MEAN COMFORT RATINGS FOR RIDE SEGMENTS BY GROUP, BUS AND DIRECTION (SEGMENTS ARE ARRAYED BY IDENTITY, NOT ORDER OF EXPERIENCE)*.

			Segments									
Group	Bus	Direction	A	B	C	D	E	F	G	H	I	Time Sequence
A	Good	CW	3.1	2.5	3.3	3.3	3.8	2.5	3.0	2.4	6.3	→
A	Good	CCW	4.0	2.6	3.7	3.6	3.5	2.6	3.3	2.6	6.2	←
A	Bad	CW	3.3	2.6	3.4	3.2	3.7	2.4	3.0	2.2	6.3	→
A	Bad	CCW	4.0	2.4	3.4	3.4	3.4	2.6	3.1	2.6	5.9	←
B	Good	CW	4.0	3.0	3.9	3.6	4.1	3.0	3.3	3.1	6.2	→
B	Good	CCW	4.1	2.3	3.7	3.2	3.2	2.3	2.9	2.2	5.3	←
B	Bad	CW	3.3	2.3	3.2	3.3	3.2	2.5	2.4	2.2	6.1	→
B	Bad	CCW	4.3	2.6	4.0	3.6	3.6	2.5	2.8	2.5	5.0	←
Mean over all subjects			3.8	2.5	3.6	3.4	3.6	2.6	3.0	2.5	5.9	

*Data are from Bus Field Study (Phase 1, Part 1)

TABLE F-3. CORRELATION OF RATINGS AVERAGED OVER EACH THIRD OF THE TRIP WITH COMFORT RATING FOR THE TOTAL TRIP.*

			First Third	Middle Third	Last Third
A	Good	CW	.63	.67	.56
A	Good	CCW	.48	.69	.58
A	Bad	CW	.72	.75	.75
A	Bad	CCW	.65	.68	.72
B	Good	CW	.55	.50	.49
B	Good	CCW	.56	.68	.71
B	Bad	CW	.64	.60	.68
B	Bad	CCW	.49	.33	.55
	Overall		.56	.62	.61

*Data are from Bus Field Study (Phase 1, Part 1)

TABLE F-4. MEAN COMFORT RATING FOR EACH RIDE SEGMENT BY GROUP.*

	Segment Number								
	1	2	3	4	5	6	7	8	Overall
Group 1	2.7	3.2	4.0	3.7	2.9	2.7	3.8		3.1
Group 2	4.5	2.8	2.7	3.2	2.8	3.6	3.7		3.4
Group 3	4.1	2.7	2.2	3.0	2.8	3.4	2.7		2.7
Group 4	3.3	2.8	2.6	2.4	3.0	2.6	3.3	5.1	3.1

*Data are from Bus Validation Study (Phase 2)

TABLE F-5. CORRELATIONS OF RATINGS FOR RIDE SEGMENTS WITH OVERALL COMFORT RATING FOR TOTAL TRIP.*

	Segment Number							
	1	2	3	4	5	6	7	8
Combined Groups 1, 2, 3	.48	.58	.52	.62	.50	.60	.62	
Group 4	.67	.52	.67	.62	.65	.59	.77	.39

*Data are from Bus Validation Study (Phase 2)

TABLE F-6. MEAN RATINGS FOR EACH RIDE SEGMENT AND TOTAL TRIP FOR BUS CURVE DATA (PHASE 1, PART 2).

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Overall
Means	All Subjects	2.8	2.7	2.8	3.0	2.7	3.0	2.2	3.3	4.3	3.9	3.8	2.5	3.5	3.2	2.4	2.9	1.7	2.0	2.2	6.0	2.1	2.7	2.2	6.4	2.1	2.8
	Group A	2.7	2.6	2.8	2.3	2.2	2.4	2.0	2.5	3.6	3.6	3.0	2.1	3.3	2.1	2.0	2.6	2.0	2.1	2.5	6.3	2.1	2.7	2.1	6.7	2.1	2.6
	Group B	2.9	2.9	2.8	3.7	3.1	3.6	2.3	4.1	4.9	4.2	4.5	3.0	3.7	4.2	2.8	3.1	1.5	2.0	1.9	5.7	2.1	2.7	2.3	6.1	2.1	3.0

TABLE F-7. CORRELATIONS OF RATINGS AVERAGED OVER EACH FIFTH OF THE TRIP WITH COMFORT RATING FOR THE TOTAL TRIP (BUS CURVE DATA).*

	Fifth of Trip				
	1	2	3	4	5
All Subjects	.59	.72	.64	.75	.71
Group A	.47	.79	.86	.91	.86
Group B	.71	.73	.59	.65	.51

*Data from Bus Curve Study (Phase 1, Part 2)

TABLE F-8. MEAN COMFORT RATINGS FOR RIDE SEGMENTS BY GROUP AND TRIP.*

		Segment Number																				
Group	Trip	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Overall
A	1	2.2	2.2	3.0	2.8	2.7	3.8	2.8	3.5	2.6	2.2	2.9	2.2	2.8	3.4	3.0	2.9	2.5	2.2	2.0	3.9	2.0
A	2	1.7	1.7	2.2	2.4	2.9	2.6	2.7	2.5	2.6	3.2	2.3	2.8	3.3	2.9	2.8	2.4	2.9	2.9	2.6	2.4	2.0
B	1	2.8	3.2	2.6	2.6	3.3	3.8	4.6	4.2	3.0	2.8	2.3	3.4	4.4	4.8	4.8	2.9	4.6	4.5	2.9	4.4	2.9
B	2	2.2	2.5	2.7	3.0	4.3	2.4	3.2	2.0	2.5	2.5	2.5	2.2	3.8	3.6	2.7	2.3	2.4	2.2	1.9	3.0	2.1
Pooled		2.2	2.4	2.6	2.7	3.3	3.2	3.3	3.0	2.7	2.7	2.5	2.6	3.6	3.7	3.3	2.6	3.1	2.9	2.3	3.4	2.3

*Data from Train Field Study (Phase 1)

TABLE F-9a. MEAN COMFORT RATINGS AS A FUNCTION OF TIME PERIOD AND ROLL LEVEL (FROM BUS FIELD DATA).

		Time Period				
		T_1	T_2	T_3	T_4	$\bar{X}_R$
Roll Level	R_1	2.48	3.76	2.96	2.34	2.88
	R_2	3.34	3.43	2.38	2.24	2.85
	R_3	5.90	3.72	3.50	6.31	4.86
	$\bar{X}_T$	3.91	3.64	2.95	3.63	

TABLE F-9b. ACTUAL ROLL RATE OBSERVED FOR EACH TIME PERIOD AND ROLL LEVEL (FROM BUS FIELD DATA).

		Time Period				
		T_1	T_2	T_3	T_4	$\bar{X}_R$
Roll Level	R_1	1.43	1.33	1.44	1.26	1.36
	R_2	2.03	2.25	2.29	2.10	2.17
	R_3	3.46	2.81	2.50	4.22	3.25
	$\bar{X}_T$	2.31	2.13	2.08	2.53	

Entries are observed RMS roll rates.

TABLE F-10. MEAN COMFORT RATINGS (N=30) FOR SELECTED LEVELS OF ROLL AT FOUR TIME INTERVALS (DATA FROM TRAIN FIELD STUDY).

a) Selected data, averaged over groups:

	Time Period				
	T_1	T_2	T_3	T_4	$\overline{X}_R$
ω_{R_1}	2.16	3.33	2.73	2.62	2.71
ω_{R_2}	2.36	2.65	2.36	2.77	2.53
ω_{R_3}	3.12	3.38	3.34	3.66	3.37
$\overline{X}_T$	2.55	3.12	2.81	3.02	

b) Selected data, Group A:

Roll				
$\omega_R = 1.12$	1.73	2.90	3.20	2.37
$\omega_R = 1.37$	2.16	2.80	2.17	2.87
$\omega_R = 1.60$	2.97	3.53	2.26	2.90

c) Selected data, Group B:

Roll				
$\omega_R = 1.17$	2.60	3.77	2.27	2.87
$\omega_R = 1.40$	2.57	2.50	2.55	2.67
$\omega_R = 1.60$	3.27	3.23	4.43	4.43

d) All data--forced into design:

					$\overline{X}_R$
R_1	2.32	2.87	2.73	2.37	2.57
R_2	2.71	3.02	2.82	2.91	2.86
R_3	2.85	3.52	3.69	3.28	3.33
$\overline{X}_T$	2.63	3.14	3.08	2.85	

TABLE F-11. CORRELATIONS OF OBSERVED OVERALL COMFORT RATINGS WITH PREDICTIONS FROM COMPOSITE MODELS BASED ON RIDE SEGMENTS.

DATA SET	Composite From Equal Weighting	Best Regression	$W(I) = I^{.75}$	N
Buses				
Field	.66	.66	.66	225
Curves	.81	.84	.83	56
Validation				
7 segments	.80	.82	.77	82
8 segments	.85	.88	.82	29
Trains				
Field	.51	.52	.51	120
Validation	.55	.53	.53	49

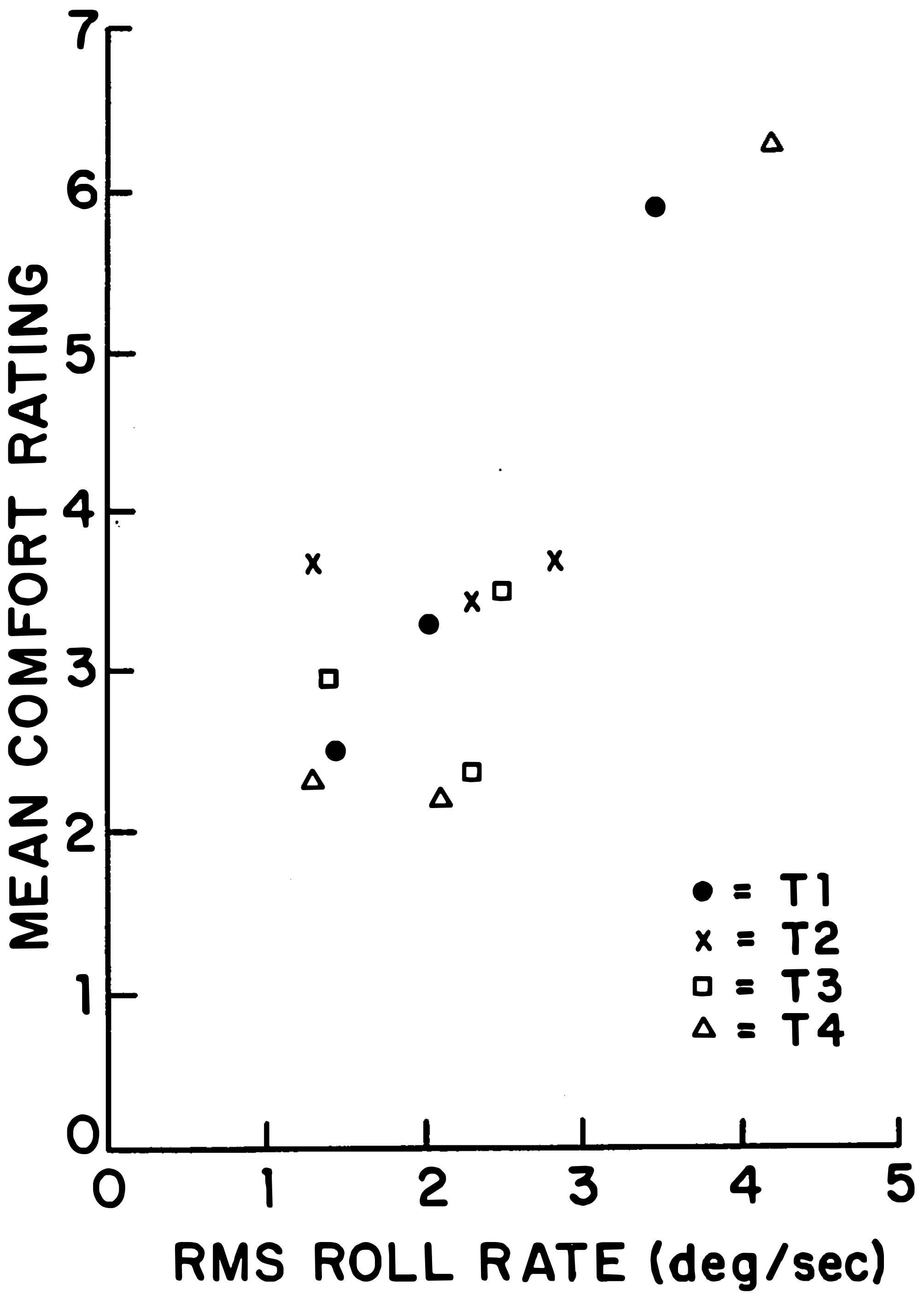

FIGURE F-1. RATED COMFORT AS A FUNCTION
OF RMS ROLL RATE AND TIME PERIOD FOR SELECTED BUS FIELD DATA.

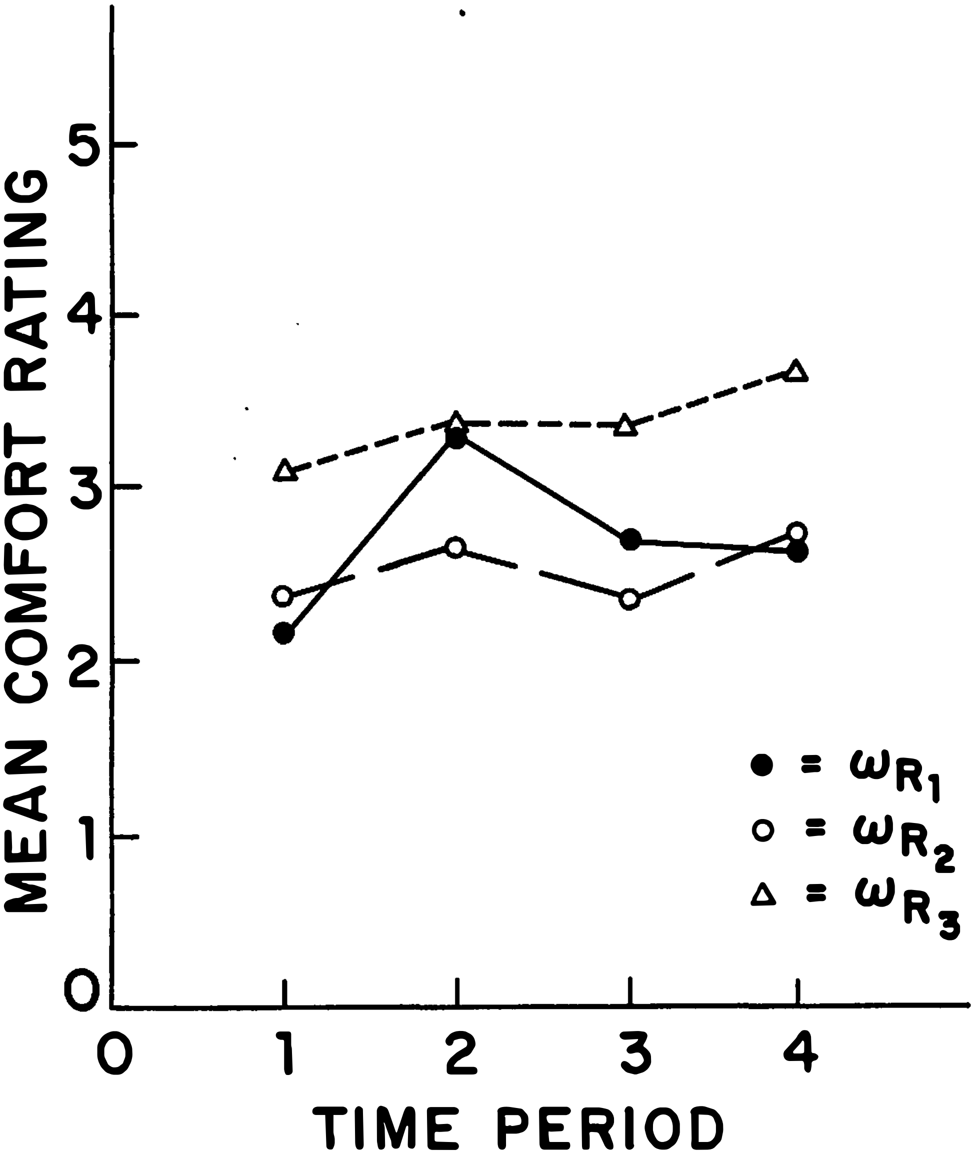

FIGURE F-2. RATED COMFORT AS A FUNCTION OF TIME PERIOD AND LEVEL OF RMS ROLL RATE FOR SELECTED TRAIN FIELD DATA.

APPENDIX G.

COMPARISON OF ACTUAL RATED COMFORT WITH ISO GUIDELINES.

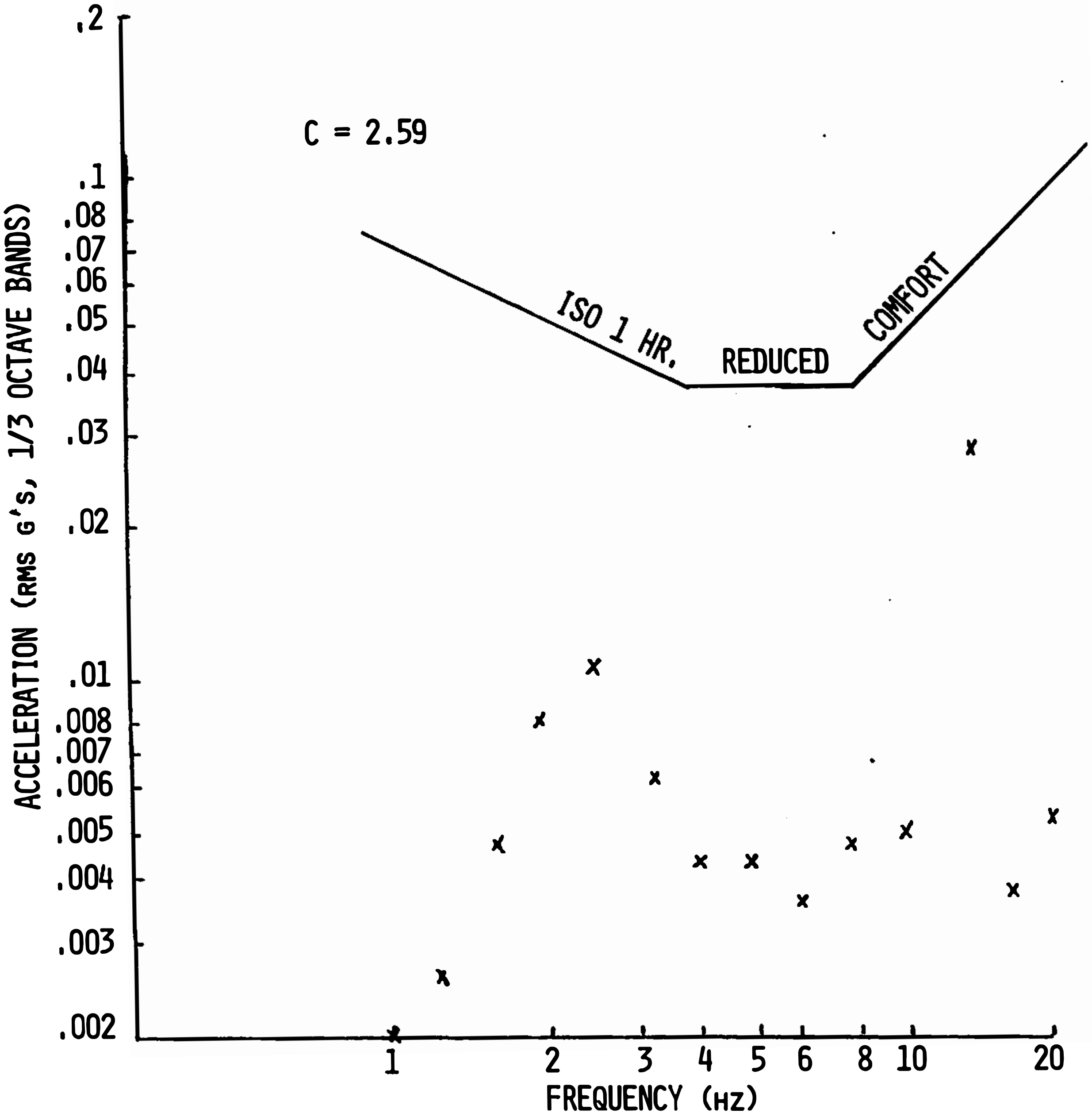

FIGURE G-1. VERTICAL DIRECTION--BUS SEGMENT 4.

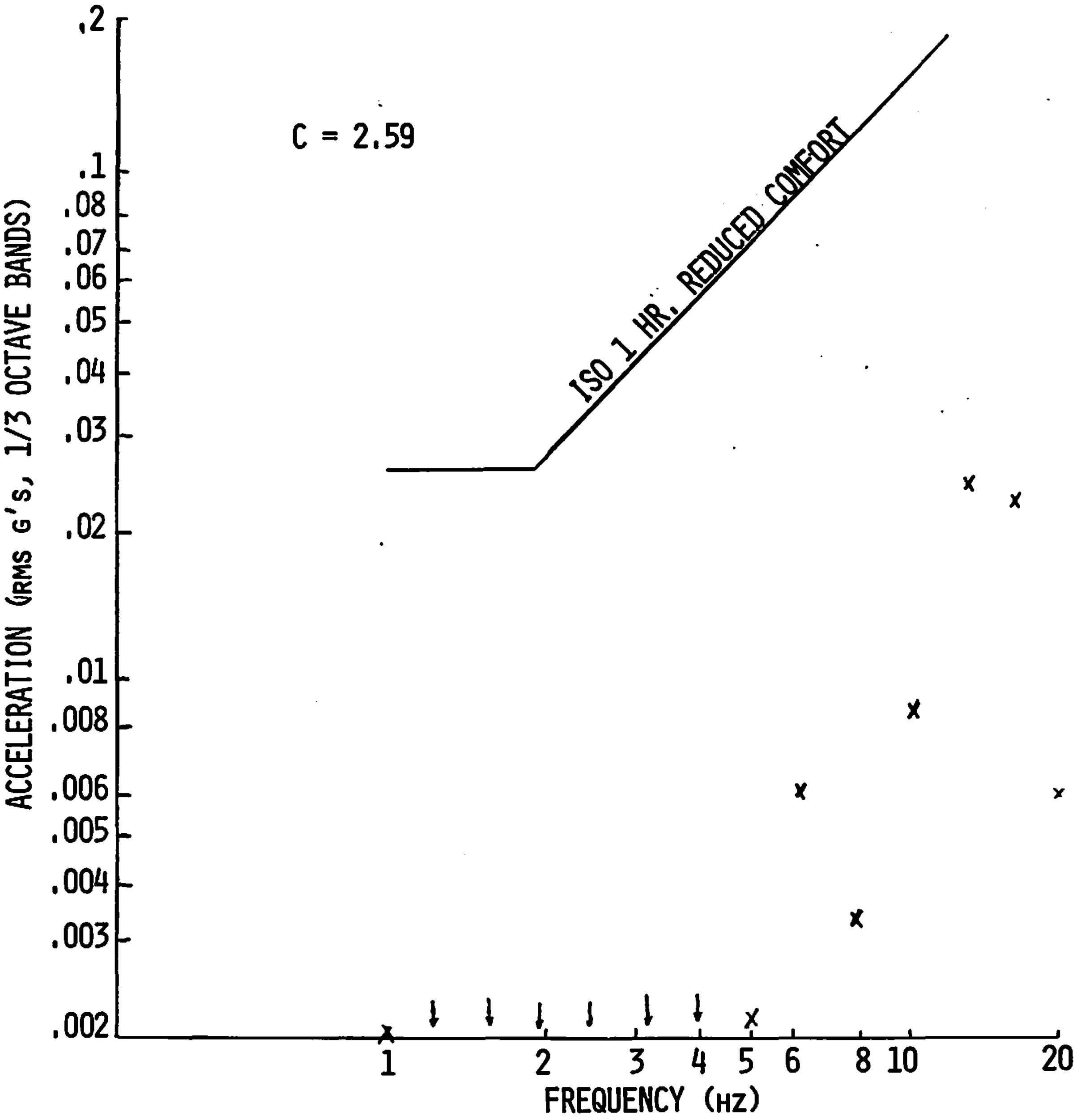

FIGURE G-2. LATERIAL DIRECTION--BUS SEGMENT 4.

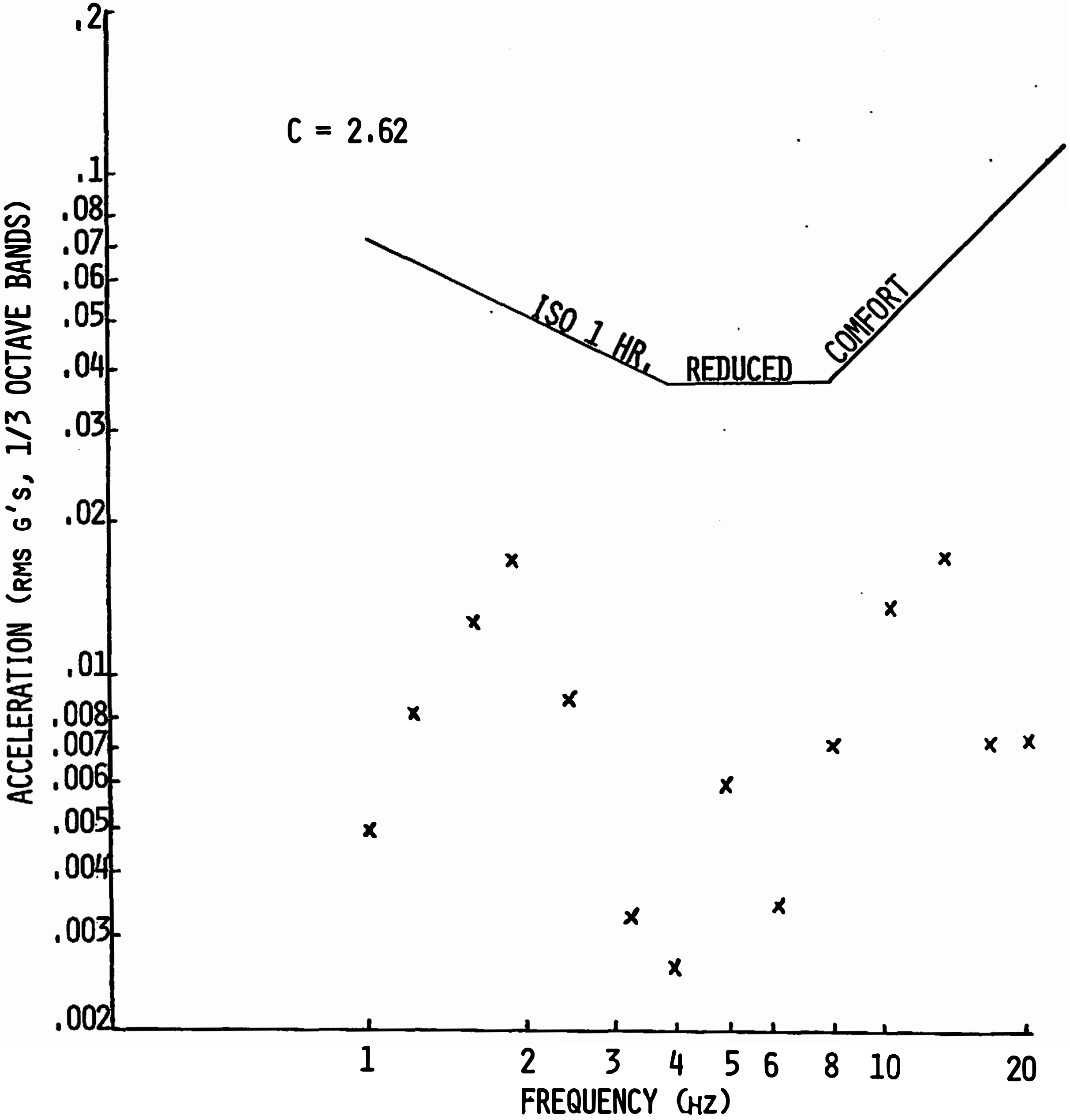

FIGURE G-3. VERTICAL DIRECTION--BUS SEGMENT 8.

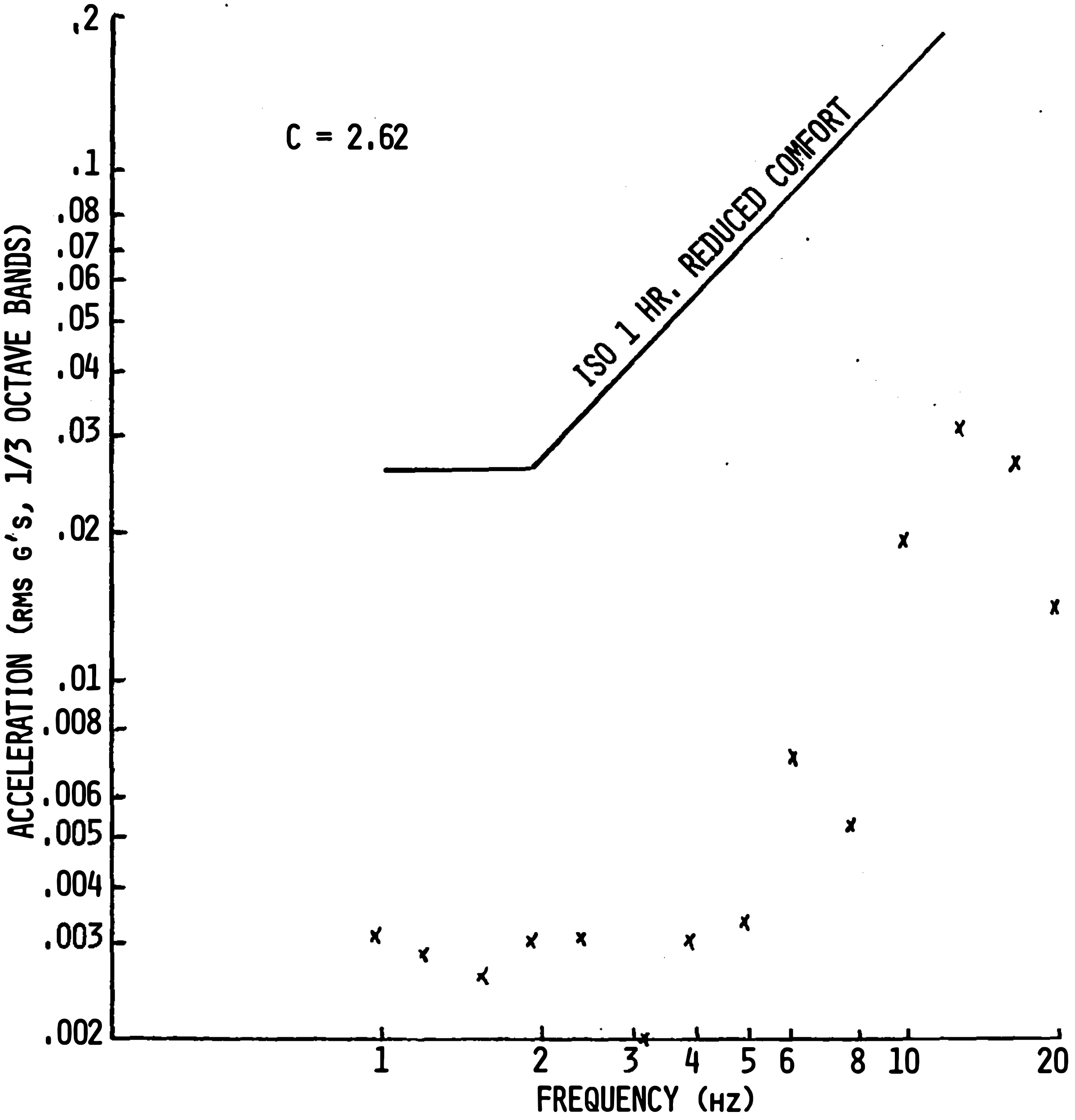

FIGURE G-4. LATERAL DIRECTION--BUS SEGMENT 8.

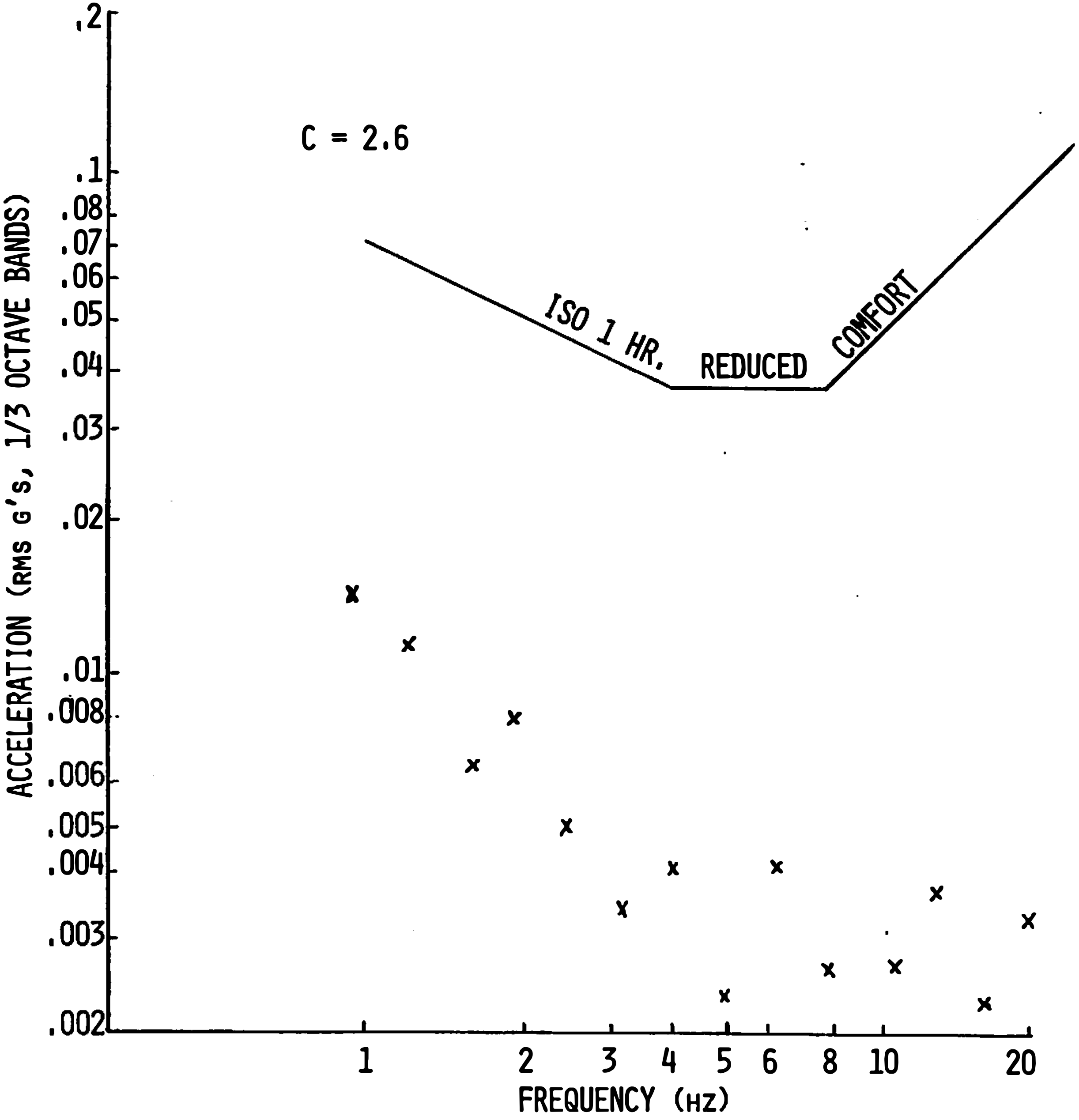

FIGURE G-5. VERTICAL DIRECTION--TRAIN SEGMENT 3.

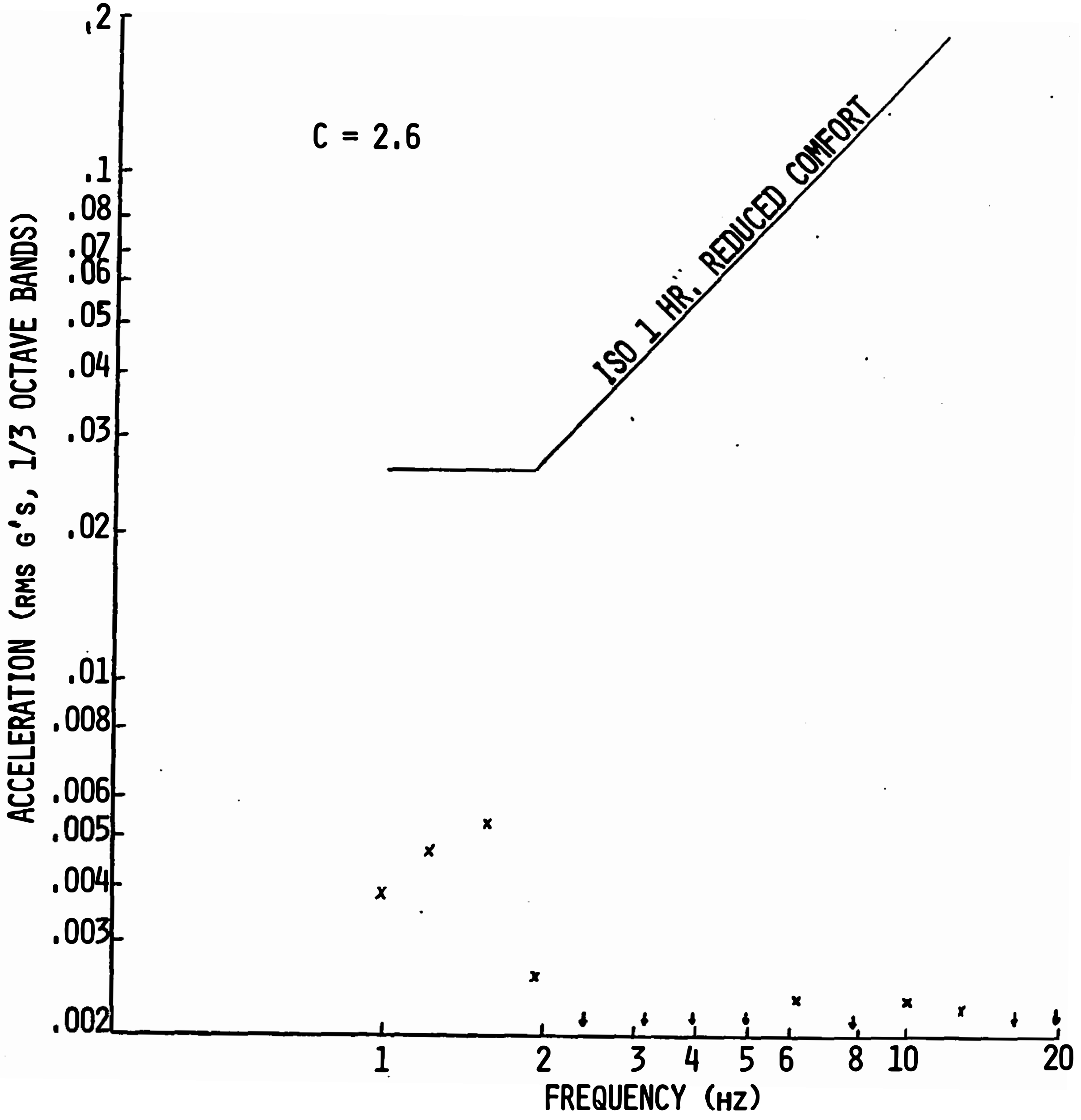

FIGURE G-6. LATERAL DIRECTION--TRAIN SEGMENT 3.

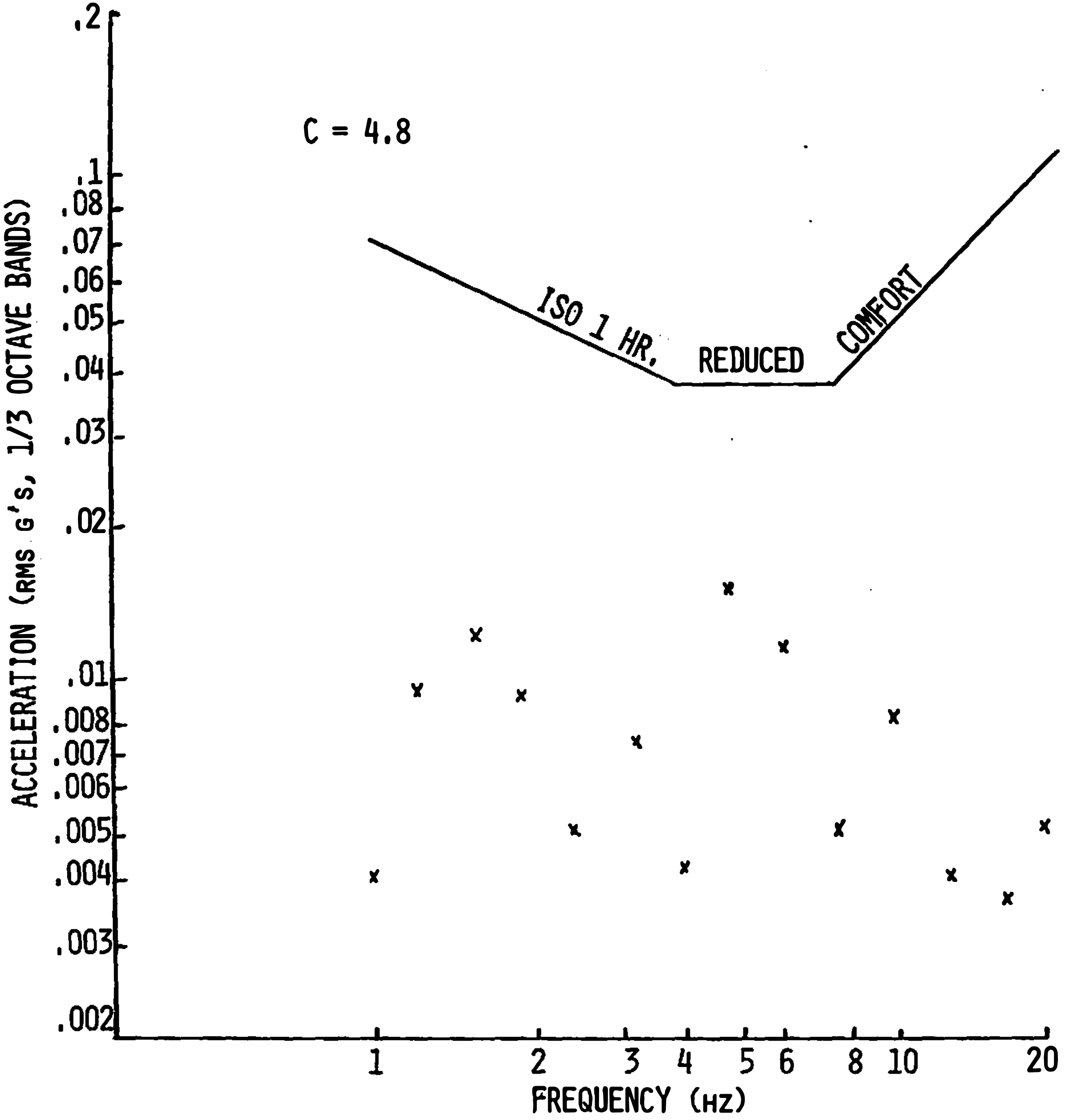

FIGURE G-7. VERTICAL DIRECTION--TRAIN SEGMENT 14.

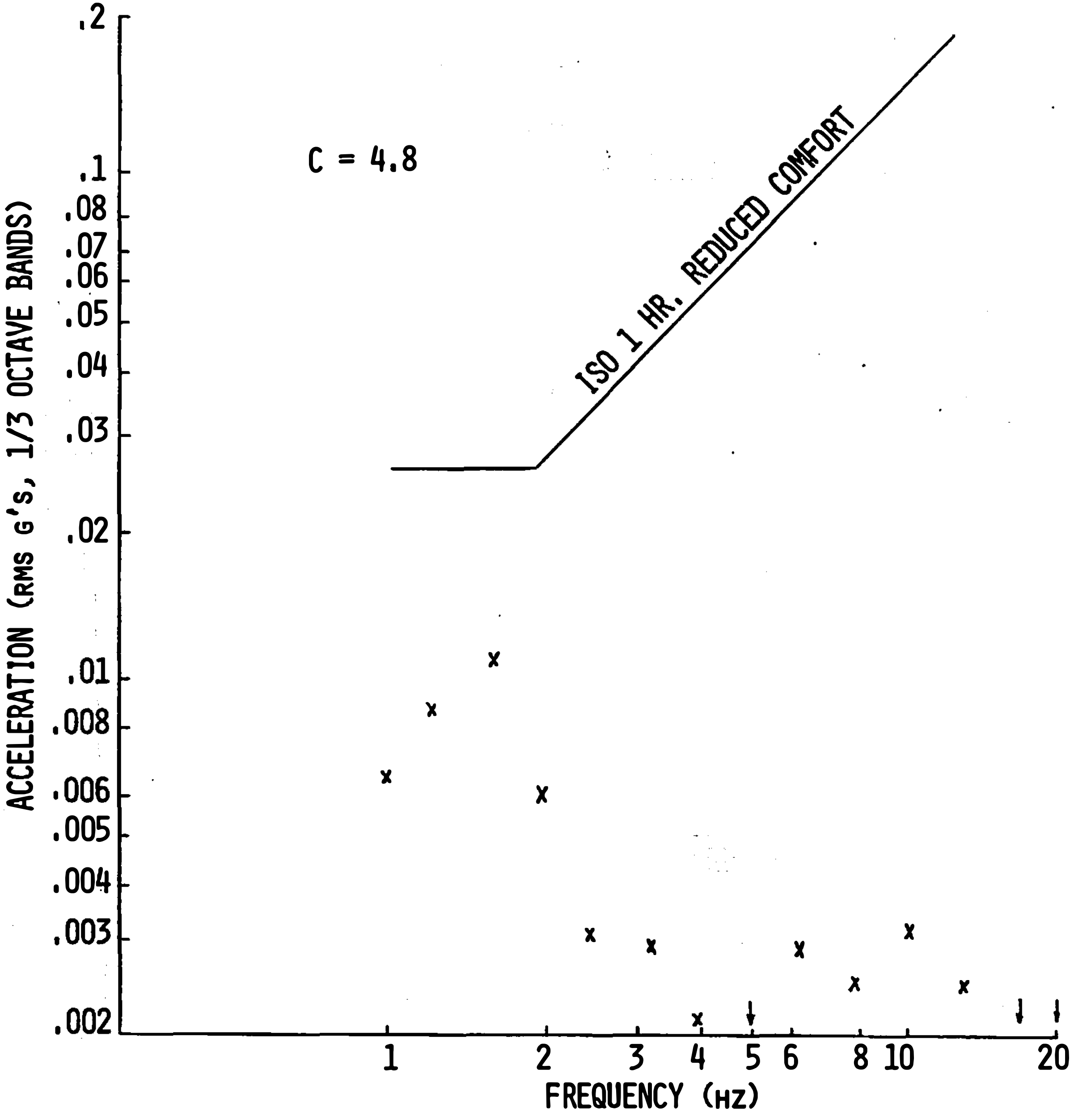

FIGURE G-8. LATERAL DIRECTION--TRAIN SEGMENT 14.

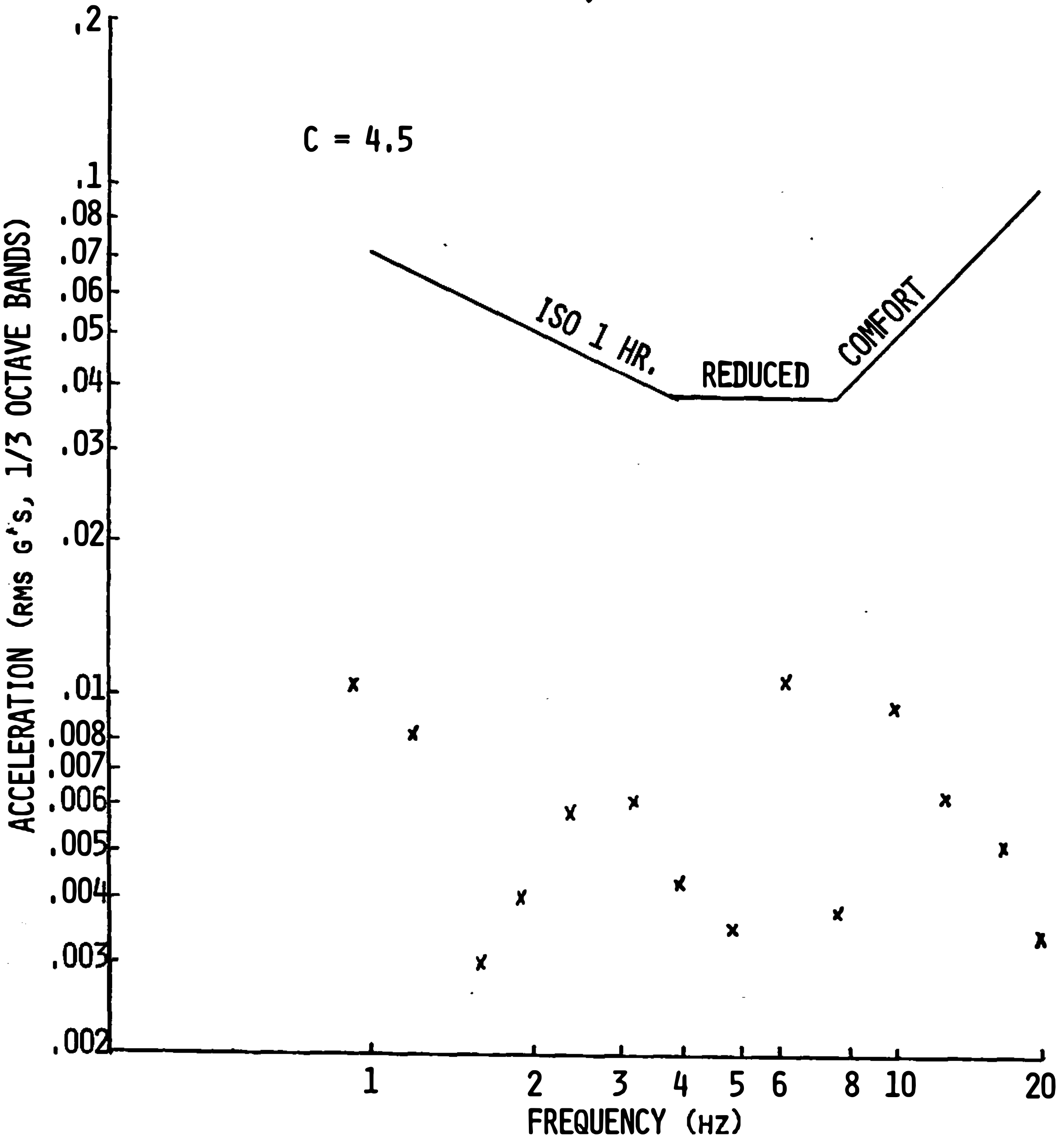

FIGURE G-9. VERTICAL DIRECTION--TRAIN SEGMENT 18.

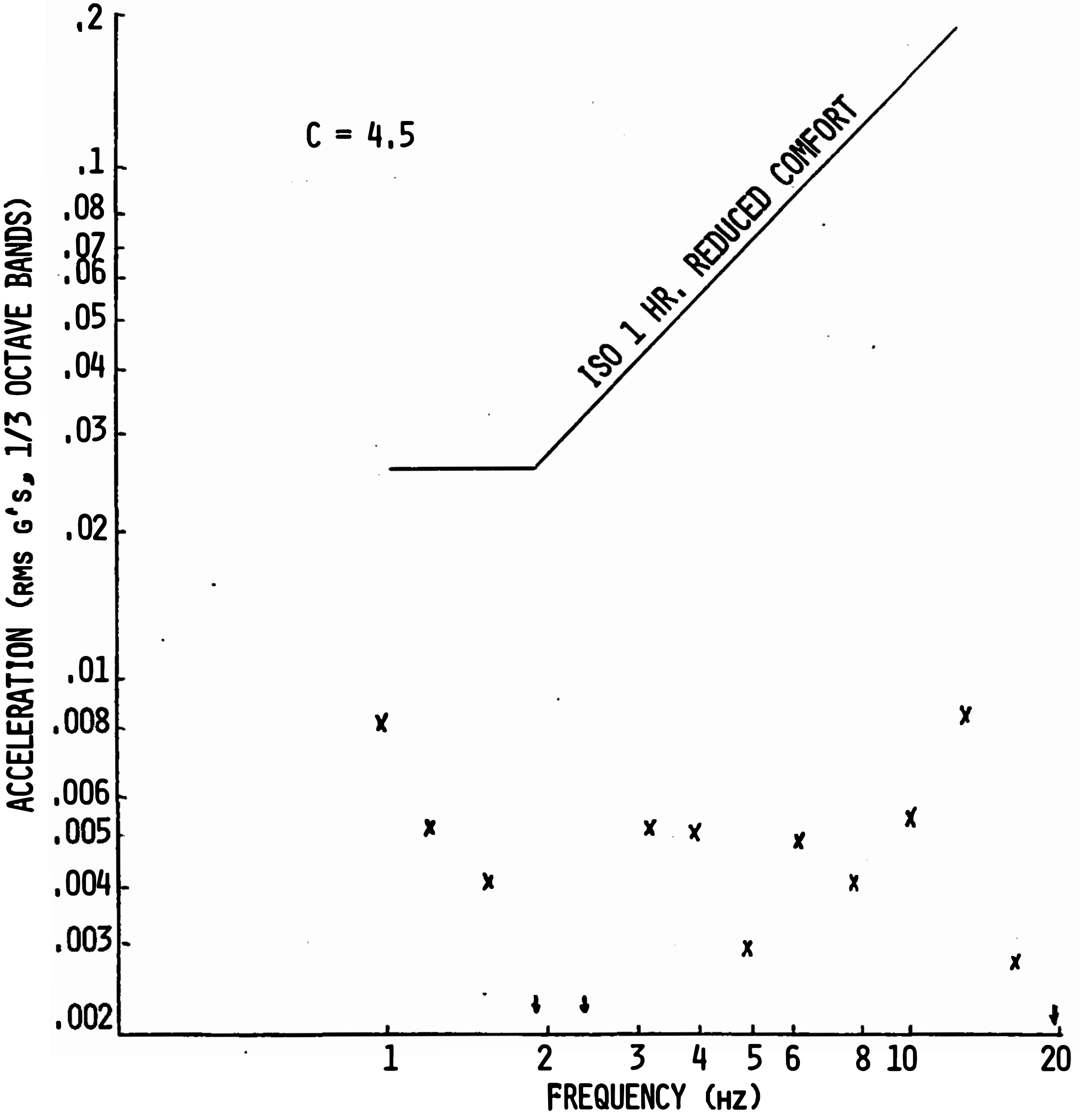

FIGURE G-10. LATERAL DIRECTION--TRAIN SEGMENT 18.

APPENDIX H.

REPORT OF INVENTIONS

Under this contract (DOT-TSC-1090), no new equipment, patentable procedures or any other materials were invented. Neither was there any revision or modification to existing equipment, procedures, etc., that would appear patentable. However, an innovative ride quality model was developed for interurban trains that involves two terms: one is motion and the other is overall noise level in dB(A), and is expressed as:

Train Model:

$$C' = 1.0 + 0.96\, W_R + 0.10\, (\mathrm{dB(A)} - 63).$$

The correlation coefficient between comfort ratings and motion data for this mode is $R = .72$.

In addition, procedural guidelines were developed that could be employed by transportation specialists in developing and using ride quality models to evaluate passenger comfort in other existing or future systems. Specific guidelines (as described in detail in Volume II) were developed for: 1) collecting vehicle motion and passenger comfort data in the field; 2) generating ride quality models based on these data; 3) validating models against data from passengers on scheduled services; 4) using models to evaluate or predict vehicle ride quality; and 5) specifying ride characteristics for new vehicles.

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