AFRL-HE-WP-TR-2006-0133

Vibration Transmissibility Characteristics of Occupied Suspension Seats

Federal Railroad Administration

Suzanne D. Smith

Air Force Research Laboratory

Jeanne A. Smith
Raymond J. Newman

Advanced Information Systems Inc.
A General Dynamics Company
5200 Springfield Pike Suite 200
Dayton OH 45431-1289

September 2006
Interim Report for December 2001 to January 2006

Air Force Research Laboratory
Human Effectiveness Directorate
Biosciences and Protection Division
Biomechanics Branch
Wright-Patterson AFB OH

NOTICE AND SIGNATURE PAGE

AFRL-HE-WP-TR-2006-0133 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

The voluntary informed consent of the subjects used in this research was obtained as required by Air Force Instruction 40-402.

FOR THE DIRECTOR

//signed//

MARK M. HOFFMAN
Deputy Chief, Biosciences and Protection Division
Air Force Research Laboratory

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 074-0188

1. REPORT DATE (DD-MMM-YYYY)
September 2006

2. REPORT TYPE
Interim Report

3. DATES COVERED (From – To)
December 2001-January 2006

4. TITLE AND SUBTITLE
Vibration Transmissibility Characteristics of Occupied Suspension Seats

5a. CONTRACT NUMBER
FA8650-04-D-6472

5b. GRANT NUMBER
N/A

5c. PROGRAM ELEMENT NUMBER
62202F

6. AUTHOR(S)
Suzanne D. Smith (AFRL), Jeanne A. Smith, Raymond J. Newman (General Dynamics AIS)

5d. PROJECT NUMBER
7184

5e. TASK NUMBER
02

5f. WORKUNIT NUMBER
15

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Materiel Command
AFRL, Human Effectiveness Directorate
Biosciences & Protection Division
Biomechanics Branch
Wright-Patterson AFB OH 45433-7947

General Dynamics AIS
5200 Springfield Pike
Suite 200
Dayton, OH 45431-1289

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-HE-WP-TR-2006-0133

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
Office of Research and Development
Volpe National Transportation Systems Center
Cambridge MA 02142

Air Force Material Command
AFRL, Human Effectiveness Directorate
Biosciences & Protection Division
Biomechanics Branch
Wright-Patterson AFB OH 45433-7947

10. SPONSOR / MONITOR'S ACRONYM
AFRL/HEPA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited Document Number AFRL-WS 06-2711, 11/20/2006

13. SUPPLEMENTARY NOTES

14. ABSTRACT A study was conducted to evaluate the transmissibility characteristics of occupied suspension seats in multi-axis vibration environments using locomotive seats. Exposures included a flat acceleration spectrum and two signals extracted from locomotive floor data. The multiple input/single output system transfer matrix and overall transmission were calculated at the seat and several anatomical sites. While the transmissibilities showed minimal off-axis contributions to the seat responses, off-axis contributions were evidenced at the chest and head for the flat spectrum exposure. Off-axis vibration and other factors contributed to the seat, chest, and head motions during exposure to the locomotive vibrations. Significantly higher overall transmissions were observed in the vertical direction at the seat and head, and in the fore-and-aft and vertical directions at the chest using the suspension seat with shocks removed. The relatively large, low frequency multi-axis motions observed at the chest may be a contributor to discomfort in locomotive engineers. Seat Effective Amplitude Transmissibility values were determined for estimating the overall seat pan acceleration from monitored locomotive floor accelerations for targeting potentially harmful vibration exposures at the cab seat (ISO 2631-1: 1997).

15. SUBJECT TERMS
Human vibration, transmissibility, suspension seats, locomotive vibration

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON:
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	SAR	61	

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39-18

This page intentionally left blank.

Table of Contents

Figures and Tables

This page intentionally left blank.

Preface

This report describes the results of work performed to evaluate the transmissibility characteristics of suspension seats, specifically those used by locomotive engineers in passenger and freight trains, to develop a scheme for targeting potentially harmful vibration exposure from monitored vehicle floor accelerations. The work was performed from December 2001 to January 2004 by the Air Force Research Laboratory, Human Effectiveness Directorate (AFRL/HE), Wright-Patterson AFB, OH. The Principal Investigator for the project was Dr. Suzanne D. Smith, Biosciences and Protection Division, Biomechanics Branch (AFRL/HEPA). The study was funded by the Department of Transportation, Research and Special Programs Administration, Volpe National Transportation Systems Center, under the Interagency Agreement Number DTRS57-02-X-70014 in support of the Federal Railroad Administration, Office of Research and Development, Amtrak.

This page intentionally left blank.

Acknowledgments

The authors acknowledge the Volpe National Transportation Systems Center, particularly Dr. Donald Sussman, Chief, Operator Performance and Safety Analysis Division (retired), and Mr. John Pollard for their guidance and support on this study. The authors also recognize Mr. Steve Mosher, General Dynamics AIS, who developed the software to calculate the system transfer matrix for multi-axis vibration.

This page intentionally left blank.

Executive Summary

This report describes the study conducted by the Air Force Research Laboratory, Human Effectiveness Directorate (AFRL/HE) at Wright-Patterson AFB, OH to evaluate the transmissibility characteristics of suspension seats and their effects on human body biodynamics in multi-axis vibration environments. Due to several reports of back pain from locomotive engineers, the Federal Railroad Administration, Office of Research and Development, Amtrak, requested the assistance of the Volpe National Transportation Systems Center in collecting floor and seat frame triaxial acceleration data in passenger locomotives. The data were to be used to assess the potential health risk of the engineers exposed to whole-body vibration. The current international standard (ISO 2631-1: 1997) and national standard (ANSI S3.18-2002) recommend that the assessment be conducted on vibration collected at the interface between the human and seating surface. The interface vibration can be estimated from the transmission characteristics of the seating system. AFRL, in their continuing efforts to establish appropriate techniques for analyzing the effects of seating systems on human occupants exposed to multi-axis vibration, conducted a study to evaluate the multi-axis transmissibility characteristics of selected seat configurations including suspension and non-suspension seating systems provided by the United States Seating Company. The goal was to develop a scheme for targeting potentially harmful vibration exposures from known floor accelerations, specifically those accelerations transmitted to the locomotive cab seats.

In addition to a multi-axis flat spectrum acceleration signal (1-80 Hz) (FLAT), two multi-axis locomotive signals were extracted from the locomotive floor data collected by the Volpe National Transportation Systems Center (LOCO3 and LOCO12). LOCO3 and LOCO12 showed a concentration of vibration in the frequency range below 10 Hz with notable peaks occurring around 1.5 to 2.0 Hz, particularly in the fore-and-aft (X) direction of the seated occupant. The Six Degree-of-Freedom Motion Simulator (SIXMODE), located in AFRL/HE, was used to generate the vibration. Three locomotive seats were tested including a suspension seat with good shocks (GS), one with bad shocks, i.e., the shocks removed (BS), and a non-suspension freight seat (FS). A rigid seat was also tested for comparison (RS). Two postures, back-on and back-off, were used in the study. Seven subjects, including females and males, participated in the study. Triaxial accelerometer packs were attached to various locations on the seat for measuring the responses of the seat in the fore-and-aft (X), lateral (Y), and vertical (Z) axes relative to the seated occupant. Two flat rubber disks, each containing an embedded triaxial accelerometer, were located at the interface between the subject and seat pan cushion and at the interface between the subject and seat back cushion. The ISO 2631-1: 1997 human vibration standard provides guidelines on using the vibration that enters the occupant at these interfaces to assess potential health risk and comfort. Triaxial accelerations were also measured at various anatomical structures including the chest, thigh, lower leg, lower spine, and upper spine. A bitebar was used to measure the triaxial accelerations of the head, and for calculating head roll, pitch, and yaw.

A multiple input/single output model was used for calculating the system transfer matrix. This model accounts for the possibility that vibration in one axis can affect the response in another axis, but assumes that the outputs are independent from one another. The overall transmission is a more simple calculation that was used to compare the transmission characteristics among the measurement sites, exposures, directions, seat configurations, and postures. The overall transmission in each translational axis was calculated as the ratio between the overall acceleration measured at a particular site and the overall acceleration measured at the floor. The overall accelerations were calculated between 1 and 10 Hz.

The results for the FLAT exposure showed that there were minimal cross-axis contributions to the vibration observed at the measured seat sites. The most notable peak transmissibilities occurred in the X and Z directions. In the X direction, the peak responses tended to occur between 2 and 3 Hz, slightly higher than the peak X motion observed in the locomotive signals (1.5 Hz). The seat back showed higher peaks as compared to the seat pan with a mean transmissibility of about 2. In the Z direction, the peak seat pan transmissibilities occurred between 3 and 3.5 Hz in the GS and FS seats, and around 2 Hz with the BS seat, coinciding closely with the peak Z motion in the locomotive signals (~2 Hz). The GS and FS seats showed a relatively flat response equal to unity at the seat back as compared to the BS seat. For the FLAT exposure, the partial and multiple coherences were relatively high between 1 and 10 Hz, but quite variable for the BS seat. In summary, for the FLAT exposure, the seat responses were almost entirely accounted for by a linear response to the measured input in the same direction with little cross-axis coupling.

In contrast to the seat results, both the chest and head did indicate that cross-axis vibration contributed to the upper torso responses during the FLAT exposure. Specifically, vertical vibration appeared to contribute to fore-and-aft chest response, suggesting the presence of some pitching. The partial coherences were quite variable. This was even more dramatic at the head, where head rotation was expected to contribute to head translation in the X and Z directions.

For exposures to the locomotive signals, the transmissibility responses were not as consistent as observed for the FLAT exposure. This was most likely due to increased nonlinear effects, as well as the negligible input accelerations associated with certain frequency components.

The overall transmission was used to compare the effects of seat configuration and posture given the difficulty encountered when using the complex system transfer matrix, particularly for the locomotive vibration exposures. Significant effects of seat configuration and posture were observed. Higher overall seat pan transmissions occurred in the X direction when using the locomotive seats as compared to the rigid seat. In the Z direction, the overall seat pan transmission for the BS seat was greater than 1.8 times the floor input. The back-off posture showed overall seat pan transmissions that were statistically higher than the back-on postures in the horizontal directions, although the differences appeared to be small. In contrast, the back-on posture showed significantly higher overall chest transmission in the X direction. Higher overall seat back transmissions occurred in the horizontal directions when using the locomotive seats as compared to the rigid seat. The overall seat back transmissions were higher for the BS seat in the Z direction for the locomotive exposures, but not for the FLAT exposure. The back-off posture produced higher seat back transmissions in the Z direction but with no great consequence. The back-on posture showed higher overall head transmission for most seats. The back-on posture appeared to have a significant influence on amplifying the upper torso motions.

The original objective was to use the system transfer matrix to predict the multi-axis responses at the seat pan and seat back, and then apply the ISO 2631-1: 1997 to evaluate operator health and comfort. The results for the locomotive exposures rendered it difficult to develop a simple and reliable transfer function for predicting the effects of the input or floor vibration on motions at the seat and body. However, the data collected in this study could be used to determine the Seat Effective Amplitude Transmissibility (SEAT), defined in this study as the ratio between the overall weighted seat pan accelerations and overall weighted floor accelerations between 1 and 10 Hz in each translational direction. One overall SEAT value was determined for each axis: 1.3 for X, 1.0 for Y, and 1.3 for Z. The value for the Z direction was primarily based on the higher vibration transmission occurring with the BS seat. The weighted overall floor accelerations in each direction for a one-hour operational exposure were multiplied by the respective SEAT value to obtain the weighted seat pan accelerations. The Vibration Total Value (VTV) was calculated as the square root of the sum-of-squares of the accelerations in each direction using 1.4 as the multiplying factor in the X and Y directions for assessing health. The seat pan VTV for health was 0.743. The lower boundary of the Health Guidance Caution Zone in ISO 2631-1: 1997 was reached in about 3 hours. It is recommended that vibration within the lower and upper boundaries be avoided. The seat pan VTV for comfort (using 1.0 as the multiplying factor) was 0.669, corresponding to a reaction of "fairly uncomfortable." The VTV would be even higher if the weighted seat back data were included. These reactions imply less than ideal ride quality.

Given the complexity of the locomotive seat vibration, the application of the SEAT values to the monitored operational floor accelerations weighted in accordance with ISO 2631-1: 1997 can provide an effective method for targeting potentially harmful seat vibration, as long as the monitored floor accelerations generate similar frequency distribution characteristics as shown in the data used in this study. This approach could be applied to other vehicles, such as propeller aircraft, where the frequency distribution is quite predictable.

The locomotive signals used in this study produced relatively large and complicated motions in the upper torso that were physically observed in the subjects. These large multi-axis motions may be a major contributor to discomfort during the operation of locomotives under the more severe conditions reflected by the signals used in this study. The approach developed in this study to predict potential health risks and comfort reactions supports these observations. It is recommended that potential factors that may contribute to the large locomotive motions be investigated and mitigation strategies applied to reduce the transmission of these motions to the occupant.

Vibration Transmissibility Characteristics of Occupied Suspension Seats

Introduction

Background

Numerous human vibration studies conducted over the past several decades have shown that the human body is sensitive to low frequency vibration occurring below 10 Hz (Griffin, 1990). Although posture and poor seating have been associated with discomfort and back pain, prolonged exposure to occupational vibration has been considered a contributing factor in the generation of these symptoms in civilian and military operations (ISO, 1997). Passive, low frequency suspension seats are being used to minimize this vibration, particularly in heavy commercial and off-road vehicles. In general, the passive, low frequency suspension system consists of a low stiffness spring and damper structure, designed to attenuate vehicle vibration in the frequency range where the major human body resonance occurs in the vertical direction (4 to 8 Hz). As a consequence, the suspension seat amplifies both fore-and-aft and vertical vibration below 3 Hz (Corbridge, 1987; Smith, 1997). Locomotive engineers in passenger trains are using suspension seats similar to the passive, low frequency design concept described above. At the request of the Federal Railroad Administration's (FRA) Office of Research and Development, with the cooperation of Amtrak, the Department of Transportation (DOT) Volpe National Transportation Systems Center conducted a field study to collect floor and seat frame triaxial accelerations in specific passenger train locomotives. These data were to be used for assessing the exposure experienced by the locomotive engineers to whole-body vibration. The current internationally-accepted method is described in ISO 2631: 1997 "Mechanical Shock and Vibration–Evaluation of Human Exposure to Whole-Body Vibration Part 1: General Requirements" (also in ANSI S3.18-2002). This method recommends that the vibration be assessed at the interface between the human body and seating surface, taking into account any effects that the seat dynamics may have on the floor vibration before entering the body. It was unclear whether the measured floor and seat frame data provided an accurate estimate of the vibration entering the human body for assessing the exposure effects in accordance with the standards. The interface vibration can be estimated using the transmission characteristics of the seating system. One specific method is to estimate the appropriate transfer functions between the floor and seat/occupant interface. The Air Force Research Laboratory (AFRL) is very interested in establishing appropriate techniques for analyzing the effects of seating systems on humans exposed to complex multi-axis vibration environments. These techniques can be used to develop mitigation strategies and equipment design criteria. In a collaborative agreement between DOT Volpe Research Center, AFRL conducted a laboratory study at Wright-Patterson Air Force Base to evaluate the transmissibility characteristics of suspension seats and their effects on human body biodynamics in multi-axis vibration environments.

Purpose

The primary purpose of this study was to characterize the vibration transmission characteristics of suspension seats, specifically those used by the locomotive engineers in passenger and freight trains. The goal was to develop a scheme for targeting potentially harmful vibration exposures transmitted by the locomotive cab seats from the monitored locomotive floor accelerations. A flat spectrum acceleration profile was used to characterize the frequency response of the occupied seating systems. In addition, vibration signatures were selected from the DOT field data to determine if the transmission characteristics were similar between the flat spectrum exposure and more severe occupational exposures. Since vibration at the locomotive floor includes motions in all three orthogonal directions, the multiple input/single output system transfer matrices were calculated for estimating the transmission of vibration from the vehicle floor to the occupant/seat interface, as well as to selected anatomical locations. Overall acceleration levels were also used to evaluate the transmission characteristics. An approach was developed for estimating the weighted overall seat pan accelerations from the weighted floor measurements for conducting exposure assessments in accordance with the ISO 2631-1: 1997 and ANSI S3.18-2002.

Materials and Methods

Subjects

Seven subjects participated in the study, including three females and four males. The subjects were members of the Impact Acceleration Panel at Wright-Patterson AFB, OH. This study was approved by the Institutional Review Board at Wright-Patterson AFB, OH. Table 1 includes the mean body weight and standard deviation for each subject over the testing period.

Table 1. Mean Subject Body Weight (kg)

SUBJECT	SEAT CONFIGURATION					
	RS	GS	BS	FS	MEAN	SD
1	54.9	53.1	53.1	53.5	53.6	0.86
2	71.7	72.6	72.6	72.6	72.4	0.45
3	94.8	93.4	94.4	93.4	94.0	0.68
4	65.3	64.9	65.8	65.3	65.3	0.37
5	75.3	76.2	75.3	75.8	75.6	0.43
6	86.6	86.0	86.2	86.6	86.4	0.34
7	96.2	96.2	96.6	97.1	96.5	0.43

Seating Configurations and Postures

This study evaluated four seating configurations. Three of the configurations used locomotive seats provided by the United States Seating Company (USSC). Two of the seats were suspension seats (USSC 9002). One represented a seat with good shocks (GS) and the other a seat with bad shocks (BS) (suspension seat with shocks removed). The third seat was a freight seat (FS) without a suspension system (USCC 9012). The fourth seat was a rigid seat (RS) available in the laboratory for comparison.

The seat back angle for the locomotive seats was adjusted to six degrees for all subjects. The seat heights were adjusted so that the bottom of the subjects' feet just contacted the floor. Table

Table 2. Seating Heights (cm)

SUBJECT	SEAT CONFIGURATION		
	GS	BS	FS
1	34.3	*32.7	25.7
2	*32.4	*32.7	25.7
3	Not recorded	*32.7	25.7
4	39.0	*32.7	25.7
5	36.2	36.2	29.5
6	Not recorded	33.3	25.7
7	Not recorded	*32.7	25.7

2 lists the subjects and their adjusted seating heights. For the GS and BS, the seating height was measured between the floor and the lower edge of the metal bracket located on the side of the seat that connected the rigid seat back frame to the seat pan frame. For the FS, the seating height was measured between the floor and the lower edge of the metal seat pan support structure. In Table 2, an asterisk marks those subjects and seats where the adjustment resulted in contact between the snubber and suspension mechanism. For subjects 2 and 4, the FS could not be adjusted low enough to provide full foot contact with the floor. For both subjects the heels were raised, but the balls of the feet contacted the floor.

This study tested two seating postures. The back-on posture included the subject sitting upright and in contact with the seat back. The back-off posture included the subject sitting upright but leaning slightly forward so as not to contact the seat back. In both cases, the subjects were loosely restrained with a lap belt.

Facility and Instrumentation

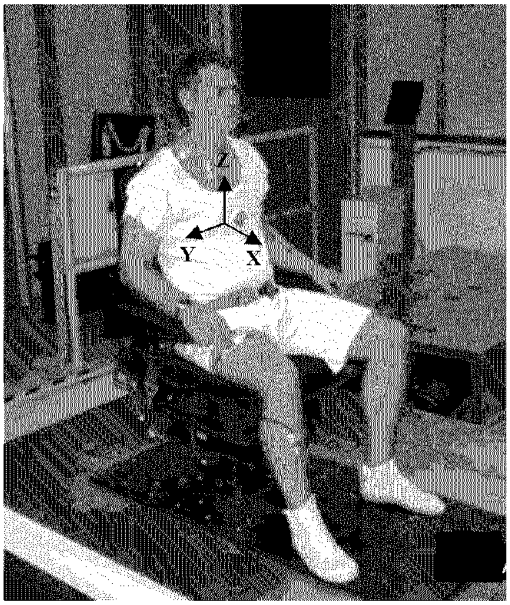
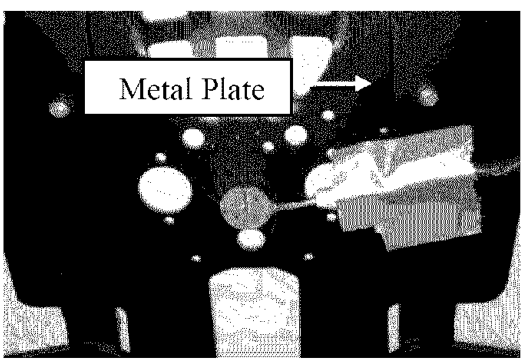
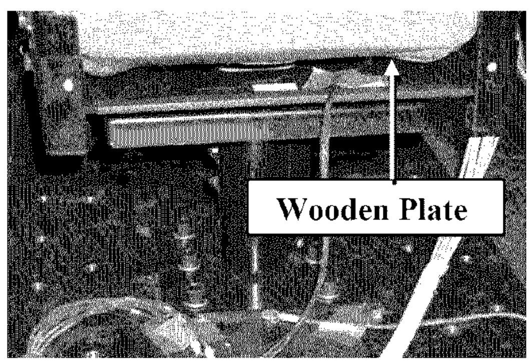


Figure 1. Locomotive Seat Attached to SIXMODE Vibration Table

All tests were conducted in the Six Degree-of-Freedom Motion Simulator (SIXMODE) located in the Air Force Research Laboratory, Human Effectiveness Directorate (AFRL/HE). Each locomotive seat was rigidly mounted to a metal plate that was, in turn, mounted onto the vibration table as illustrated in Figure 1. Triaxial accelerometer packs were used to collect acceleration data in the three orthogonal axes (fore-and-aft (X), lateral (Y), and vertical (Z)) at selected seat and body sites. The packs were comprised of miniature accelerometers (Entran EGAX-25, Entran Devices, Inc., Fairfield, NJ) arranged orthogonally and embedded in a Delrin cylinder. Each pack measured 1.9 cm in diameter and 0.86 cm in thickness and weighed approximately 5 gm. The packs were secured to the seat and body surfaces using double-sided adhesive tape. For the two suspension seats, one accelerometer pack was attached to the horizontal metal plate supporting the seat cushion for estimating the motion at the suspension/cushion interface (Figure 2a). For the FS, a triaxial accelerometer pack was located beneath the wooden plate supporting the cushion/spring ensemble for estimating the motion at this interface (Figure 2b). A second pack was located on the metal floor plate used to connect the seat to the vibration table for measuring the input vibration.



a.



b.

Figure 2a. GS and BS Suspension/Cushion Interface
Figure 2b. FS Wooden Plate Supporting Cushion/Spring Ensemble

Acceleration pads were similarly attached to the seat pan and seat back on all seats at the seat/occupant interface as shown in Figure 3. Each pad consisted of a rubber disk measuring approximately 20 cm in diameter and weighing 355 gm (with connecting cables). Each pad

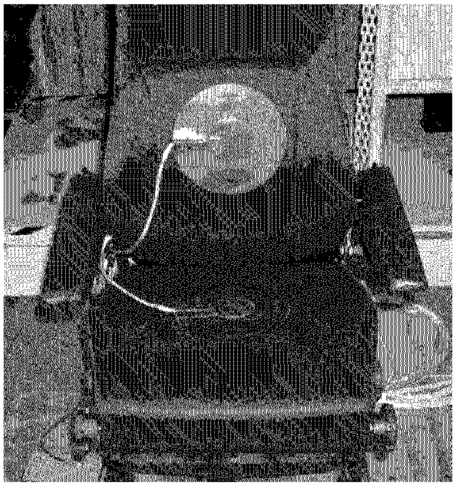


Figure 3. Seat Pan and Seat Back Acceleration Pads

contained a triaxial accelerometer pack as described above. The seat pads were in accordance with the recommended guidelines given in ISO 2631-1: 1997 and ANSI S3.18-2002.

In addition to measuring vibration at several seat locations, triaxial accelerometer packs were also used to measure translational motion at the thigh, chest (at the manubrium), lower spine (lumbar region), and upper spine (at C7). A six-axis bitebar was used to estimate head translation and to calculate head rotation including roll, pitch, and yaw. Figure 1 shows an instrumented subject sitting in a suspension seat with the attached accelerometer packs. Figure 4 shows the six-axis bitebar. Accelerometers X1, Y1, and Z1 were used to estimate head motion.

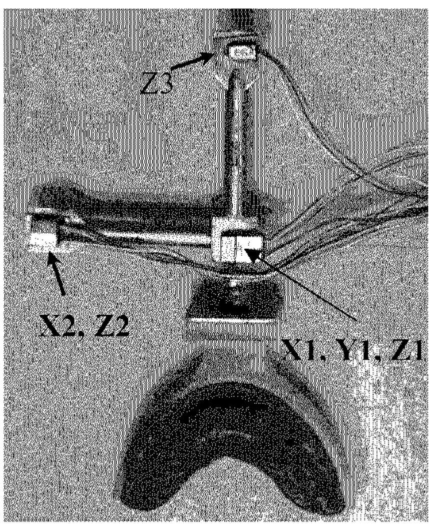


Figure 4. Six-Axis Bitebar

The head rotational accelerations were calculated as follows:

$$a_{ROLL}(t)=\frac{\left(a_{Z1}(t)-a_{Z2}(t)\right)}{d} \qquad 1$$

$$a_{PITCH}(t)=\frac{\left(a_{Z1}(t)-a_{Z3}(t)\right)}{d} \qquad 2$$

$$a_{YAW}(t)=\frac{\left(a_{X1}(t)-a_{X2}(t)\right)}{d} \qquad 3$$

where d is the moment arm and equal to 5.08 cm between accelerometer locations. A total of 30 channels of acceleration data were collected.

Selection and Generation of Exposure Signals

This study used three exposure signals, including one flat acceleration spectrum (FLAT) and two signals extracted from the field acceleration time histories recorded at the floor of the locomotive (LOCO3 and LOCO12). The 10-s FLAT signal was computer-generated at 1024 samples/s with similar levels of acceleration at all frequency components between 1 and 80 Hz. Figure 5 illustrates the two selected locomotive time histories, LOCO3 and LOCO12. Both time histories were extracted from data collected on the same locomotive equipment on two different legs of a scheduled run on the same day. The 10-s locomotive signals were selected to represent the higher levels of vibration exposure experienced by the engineers. The data were originally

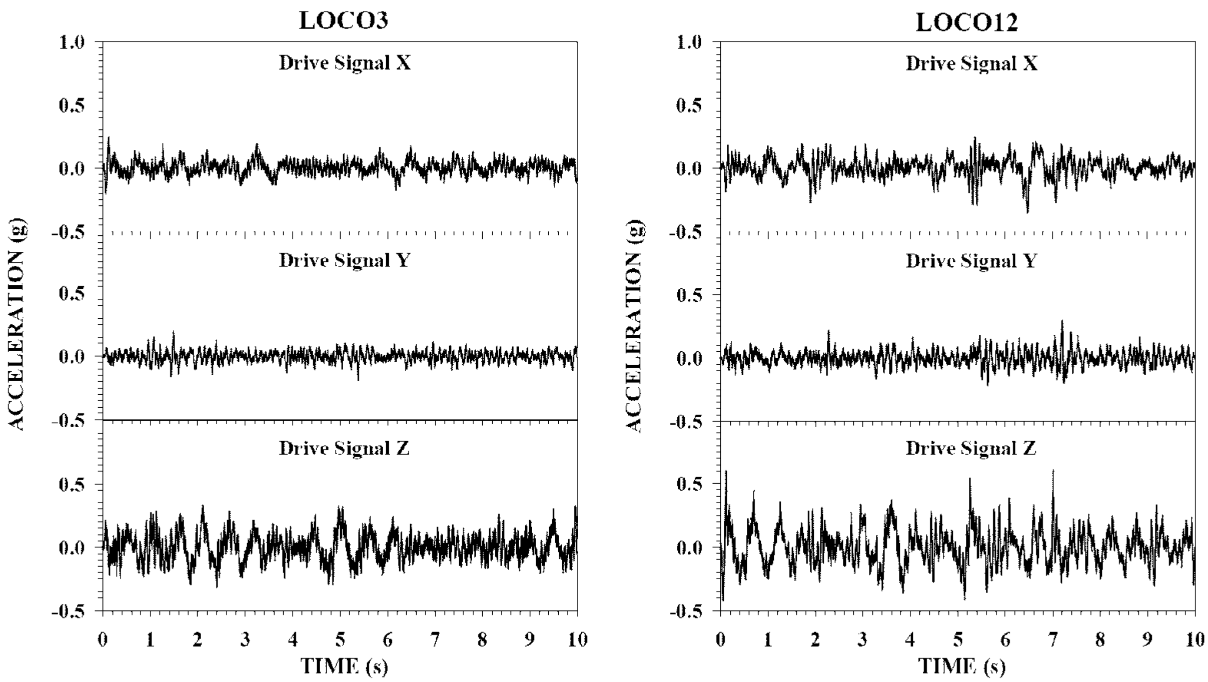


Figure 5. Locomotive Vibration Time Histories

collected at 320 samples per second but were resampled at 1024 samples/s (MATLAB®). The 10-s signals were regenerated in the SIXMODE using an iterative process that minimized the error between the original (desired) and table vibration. All signals were repeated to provide 20-s exposures. A male subject weighing approximately 86 kg was used to recreate the signals. This process was conducted for the RS and one of the locomotive seats (GS). The resultant drive file for the RS was used to generate the vibration for the RS configuration for all subjects. The resultant drive file for the GS was used to generate the vibration for locomotive seats GS, BS, and FS for all subjects. Figure 6 illustrates the frequency spectra (rms accelerations) of the two selected locomotive signals, LOCO3 and LOCO12 (see **Data Collection and Analysis** for processing details.) The figure includes the floor spectra measured for one of the subjects using the BS. This scheme was used to insure that the exposures were consistent for all seating configurations and subjects and that they reasonably represented the field data. The figure shows the concentration of vibration in the frequency range below 10 Hz with notable peaks occurring around 1.5 to 2.0 Hz, particularly in the X and Z directions. Appendix A includes a more detailed analysis of the 1-hour signal from which LOCO12 was extracted.

Data Collection and Analysis

Table 3 illustrates the test matrix for each test session. Each session included all testing for a selected seat configuration at both postures for exposures to all three signals. Each seat configuration, posture, and exposure comprised a test condition. For a selected seat, each test condition was repeated three times during a test session for a total of 18 test runs per session. Four test sessions were required for the four seat configurations.

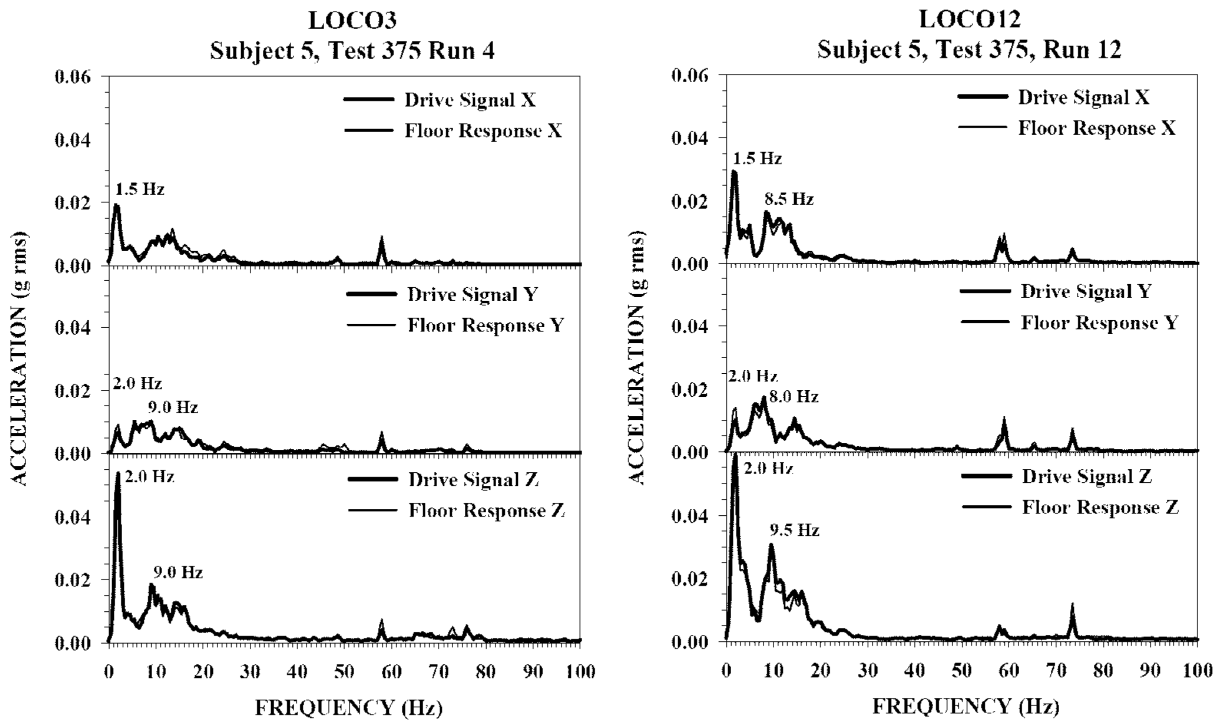


Figure 6. Locomotive Vibration Frequency Spectra

Table 3. Test Matrix

RUN	SIGNAL	POSTURE
1	LOCO3	ON
2	FLAT	OFF
3	LOCO12	OFF
4	LOCO3	ON
5	LOCO12	OFF
6	FLAT	ON
7	LOCO12	ON
8	LOCO3	OFF
9	FLAT	ON
10 MIN REST PERIOD		
10	LOCO3	OFF
11	FLAT	OFF
12	LOCO12	ON
13	FLAT	OFF
14	LOCO12	OFF
15	LOCO3	ON
16	FLAT	ON
17	LOCO3	OFF
18	LOCO12	ON

For each of the 30 data channels, accelerations were simultaneously collected for 10 s during each 20-s exposure, filtered at 100 Hz (antialiasing), and digitized at 1024 samples/s. The acceleration spectra were calculated using Welch's Method (1967) and MATLAB®. The 10-s signals were divided into two-second segments with 50 percent overlap, providing a frequency resolution of 0.5 Hz. A Hamming window was applied to these segments. The rms acceleration, a_{rms}, was calculated from the estimated power spectral density (PSD) as follows:

$$a_{rms} = \sqrt{PSD * 0.5} \quad (4)$$

System Transfer Matrix

Since the locomotive vibration exposures included accelerations in all three translational axes (X, Y, and Z), the multiple input/single output model was used to estimate the linear contribution of each axis of floor vibration to each of the output axes (at each measurement site) via the system transfer matrix (Bendat and Piersol, 1993; Newland, 1984; Naidu, 1996).
Figure 7 illustrates the general concept of the multiple input/single output model (Bendat and Piersol, 1993).

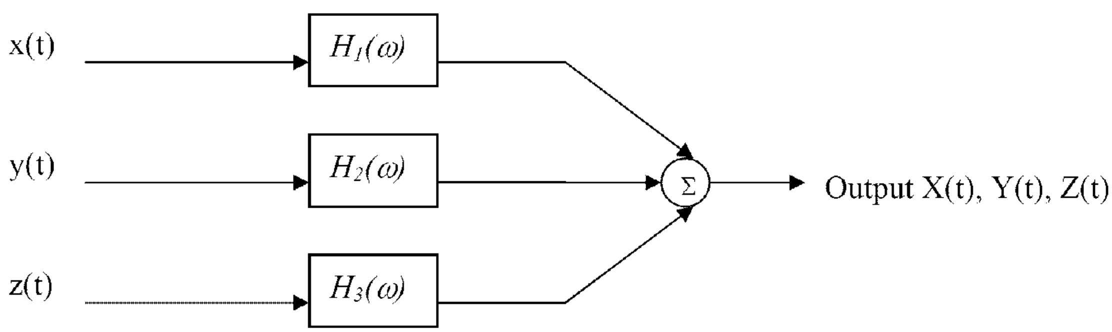


Figure 7. Multiple Input/Single Output Model for Three Inputs and Three Independent Outputs

For the simple case where only one input and one output exist, the following relationship defines the transfer function H(ω) between the input and output, excluding any contribution from other factors (noise):

$$H(\omega) = P_{zZ}(\omega) / P_{zz}(\omega) \quad (5)$$

where P_{zZ} is the cross-spectrum between the input z and output Z, and P_{zz} is the auto-spectrum of the input z. For this case, the ordinary coherence, $C(\omega)$, is estimated as follows:

$$C(\omega) = |P_{zZ}(\omega)|^2 / P_{zz}(\omega)P_{ZZ}(\omega) \quad (6)$$

The ordinary coherence indicates the extent to which the output is linearly related to the input. Values less than unity reflect the contribution of other factors (noise). For the case where the three input directions (x, y, and z) may contribute to the output Z, the system transfer matrix is defined as (ω has been omitted for simplification) (Newland, 1984):

$$\begin{bmatrix} P_{xZ} \\ P_{yZ} \\ P_{zZ} \end{bmatrix} = \begin{bmatrix} P_{xx} & P_{xy} & P_{xz} \\ P_{yx} & P_{yy} & P_{yz} \\ P_{zx} & P_{zy} & P_{zz} \end{bmatrix} \begin{bmatrix} H_1 \\ H_2 \\ H_3 \end{bmatrix} \qquad 7$$

Similar equations can be written for the cross-spectra for outputs X (P_{xX}, $P_{yX,}$ P_{zX}), and Y (P_{xY}, P_{yY}, P_{zY}) for a total of nine equations and nine transfer functions. The estimated contributions of the known inputs are removed from these transfer functions. Contributions from other factors (noise) besides the multi-axis input vibration are not removed. Partial and multiple coherences were also calculated (Naidu, 1996). Due to the complicated nature of these coherences, the equations are not shown. There is a partial coherence associated with each transfer function, H, in Equation 7. The partial coherence reflects the extent to which the particular input linearly contributes to the output after removing the effects of the other known inputs. Partial coherences less than unity indicate the presence of other factors (noise). The multiple coherence reflects the extent to which all known inputs linearly contribute to the output. If the output is completely accounted for by a linear response to the known inputs, the result will be unity (Newland, 1984). Values less than unity indicate the contribution of other factors.

Overall Transmission

The rms accelerations described previously were used to calculate the overall transmission between the input at the floor and output at the seat and body occurring in the same direction. The overall rms acceleration, a_{rmsT}, in a given direction (X, Y, or Z) for any site was calculated as:

$$a_{rmsT} = \sqrt{\Sigma (a_i)^2} \qquad 8$$

where a_i is the rms acceleration estimated at frequency *i*. The calculation of the overall acceleration levels was restricted to the frequency range of 1 to 10 Hz. The overall seat and body acceleration levels were divided by the overall floor or input acceleration levels to produce the overall transmission in each direction. This ratio is similar to the Seat Effective Amplitude Transmissibility (SEAT) defined in Griffin (1990) and ISO 10326-1: 1992 but does not include weighting of the input and output power spectra.

Results

As shown in Figure 6, the major vibration of concern in the locomotive occurred below 20 Hz. The highest vibration occurred primarily in the frequency range of 1 to 10 Hz, the frequency range associated with the greatest human body sensitivity (ISO, 1997). This report focuses on the response characteristics associated with this low frequency range. However, higher frequency effects were observed in the seat data. Appendix B provides a summary of the higher frequency effects. While acceleration data were collected at several anatomical locations, only the results for the chest and head are presented. The response characteristics of these two locations have consistently illustrated the low frequency sensitivity of the body to vibration and were best suited for describing the upper torso motions. The results also showed no clear evidence of motions that could be categorized as shock impact, regardless of the height setting for some subjects. Appendix C shows all tables and graphs referenced in the **Results**.

Low Frequency (1–10 Hz) Seat and Body Transmissibilities

FLAT Exposures

Careful observation of all nine transfer functions or transmissibilities showed minimal off-axis contributions to the seat responses (suspension, seat pan, and seat back). This was reflected in the relatively low transmissibilities associated with the off-axis relationships. Figures C-1 and C-2 in Appendix C illustrate the seat pan and seat back transmissibilities and partial coherences between 1 and 10 Hz for 4 of the 7 subjects (Subjects 1, 3, 5, and 7) exposed to the FLAT vibration. The figures show the results calculated for the input/output relationships occurring in the same orthogonal direction (X, Y, or Z). Plots are included for all three locomotive seats (GS, BS, FS) with the back-on posture. The seat transmissibility results for the RS configuration are not included for the FLAT exposures since the magnitudes were fairly flat and around 1.0 at the low frequencies, as expected. Figures C-1 and C-2 show regions of peak or maximum transmissibility depending on the direction of vibration. They also show that the frequency location and magnitude of the peak or maximum response varied among the subjects. Table C-1 and Figure C-3 include the mean frequencies, mean seat transmissibilities, and the mean partial and multiple coherences ±1 standard deviation associated with the peak seat responses for input/output relationships occurring in the same direction (FLAT exposure). The data include the results for all seven subjects in the back-on posture. It is emphasized that the suspension site for the freight seat was the supporting wooden plate located beneath the cushion and spring ensemble.

For the FLAT exposure in the X direction, the peak seat transmissibility responses occurred at a slightly higher frequency location (2–3 Hz) for all three locomotive seats as compared to the peak X motion observed in the locomotive signals (1.5 Hz) (Figure 6). The magnitude of any selected peak seat transmissibility in the X direction was, in general, similar among the three locomotive seats. Table C-1 and Figure C-3 show that the suspension had very little influence on the X input motions at low frequencies (mean TR~1). Some amplification of X vibration by the seat pan cushion tended to occur in the vicinity of 2 to 3 Hz. The low frequency X vibration at the seat back was more dramatic, the vibration associated with the peak transmissibility being about twice that at the floor (mean TR~2).

For the FLAT exposure in the Y direction, the peak seat responses occurred in the vicinity of the peak Y locomotive vibration (~5.5–9.0 Hz). These peaks were not as distinct for some subjects as compared to the X seat responses (Figures C-1 and C-2). Minimal differences were observed in the magnitude of the Y peaks for the suspension and seat pan. The seat back did show higher peak transmissibility in the Y direction as compared to the suspension and seat pan, particularly for the BS (mean TR~2).

For the FLAT exposure in the Z direction, the peak seat transmissibilities at all sites for the GS and FS occurred at a higher frequency (3–3.5 Hz) as compared to the peaks observed for the BS (around 2 Hz). The frequency location of the peak seat transmissibilities in the BS (FLAT exposure) corresponded closely to the frequency associated with the dramatic peak observed around 2 Hz in the locomotive vibration signals (Figure 6). The peaks were quite distinct at the seat pan but not very distinct at the seat back. In the Z direction, the magnitude of the peak transmissibility at the seat pan was higher as compared to the suspension and seat back for the GS and FS, and more similar among the seat sites for the BS (noting that the FS did not include a suspension system). The Z seat pan transmissibility was quite dramatic as compared to the other measurement sites for the FS. Of particular interest was the response behavior of the seat back as compared among the seating configurations. For the GS and FS, the response was relatively flat and equal to unity across the frequency range. For the BS, the mean peak was higher at the seat back as compared to the other seats, but the response was dampened between 4 and 10 Hz (Figure C-2).

For the FLAT exposures, the partial coherences were high (primarily 0.9 and above) in the frequency range of 1 to 10 Hz, although observed to be quite variable for the BS at the nonpeak locations (Table C-1 and Figures C-1, C-2, and C-3). The multiple coherences (Table C-1 and Figure C-3) were also relatively high. In summary, with little contribution from off-axis motions or noise, the seat responses in a given direction were almost entirely accounted for by a linear response to the measured input in the same direction for exposures to FLAT.

In contrast to the seat results, the nine transmissibilities and partial coherences estimated for the chest and head did indicate that off-axis vibration contributed to the upper torso responses. Figures C-4, C-5, and C-6 illustrate the chest and head transmissibilities and partial coherences for the same four subjects described previously for the seat responses. The transmissibilities and partial coherences for the input/output relationships occurring in the same direction are shown for the FLAT exposures. Figures C-4 and C-5 also show the transmissibility and partial coherence data for the major off-axis effect observed at the chest. Both the chest and head transmissibilities were quite variable among the subjects. Table C-1 and Figure C-3 include the mean frequency, mean transmissibility, and the mean partial and multiple coherences ±1 standard deviation associated with the peak chest response for input/output relationships occurring in the same direction. The data are from the FLAT exposure and back-on posture among all seven subjects.

Table C-1 and Figure C-3 show that the frequency location of the peak chest response in the X direction was similar to the peak seat frequency locations. The magnitude of the peak X chest transmissibility associated with the X input was similar to that observed at the seat back and higher than observed at the suspension or seat pan. In contrast, the peak chest response in the Y direction occurred at a lower frequency (mean FR~1.8–2.0 Hz) as compared to the seat sites (mean FR~7–8.5 Hz). The magnitude of the mean peak chest transmissibility in the Y direction was only slightly higher than the mean peaks observed at the suspension and seat pan, but the peak responses showed greater variability among the subjects. The peak chest transmissibility response in the Z direction showed a similar trend among the seat configurations as observed for the seat sites: a lower peak frequency with the BS (mean FR~2.4 Hz) as compared to the GS and FS (mean FR~3.6 and 3.8 Hz) with greater variability. As indicated in Table C-1 and Figure C-3, the magnitude of the peak Z chest transmissibility was notably higher than the peak seat transmissibilities for the GS and FS but were similar for the BS. The results did show that the frequency location of the peak chest transmissibility in the vertical direction was shifted downward with the use of the locomotive seats (GS, BS, and FS) as compared to the RS. The peak response occurred around 4.5 Hz with the RS in the vicinity of greatest human vibration sensitivity (not shown).

Although not included in the mean peak data, Figure C-4 shows that vibration in the Z axis contributed to X motion for some subjects. The frequency location of the peak chest X transmissibility resulting from the Z input was more closely associated with the vertical chest peaks. This suggested that the X and Z chest motions at these frequencies were coupled, as would occur with upper torso pitching. It is emphasized that the input vibration levels in the X and Z directions were identical for the FLAT exposure.

The partial coherences associated with the peak chest responses occurring in the same axis as the input motions were slightly lower as compared to the seat but were still primarily above 0.8 (Table C-1). Other factors had a minimal influence on the peak chest motions. The off-axis partial coherences were quite variable, as shown in Figure C-5. The high multiple coherences illustrated in Table C-1 did indicate that the estimated system transfer matrix accounted for the chest responses, at least in the vicinity of the peak responses.

Given the variability in the head transmissibility data and the extent to which the cross-axis inputs and noise affected the responses, the mean peak head transmissibilities were not included in Table C-1 and Figure C-3. Figure C-6 does show that, in general, the peak head transmissibilities resulting from input motions in the same direction occurred at frequencies similar to those observed for the peak chest motions. As with the chest, the frequency location of the peak head transmissibility was shifted downward with the use of the locomotive seats. Lower peaks were observed at higher frequencies (but < 10 Hz) for some subjects, particularly with the GS and FS. With the RS, the highest peaks occurred above 5 Hz. Vibration in either the X or Z direction can affect head rotation. This was suggested by the off-axis components of the system transfer matrix. It was expected that head rotation contributed to the measured translational head response in both the X and Z directions. This report discusses head rotation later.

Locomotive Vibration Exposures (LOCO3 and LOCO12)

For exposures to the locomotive signals, the seat transmissibility data were not as consistent as observed for the flat spectrum exposure. In several instances, multiple peaks were identified between 1 and 10 Hz. Off-axis vibration showed transmissibilities above unity but were associated with low coherences. In addition to nonlinear effects, this may have been due to the concentration of vibration at distinct frequencies and negligible vibration at other frequencies, resulting in unreliable transmissibility characteristics.

Figures C-7 and C-8 illustrate the seat pan and seat back transmissibilities and partial coherences associated with the input/output relationships in the same orthogonal direction (X, Y, or Z) for exposures to LOCO12. The results for LOCO3 showed similar trends. Data are included for the four subjects with the back-on posture. Regardless of the multiple peaks, Figures C-7 and C-8 show that peak transmissibilities existed for the locomotive exposure that were coincident with the peaks observed for the FLAT exposure. Although variable, the coherences associated with these peaks tended to be higher than the coherences associated with any additional peaks. The coherences associated with the seat pan and seat back Z transmissibilities for the BS were quite low (primarily below 0.5), suggesting the strong influence of other factors on the Z seat response. In general, the relatively lower partial coherences shown in Figures C-7 and C-8 did indicate that other factors contributed to the seat output responses for the locomotive exposures as compared to the very minimal effects of off-axis coupling and noise shown for the flat spectrum exposure.

The upper torso responses resulting from exposures to the locomotive input signals indicated even greater off-axis contributions and the effects of other factors as compared to the seat. The results were quite variable among the subjects. As suggested above, these results may have been due to nonlinear effects and the frequency distribution characteristics associated with the locomotive signals. In summary, the results for the locomotive exposures rendered it difficult to develop a simple and reliable transfer function for predicting the effects of the input or floor vibration on motions at the seat and body.

Low Frequency (1–10 Hz) Overall Transmissions

Given the complexity of the system transfer matrices, particularly for exposures to the locomotive signals, it was difficult to develop a simple model for predicting the seat and upper torso responses from the transmissibility frequency responses. It was also difficult to compare the effects of seat configuration and posture from these results, particularly with the influence of off-axis vibration. The overall transmission allowed for the effective comparison of transmissibility characteristics among the measurement sites, exposures, directions, seat configurations, and postures. Figure C-9 illustrates the overall floor or input rms accelerations between 1 and 10 Hz for the flat spectrum and locomotive signals in each of the three axes. For any given exposure signal (FLAT, LOCO3, or LOCO12) and direction (X, Y, or Z), the input vibration at the floor showed very minimal variation among the seating configurations, as well as among the seven subjects. Figure C-9 shows the relative differences in the low frequency vibration among the signals and among the directions of motion.

Figures C-10 and C-11 illustrate the mean overall transmission ±1 standard deviation between 1 and 10 Hz among all subjects for the seat pan and seat back respectively. Included in the figures are the standard deviations calculated among the subjects for each seating configuration (including the RS) and posture. Although not shown, very little difference existed in the overall response between the suspension and seat pan. The Repeated Measures Analysis of Variance and post hoc Bonferroni test were used to determine significant effects of seat configuration and posture on the overall transmission. Significant effects of seat configuration, as well as posture, were found, including interactions ($P<0.05$). Figure C-10 shows that, in general, the overall transmission was near unity for the RS in the horizontal directions (X and Y), regardless of the type of exposure. The locomotive seats (GS, BS, FS) showed overall seat pan transmissions that were statistically higher as compared to the RS in the X direction for LOCO3 and LOCO12. The mean transmissions were approximately 1.2 to 1.3 as compared to being approximately 1.0 for the RS. All seats showed significantly higher transmission as compared to the FS in the Y direction, regardless of the type of exposure. In the Z direction, the BS showed significantly lower overall seat transmission as compared to the GS and FS for the FLAT exposure. The most notable and significant effect of the seating configuration on the seat pan transmission occurred during exposures to LOCO3 and LOCO12 in the Z direction. In contrast to the results observed for the FLAT exposure, the overall seat pan transmission for the BS was significantly higher as compared to the other seats. The mean overall response for the BS was greater than 1.8 times the floor response. The remaining locomotive seats (GS and FS) showed overall seat pan transmissions that were significantly higher as compared to the RS for the LOCO12 exposure only. Although the back-off posture showed overall seat pan transmissions that were statistically higher than the back-on posture, particularly for the FLAT exposure in the horizontal directions, the differences were relatively small, as noted in Figure C-10.

The overall seat back transmissions in the horizontal directions were notably higher for all seats relative to the RS, particularly for the back-off posture, regardless of the type of exposure (Figure C-11). Substantial variability was observed among the subjects, particularly in the X direction and for the GS and back-off posture. In several cases, the postural effect depended on the seat configuration, particularly in the Y direction. The trend was for the locomotive seats to show higher overall seat back transmission with the back-off posture. There were no significant postural effects in the X direction for the locomotive exposures. For the FLAT exposure in the Z direction, the overall seat back transmission was significantly lower for the BS seat and showed larger variability among the subjects, similar to the trends observed at the seat pan. For LOCO3 and LOCO12, the overall seat back transmission in the Z direction was significantly higher for the BS, similar to the results for the seat pan. In the Z direction, the postural effect was significant (back-off greater than back-on), although of no great consequence as shown in Figure C-11.

Figures C-12 and C-13 illustrate the overall transmission for the chest and head, respectively. For the FLAT exposure, the X overall chest transmission tended to be similar among the seats at each respective posture. For the locomotive exposures (LOCO3 and LOCO12), the X chest transmissions were significantly higher for the BS as compared to the other seat configurations for both postures. Regardless of the exposure, the back-on posture showed a significantly higher overall chest transmission as compared to the back-off posture in the X direction as shown in Figure C-12. The Y overall chest transmission was relatively low (below unity) for all seats and all exposures. The back-on posture did show significantly higher chest transmission in the Y direction as compared to the back-off posture for the FLAT exposure and LOCO12. The chest transmissions in the Z direction were not as dramatic as the transmissions observed in the X direction, although the input vibration level was higher in the vertical direction as shown in Figure C-9. For the FLAT exposure in the Z direction, as with the seat, the overall chest transmission showed a tendency for lower values with the BS that were statistically significant as compared to the GS and FS. For the locomotive exposures, the vertical chest transmission was significantly higher for the BS as compared to all other seat configurations, similar to the results observed at the seat. All locomotive seats showed significantly higher chest transmissions as compared to the RS for LOCO12 only. Postural effects were not easily observed in the vertical direction.

For the flat spectrum exposures, the X overall head transmission was similar among the seats (Figure C-13). For LOCO3 and LOCO12, some differences were noted, with the BS showing significantly higher levels for LOCO12 only (in contrast to the chest results). Although not as dramatic as observed for the chest, the X head transmissions were significantly higher for the back-on posture, with most ratios being greater than unity. No significant effect of seat configuration occurred in the lateral (Y) overall head transmission. The mean ratios tended to occur at or below unity with relatively large variability among the subjects. In the Z direction, the overall head transmission tended to be similar among the seats for the FLAT exposure at each respective posture and was greater than unity. For LOCO3 and LOCO12, as with the seat and chest sites, the BS showed significantly higher overall head transmission in the Z direction. All locomotive seats showed significantly higher head transmission as compared to the RS for

LOCO12. In the Z direction, the overall head transmission was higher for the back-on posture for most seats as shown in Figure C-13.

Head Rotations

Figure C-14 illustrates the overall rms acceleration levels for head roll, pitch, and yaw. The overall transmission was not calculated for the head rotations. The figure shows that head pitch was the highest and head yaw was the lowest for all exposures. Statistical analysis showed that no differences occurred in the head rotations among the seat configurations for the FLAT exposure. For the locomotive exposures, the highest head roll and pitch rotations tended to occur with the BS. The roll and pitch results were significant for LOCO3, but only the roll was significant for LOCO12. Head pitch was shown to be significantly higher with the BS as compared to the RS for LOCO12. All head rotations showed large variations among the subjects. The back-on posture showed significantly higher head pitch rotation as compared to the back-off posture for all exposures. For head roll, this was only significant for the locomotive exposures. The posture effects corresponded closely to the effects observed in the head translations.

Discussion

The vibration transmissibility characteristics were determined for selected suspension seats, specifically those seats used by the locomotive engineers in passenger and freight locomotives. The data collected for the FLAT exposure provided the optimum information for estimating the system transfer matrix of the seat and body since the acceleration levels were similar at all frequency components. The results showed that, regardless of the seat configuration or posture, the output in any given orthogonal direction at the seat pan and seat back was accounted for by a linear response to the measured input at the floor in the same direction with very minimal off-axis or other factors effects. This simplified the estimation of the seat pan and seat back responses from the floor measurements. The vibration associated with the locomotive signals selected for this study occurred at very distinct frequencies and differed among the three axes. The results for the locomotive exposures did show that other factors contributed to the seat pan and seat back motions in any given direction (i.e., the output at these locations could not be fully accounted for by either a linear response to the input in the same direction or a linear response to an input occurring in another direction). Therefore, the responses at the seat pan and seat back could not be easily predicted from the inputs at the floor for the locomotive signals. The results also showed that off-axis effects and other factors contributed heavily to the upper torso responses.

Given the difficulty in quantifying the actual responses due to off-axis contributions and noise, the low frequency overall transmission provided a simple and realistic metric for comparing the seat and body transmission characteristics among the seating configurations and between the two postures (via a normalized response). While not easily delineated from the system transfer matrix, the overall transmission revealed differences in the seat responses due to the type of exposure and seating configuration. For example, the mean vertical responses at the BS seat pan were similar for the two locomotive vibration exposures (LOCO3 and LOCO12), but significantly higher as compared to the FLAT exposures. These trends were also observed in the Z responses of the upper torso. In addition, seat configuration had a dramatic effect on the X responses of the chest and head for exposures to the locomotive signals. Posture also had a significant effect on the upper torso vibration, particularly in the X chest motion and, to a lesser extent, in both the X and Z motions of the head. The head pitch motions were consistent with the trends observed in the translational motions. It appeared that the seat back had a significant influence on amplifying the upper torso motions. It is emphasized that the overall transmission includes any off-axis and noise contributions to the output motion, particularly for the locomotive exposures and for the upper torso responses. However, these effects are expected in the working environment.

The locomotive signals used in this study produced relatively large and complicated motions in the upper torso as reflected by the chest and head system transfer matrices. These motions were observed in the subjects during testing. It is speculated that these large upper torso motions may be a major contributor to discomfort during the operation of locomotives under the more severe conditions represented by the signals used in this study. The operator may well attempt to stabilize this motion, either voluntarily or involuntarily, possibly leading to muscle fatigue, backache, or even back pain over periods of prolonged and repeated exposures. Although the back-off posture showed less upper torso motion, the extent to which the operator may have influenced the motion was not known. Appendix A includes the calculation of both the one-third octave unweighted and weighted accelerations for a 1-hour exposure period during the leg that included the vibration levels represented by LOCO12. The one-third octave frequency responses were also calculated every 10 minutes to evaluate how the exposure may have changed over time. While the results showed variations in the acceleration levels over time, the frequency response profiles were of similar shape, showing substantial motions below 10 Hz. The one exception was the last 10 minutes of the 1-hour exposure just before reaching the destination. Recently, evidence was given that the ride quality may have been improved due to changes made in the wheel turning taper (1:40 versus 1:20). At this time, it is not clear what effect this process had on the characteristics of the locomotive floor or seat responses, particularly in the X and Z directions. If low frequency vibration is still present, particularly in the X and Z directions, these motions will still be seen at the seat pan and possibly amplified depending on the seating configuration, as shown in this study.

The effect of the type of exposure, seating configuration, and posture on the vibration response at the seat pan is of particular concern since the seat pan accelerations are highly recommended for assessing the comfort and health effects of vibration exposure in accordance with ISO 2631-1: 1997. The results of this study suggest that the application of a transfer function to the measured floor data may be complicated and restricted, and it may not provide a realistic estimate of the seat pan vibration. As shown in Appendix A, the frequency response characteristics remained similar throughout most of the leg that included LOCO12. Although LOCO3 and LOCO12 were from different legs, their frequency response characteristics were also similar and showed similar effects on the seat and upper torso.

One approach for estimating the weighted seat pan accelerations required for assessment in accordance with ISO 2631-1: 1997 is to determine the SEAT value from the data collected in this study. The SEAT was calculated for the frequency ranges of 1 to 10 Hz and 1 to 80 Hz. Data from three subjects (1, 5, and 7 in Table 1) were processed in one-third octave bands as described in Appendix A. The signals in the three orthogonal axes were weighted in the frequency domain in accordance with guidelines given in Table 3 of the ISO 2631-1: 1997. The weighted accelerations reflect the influence of the vibration on human sensitivity in the respective direction. The overall weighted accelerations in each direction were calculated using Equation 8, where a_i is now the weighted one-third octave rms acceleration level with center frequency i. Table C-2 lists the mean weighted overall acceleration levels for each seat configuration, locomotive signal, and each posture in the three orthogonal directions (1-80 Hz). The SEAT was calculated as the ratio between the overall weighted seat pan acceleration and the overall weighted floor acceleration (ISO 10326-1: 1992). The SEAT was calculated for the three locomotive seat configurations (GS, BS, and FS) for the back-on posture. Figure C-15 illustrates the mean SEAT ± 1 standard deviation for the three exposures and three locomotive seats. Figure C-15a includes the frequency range from 1 to 80 Hz. Figure C-15b restricts the frequency range from 1 to 10 Hz. Figure C-15c includes the seat pan data shown in Figure C-10 for comparison of the unweighted and weighted ratios. The figure shows that the frequency range had some effect on the SEAT value, particularly in the Z direction for the flat spectrum. Differences in the seat values relative to the type of signal are shown. Figure C-15 illustrates that, for the FLAT exposure, the weighted ratios at the seat pan were only slightly higher than the weighted ratios at the floor in the horizontal axes (SEAT~1.0), but notably dampened for the BS in the Z direction. The unweighted ratios showed a less dampened response in the Z direction for the BS. In contrast, for the locomotive exposures, both the weighted and unweighted ratios were amplified in the Z direction of the BS. The weighted ratio (SEAT) appeared more dampened as compared to the unweighted ratios. Other less notable differences were observed between the weighted ratios (SEAT) and the unweighted ratios (overall transmission), but the trends were similar. The number of subjects used to calculate the unweighted ratio (four subjects) versus the weighted SEAT ratio (three subjects) may have had some effect on any differences.

From the results shown in Figure C-15, one overall SEAT value was determined for each axis. Based on these results, a SEAT of 1.0 was selected for the Y axis. In the X, the median SEAT among the seats and subjects was 1.3. A SEAT value of 1.3 was selected for the X axis. In the Z direction, the median was 1.0. However, given the dramatic effect of the BS seat on the vertical response, a SEAT value of 1.3 was selected for the Z axis. These SEAT values were applied to the 1-hour operational exposure data described above and in Appendix A to predict the overall weighted seat pan accelerations in the three orthogonal axes. The estimated weighted accelerations in each direction for the 1-hour exposure are included in Table C-2. A comparison of the results in Table C-2 shows that the estimated weighted accelerations for the 1-hour exposure in the X and Z directions were similar to the values calculated for the GS and FS during the LOCO3 exposure. The estimated weighted acceleration in the Y direction tended to be slightly lower for the one-hour exposure as compared to the levels calculated in this study for LOCO3. For this assessment, the Vibration Total Value (VTV), or a_v, was calculated as follows:

$$a_v = \sqrt{1.4^2 a_{wx}^2 + 1.4^2 a_{wy}^2 + a_{wz}^2} \qquad 9$$

where a_{wx}, a_{wy}, and a_{wz} are the overall weighted accelerations in the X, Y, and Z directions, respectively. The factor of 1.4 is the multiplying factor used for assessing health effects. (Section 7.2 of ISO 2631-1: 1997 indicates that the vector sum of the vibration, i.e. the VTV, is sometimes used to assess health risk when the vibration among axes is comparable.) Table C-2 includes the mean VTV for LOCO3 and LOCO12 for each posture and the estimated VTV for the 1-hour exposure. Figure C-16 depicts the VTV calculated for the floor (0.577) and estimated for the seat pan (0.743) using the SEAT values defined above (back-on only). While the floor and seat pan VTVs were associated with an exposure duration of 1 hour, the values were extended across the exposure durations, assuming that the 1-hour exposure level was representative of the daily exposure for the engineers. The figure shows that, based on the floor VTV, the exposure reaches the lower boundary of the caution zone in just over 4 hours. Based on the estimated seat pan VTV, the lower boundary is reached in about 3 hours. It is recommended that vibration levels falling between the lower and upper boundary be avoided since potential health risks are indicated in this region. The floor and seat pan VTVs were also estimated for evaluating the comfort reaction of the 1-hour exposure in accordance with the ISO 2631-1: 1997. The multiplying factor for the horizontal vibration is 1.0 as opposed to the 1.4 value used in Equation 9. The floor VTV for comfort was 0.518 and corresponded to a reaction of "a little uncomfortable" to "fairly uncomfortable." The seat pan VTV for comfort was 0.669, corresponding to a reaction of "fairly uncomfortable." These reactions imply less than ideal ride quality.

A few studies have been conducted in the United States for assessing the vibration exposure in freight and passenger trains. In a study conducted by Fries, et al. (1993), on eight freight locomotives, the majority of the vibration levels did not exceed the "fatigue-decreased proficiency boundary" set forth in the earlier 1985 edition of the ISO 2631-1. The highest vibration was found to occur in the vertical direction, as shown in the examples used in the current study. In a more recent study by Johanning, et al. (2002), locomotive vibration was assessed in 22 U.S. locomotives. Four of the seating systems appeared to be similar to those used in the current study. The locomotives did not include the model used in the current study. Their results showed that the weighted seat pan acceleration for these four seating systems ranged from 0.07 to 0.15 m/s^2 rms in the X direction, from 0.15 to 0.30 m/s^2 in the Y direction, and from 0.36 to 0.63 m/s^2 in the Z direction. With reference to Table C-2, the X weighted acceleration levels for LOCO3 and for the 1-hour exposure were higher as compared to the previous study, aligning more closely with the higher lateral levels (maximum of 0.30 m/s^2) measured in the Johanning, et al., study. The Y weighted accelerations for LOCO3 and the 1-hour exposure were lower than those shown for the previous study and aligned more closely with the X levels (0.07 to 0.015 m/s^2 rms.) The Z weighted acceleration levels for LOCO3 and the 1-hour exposure fell within the range found in the previous study. The investigators did indicate that some seats were found to be loosely attached at the base and may have influenced the accelerations measured at the seat pan. Johanning, et al. (2002), also calculated the SEAT value as described in the current study. For the four seating systems, the SEAT value ranged from 1.0 to 1.7 in the X direction, from 0.8 to 1.2 in the Y direction, and from 0.8 to 1.6 in the Z direction. Only one of these seating systems showed a SEAT value of 1.6 in the Z direction; the remaining five seats were at or below 1.1. The SEAT value selected to predict the seat pan accelerations in this study was identical to the median value shown in the X direction for all 22 locomotives (1.3), lower than the median value in the Y direction (1.0 compared to 1.2 for the 22 locomotives), and identical to the median value in the Z direction (1.0). However, as indicated above, a SEAT value of 1.3 was selected for the Z direction given the higher transmission characteristics associated with the BS seat.

Conclusions and Recommendations

1. The application of selected SEAT values to the weighted floor accelerations collected during actual train operation may provide a reasonable estimate of the effect of the vibration on the human relative to the ISO 2631-1: 1997. These estimates may be used to target potentially harmful cab seat vibration exposures from the monitored floor accelerations for locomotives that generate similar frequency distribution characteristics during operation.

2. It is recommended that a survey of the locomotive floor response characteristics be conducted on other field data collected during the same time period as the data reported in this study to determine if the low frequency vibration was consistent. These data should then be compared with any additional data collected at a later date (following changes in the maintenance procedures) to assess the effects of these procedures on the low frequency vibration.

3. It is speculated from the results that the operator may attempt to stabilize complex low frequency upper torso motion by voluntary and/or involuntary activity. These actions may contribute to symptoms of discomfort and back pain, particularly if conducted over longer periods of time. A preliminary evaluation of selected data collected on the locomotive indicated that low frequency vibration is prevalent during the operation of these trains.

4. For the low frequency locomotive vibration exposures used in this study, the seat pan vibration cannot be easily predicted using a frequency response transfer function without considering the effects of off-axis coupling and other noise.

5. In general, the locomotive exposures used in this study produced higher X and Z low frequency seat pan vibration as compared to a rigid seat. Higher responses in the Z direction were particularly dramatic at the seat pan, seat back, and upper torso using a seat with the shocks removed (BS). The characteristics of the seating system must be considered when assessing overall health exposure effects.

References

American National Standards Institute, Inc, 2002. Mechanical vibration and shock–Evaluation of human exposure to whole-body vibration–Part 1: General requirements. ANSI S3.18-2002.

Bendat, J.S., and Piersol, A.G., 1993. Engineering Applications of Correlation and Spectral Analysis. J. Wiley, New York.

Corbridge, C., 1987. Vibration in Vehicles: Its Effect on Comfort. Ph.D Thesis, University of Southampton. Southampton, England.

Couvreur C., 1997. Internet MATLAB computer file. Belgium: Faculte Polytechnique de Mons.

Fries, R.H., Cooperrider, N.K., and Larson, R.E., 1993. Locomotive and road vehicle ride quality assessments. Rail Transportation, Vol. 6, pp. 219-227.

Griffin, M.J., 1990. Handbook of Human Vibration. Academic Press, London, 1990.

International Standards Organization, 1992. Mechanical vibration–Laboratory method for evaluating vehicle seat vibration – Part 1: Basic requirements. ISO 10326-1: 1992(E).

International Standards Organization, 1997. Mechanical vibration and shock–Evaluation of human exposure to whole-body vibration–Part 1: General requirements. ISO 2631-1:1997(E).

Johanning, E., Fischer, S., Christ, E., Göres, B., and Landsbergis, P., 2002. Whole-body vibration exposure study in U.S. railroad locomotives–An ergonomic risk assessment. AIHA Journal, Vol. 63, pp. 439-446.

Naidu, P.S., 1996. Modern Spectrum Analysis of Time Series. CRC Press, Boca Raton.

Newland, D.E., 1984. An Introduction to Random Vibrations and Spectral Analysis. 2nd ed. Longman Inc., New York.

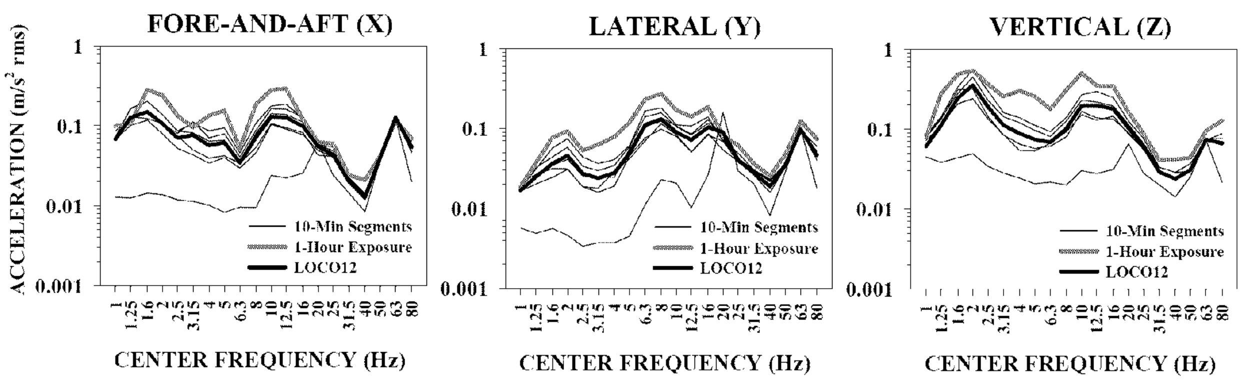
Smith, S.D., 1997. Cushions and suspensions: Predicting their effects on the transmission of vibration in the human. International Journal of Vehicle Design, Heavy Vehicle Systems, Driver-Vehicle Interactions, Vol. 4, Nos. 2-4, pp. 296-316.

Welch, P.D., 1967. The use of Fast Fourier Transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms. IEEE Trans. Audio Electroacoust., AU-15 (June 1967): 70-73.

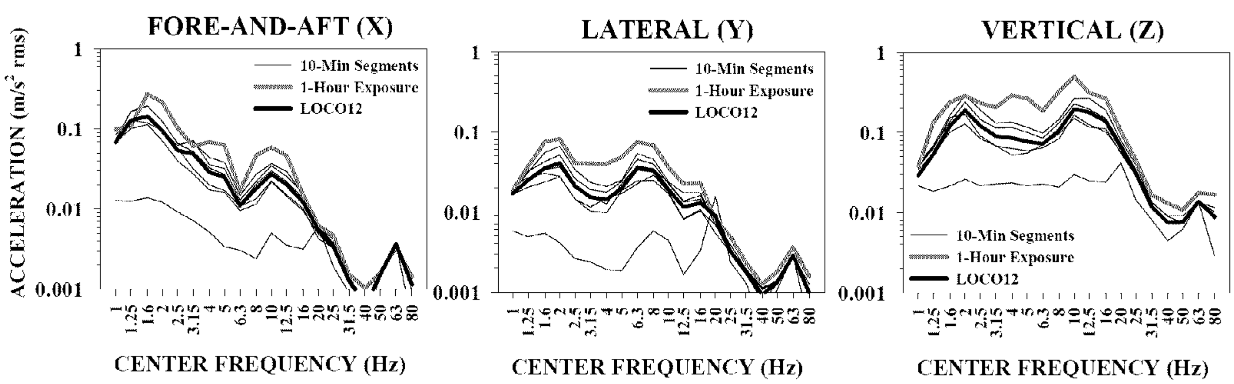
This page intentionally left blank.

Appendix A
One-Third Octave Analysis of 1-Hour Locomotive Vibration Signal

The locomotive floor data from the 1-hour leg that included LOCO12 was used to conduct a one-third octave frequency response analysis of the vibration exposure occurring over a longer period of time. This was done to evaluate the consistency in the frequency response characteristics of the actual journey relative to the extracted signal used in this study. The data file for this leg was slightly over 1 hour in length. A 1-hour time history was extracted from the original file. The 1-hour time history was divided into six 10-second segments. Using a computer program originally developed by Couvreur (1997) for Matlab®, the unweighted one-third octave frequency response spectra were determined in each orthogonal axis (X, Y, and Z) for the 1-hour time history and for the six 10-second segments. Figure A-1a illustrates the unweighted spectra. The frequency weightings given in Table 3 of ISO 2631-1 : 1997 were applied to the data to obtain the weighted one-third octave frequency spectra in each orthogonal axis. Figure A-1b illustrates the weighted spectra.



a. Unweighted



b. Weighted

Figure A-1. Unweighted and Weighted One-Third Octave Accelerations

This page intentionally left blank.

Appendix B
High Frequency (> 20 Hz) Transmissibility Response Characteristics

The transmissibility results for the flat spectrum exposure were used to assess the seat response characteristics at higher frequencies beyond 20 Hz. Figure B-1 shows the seat pan transmissibilities between 1 and 80 Hz for Subjects 1, 3, 5, and 7 for the flat spectrum exposures. The figure includes data for the back-on posture for the three locomotive seat configurations. In the X direction, both the suspension and seat pan measurement sites for the GS and BS showed similar behavior with increased transmission in a broad band between 30 and 50 Hz with the peak occurring in the vicinity of 35 to 40 Hz. The magnitudes of the transmissibility peaks ranged between 2.0 and 2.5 for the GS and between 1.5 and 2.0 for the BS, appearing more dampened with the bad shocks. For the FS, the region of increased transmission appeared to be broader, ranging between 30 and 60 Hz. The transmissibility of the peaks ranged between 1.5 and 3.0, with some subjects showing distinctly higher peaks at the seat pan site as compared to the site located beneath the cushion (defined as the suspension). These peaks were not observed at the seat back for any of the locomotive seats. In the Y direction, the GS and BS showed a peak transmissibility around 20 to 25 Hz at the suspension and seat pan sites. The magnitude of the suspension peak tended to occur around 3.0 for the GS and above 3.0 for BS; the magnitude of the seat pan peak tended to occur around 2.5 for the GS and approached 3.0 for the BS. A broader region of increased transmission was observed in the Y direction for the FS at the site located beneath the cushion (suspension) and at the seat pan, with the peak occurring around 40 to 45 Hz. The magnitude of the peak ranged between 2.0 and 3.5 and was only slightly higher at the seat pan for some subjects. Peaks in the Y direction were not observed at the seat back for any of the locomotive seats. In the Z direction, no large peaks were observed above 20 Hz in the GS and BS at any of the seat locations except for an increase in transmission above 60 Hz at the suspension site only. A small peak was observed around 50 Hz but tended to have a transmissibility of 1.0 or less. The FS did show two dramatic peaks around 30 Hz and 60 to 65 Hz at the suspension site. The transmissibilities reached around 2 to 2.5 at 30 Hz and about 3.0 at 60 to 65 Hz. The 30 Hz peak was dramatically reduced, while the 60 to 65 Hz was absent at the seat pan. At the FS back, a large peak was observed around 30 to 40 Hz with the transmissibility ranging between about 3.0 and 3.5. This appeared to coincide with the 30 Hz peak observed at the suspension and occurred regardless of the subject's posture. In general, very low transmissibilities and very low coherences were observed in the off-axis calculations at higher frequencies, indicating their minimal influence on the seat responses. The locomotive seats did show variable peaks in the transmissibility between the Z output at the seat and the X input at the floor that were associated with higher coherences, particularly at the suspension and seat back sites. These peaks were reduced or nonexistent at the seat pan. The multiple coherences were relatively high, primarily occurring around 0.8 and above.

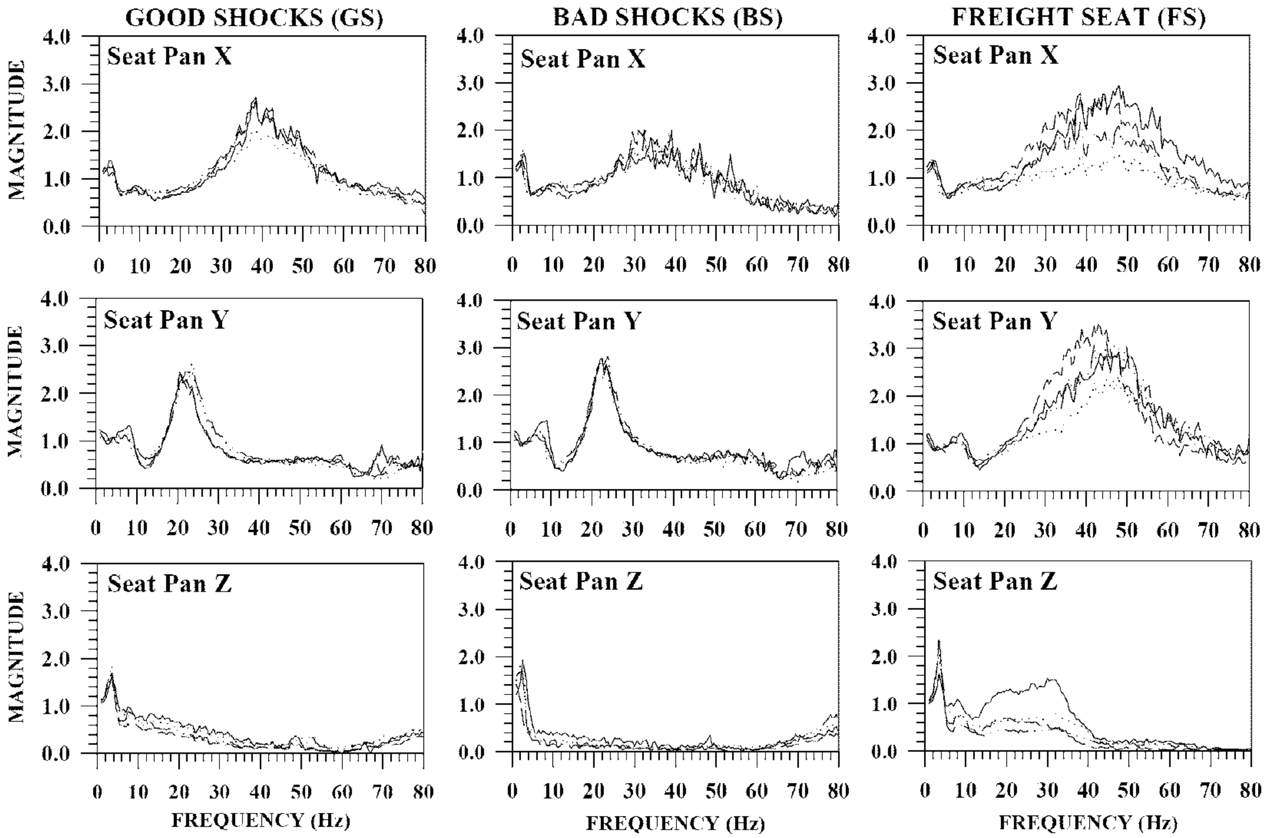


Figure B-1. Seat Pan Transmissibilities for FLAT Exposure, Back-On, 1–80 Hz

The higher frequency transmissibilities described above were not seen in the upper torso. While higher frequency vibration at the seat pan can be felt by an occupant, the locomotive signals showed only minimal higher frequency vibration. Therefore, these vibrations should be of no consequence to the locomotive engineers. In summary, the locomotive seats did show extensive damping of higher frequency vibration at the seat pan in the Z direction. However, this was not the case in the horizontal directions. The presence of fully-functional shocks in the GS did not appear to have a major influence on the higher frequency damping characteristics. Suspension seat technology may be useful for mitigating vibration in some vehicles where higher frequency components are prevalent but would require the improvement of damping characteristics in the horizontal axes.

Appendix C
Figures and Tables

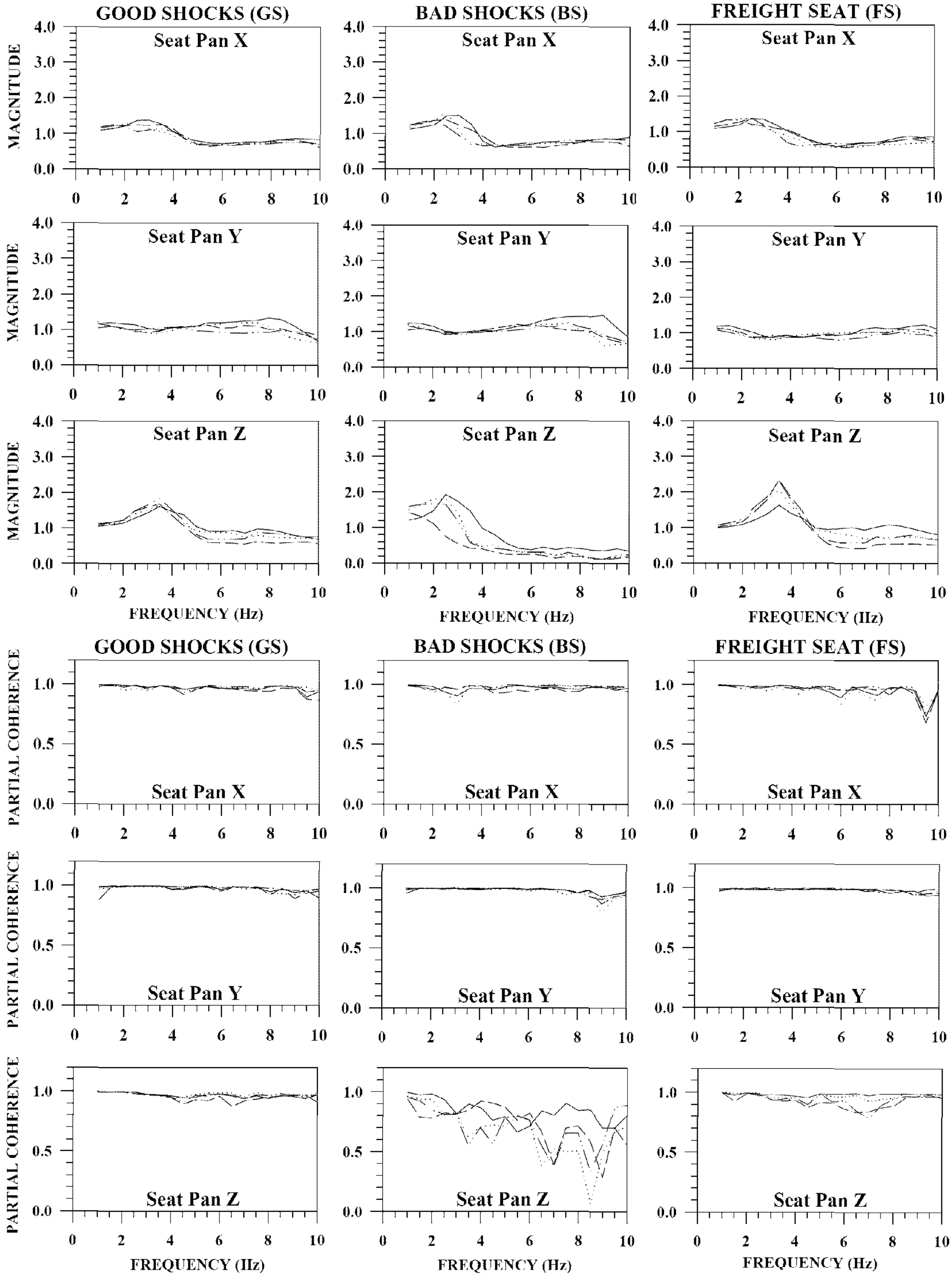


Figure C-1. Seat Pan Transmissibilities and Partial Coherences for FLAT Exposure, Back-On

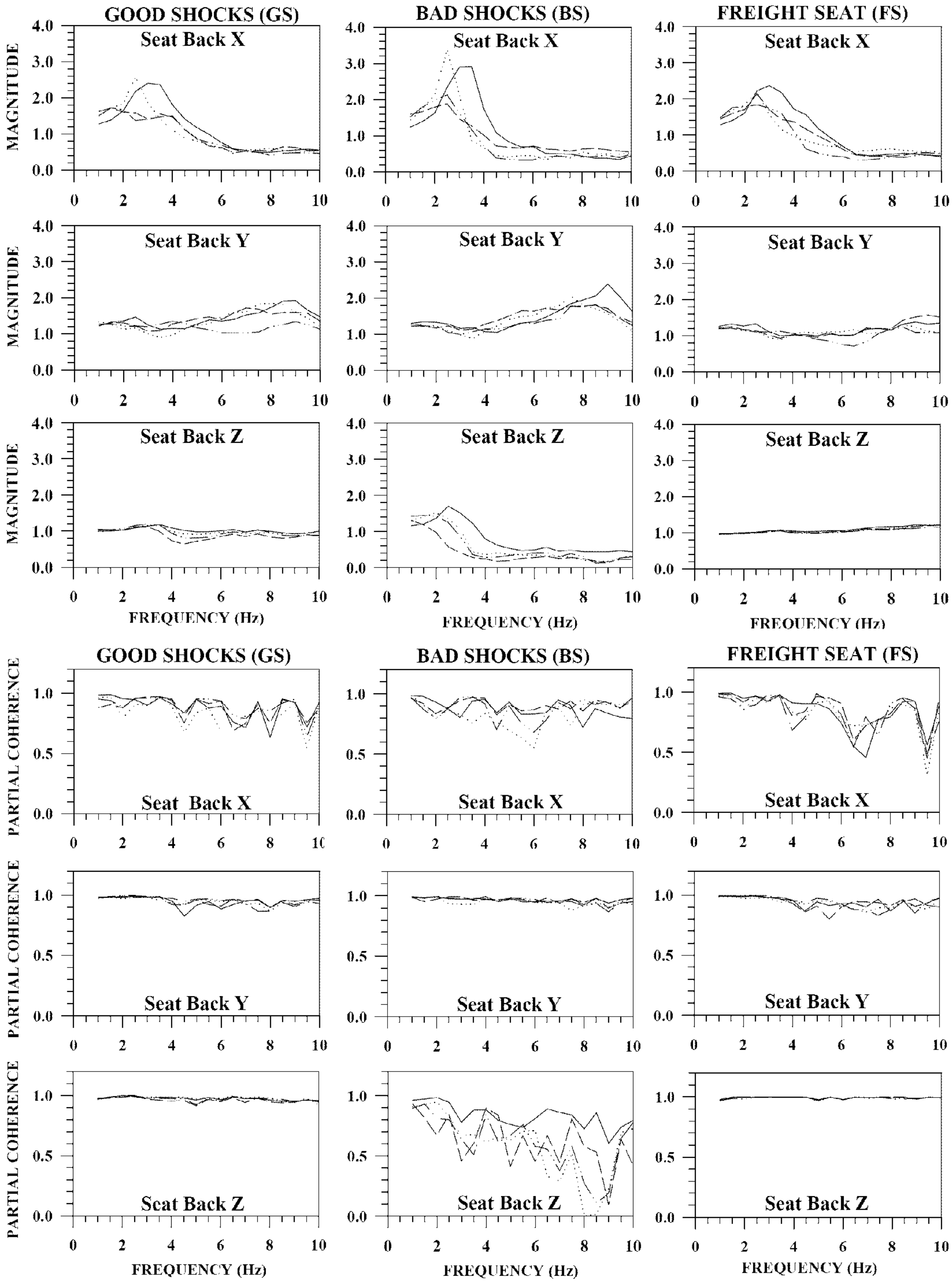


Figure C-2. Seat Back Transmissibilities and Partial Coherences for FLAT Exposure, Back-On

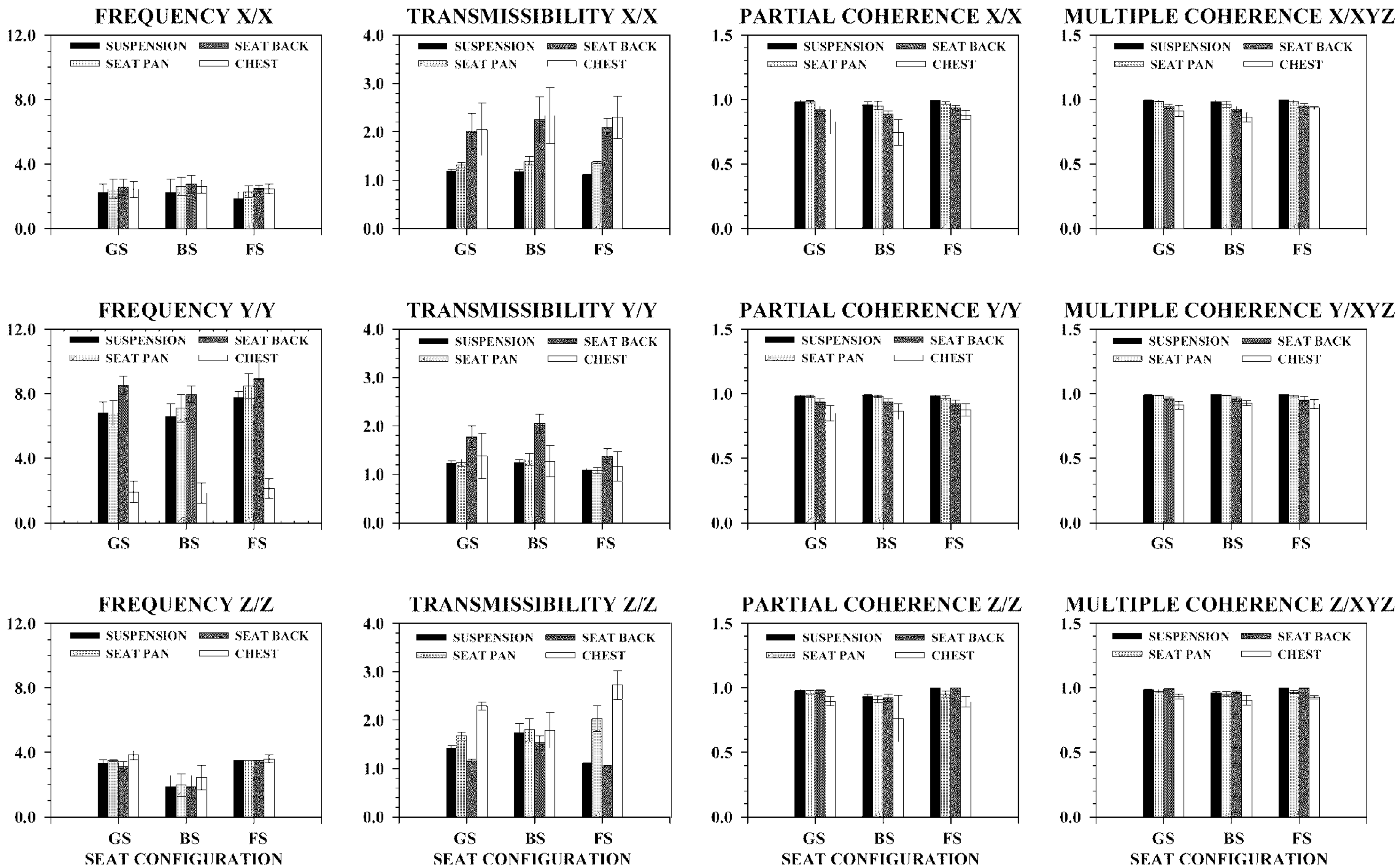


Figure C-3. Mean Frequency, Transmissibility, and Coherence ± 1 Standard Deviation of Peak Response (Back-On Only)

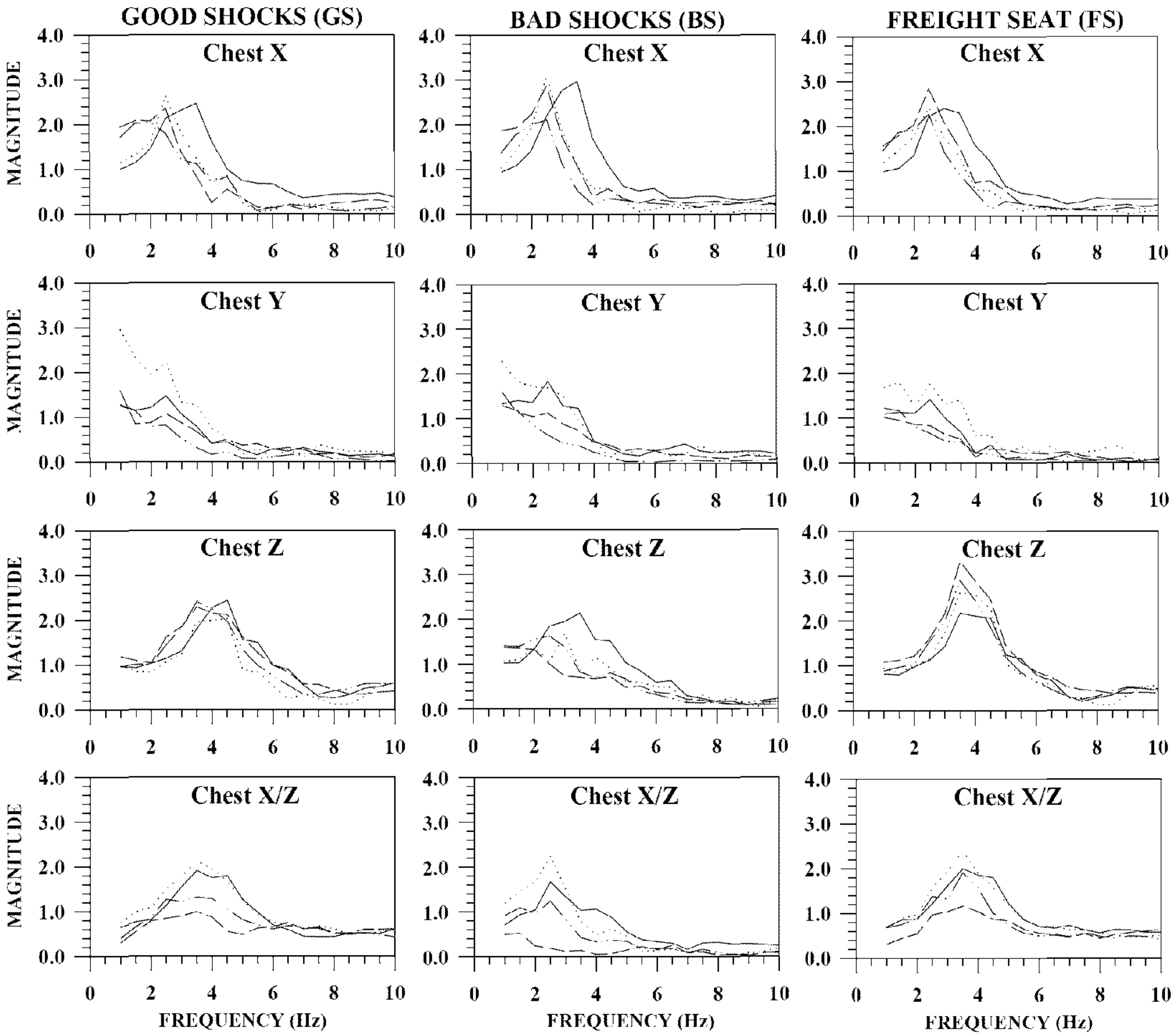


Figure C-4. Chest Transmissibilities for FLAT Exposure, Back-On

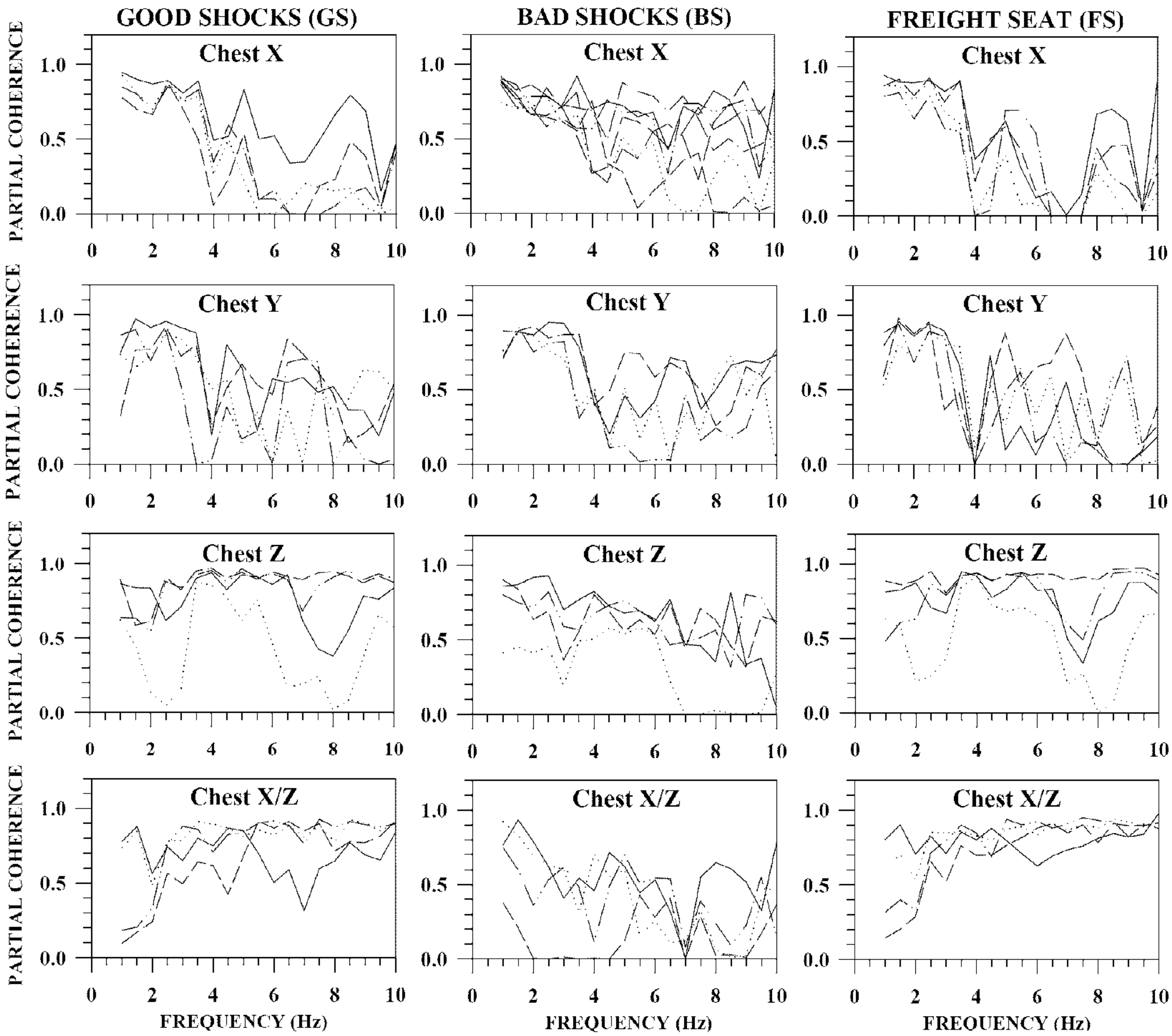


Figure C-5. Chest Partial Coherences for FLAT Exposure, Back-On

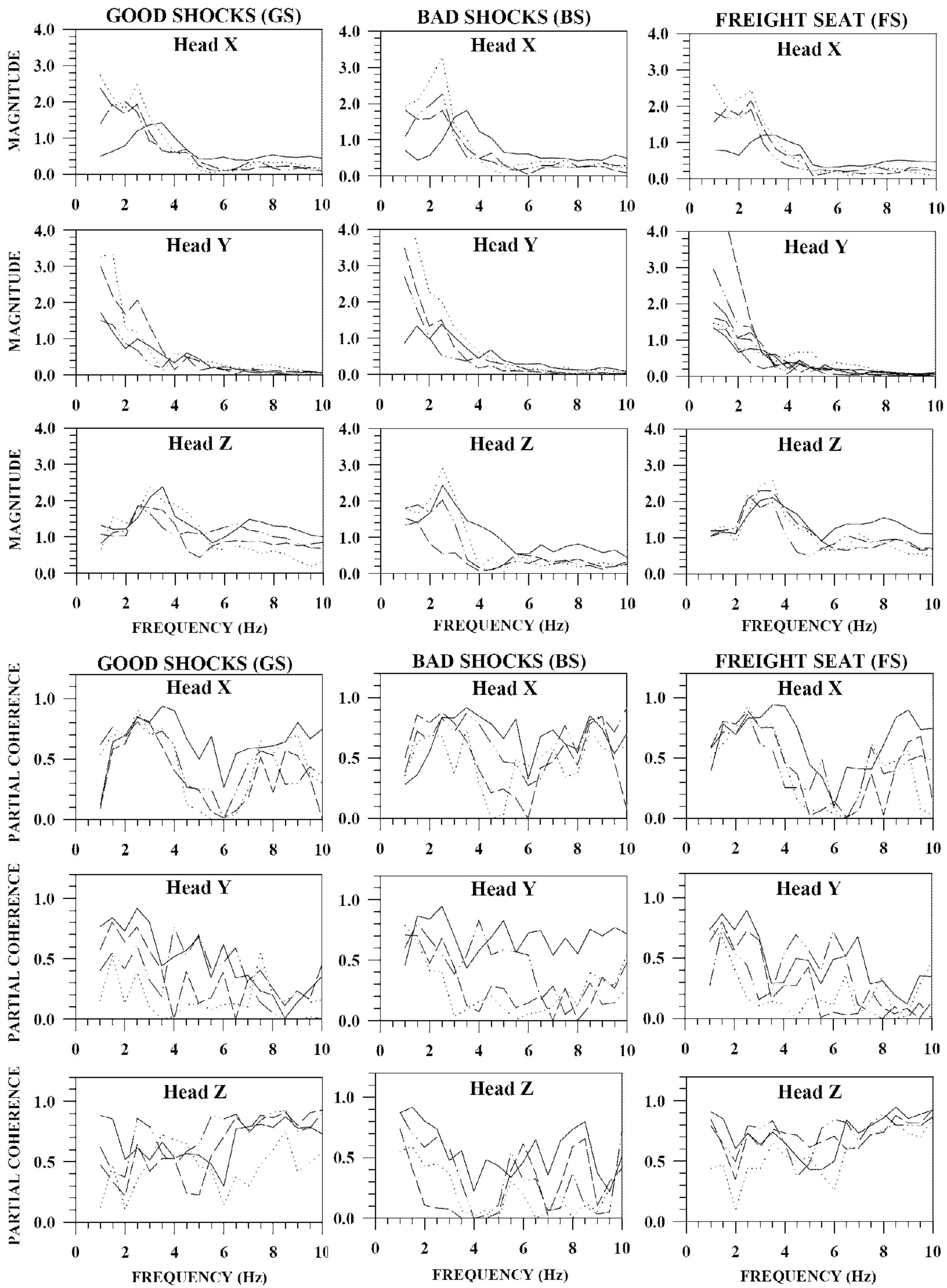


Figure C-6. Head Transmissibilities and Partial Coherences for FLAT Exposure, Back-On

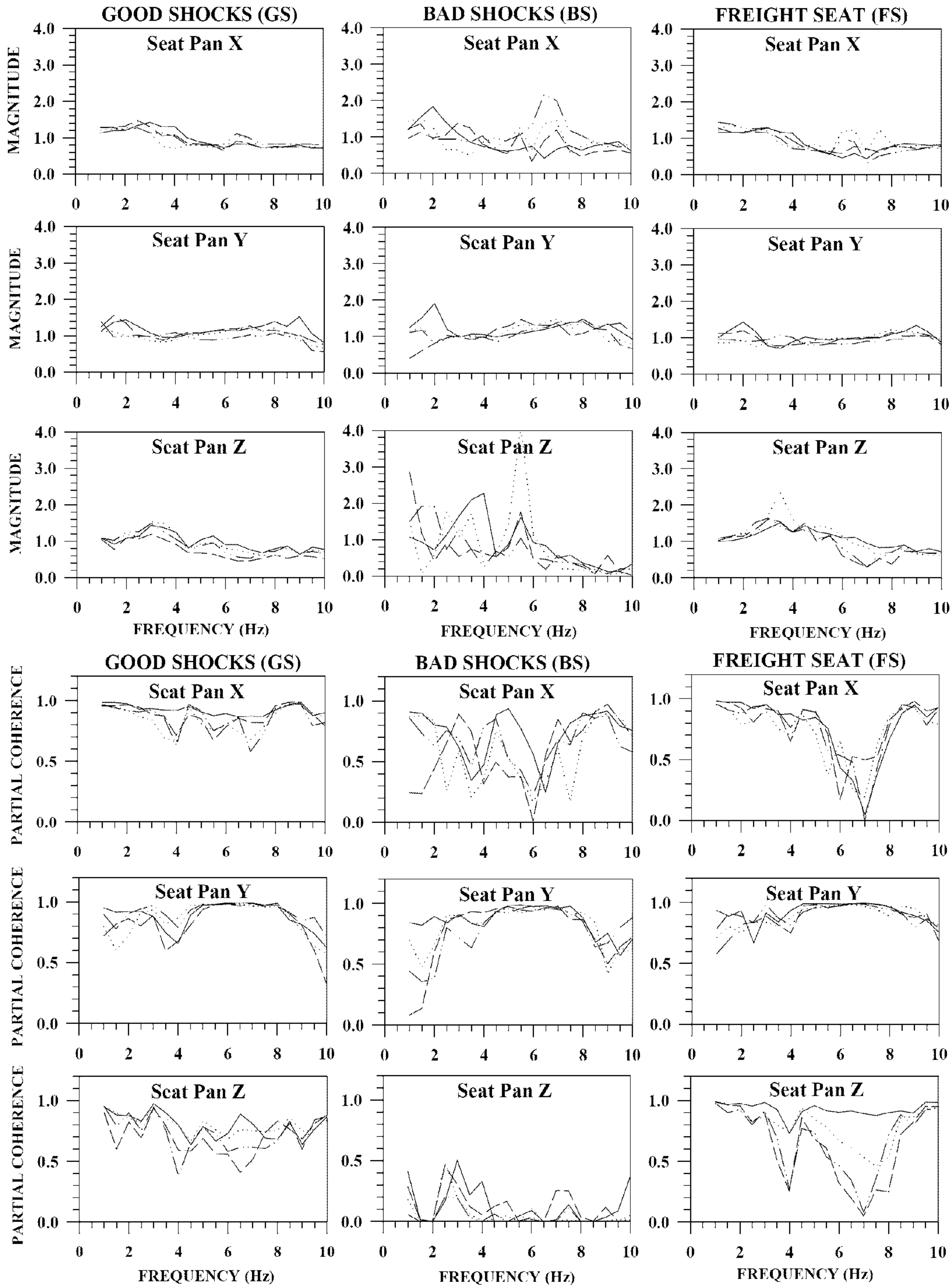


Figure C-7. Seat Pan Transmissibilities and Partial Coherences for LOCO12 Exposure, Back-On

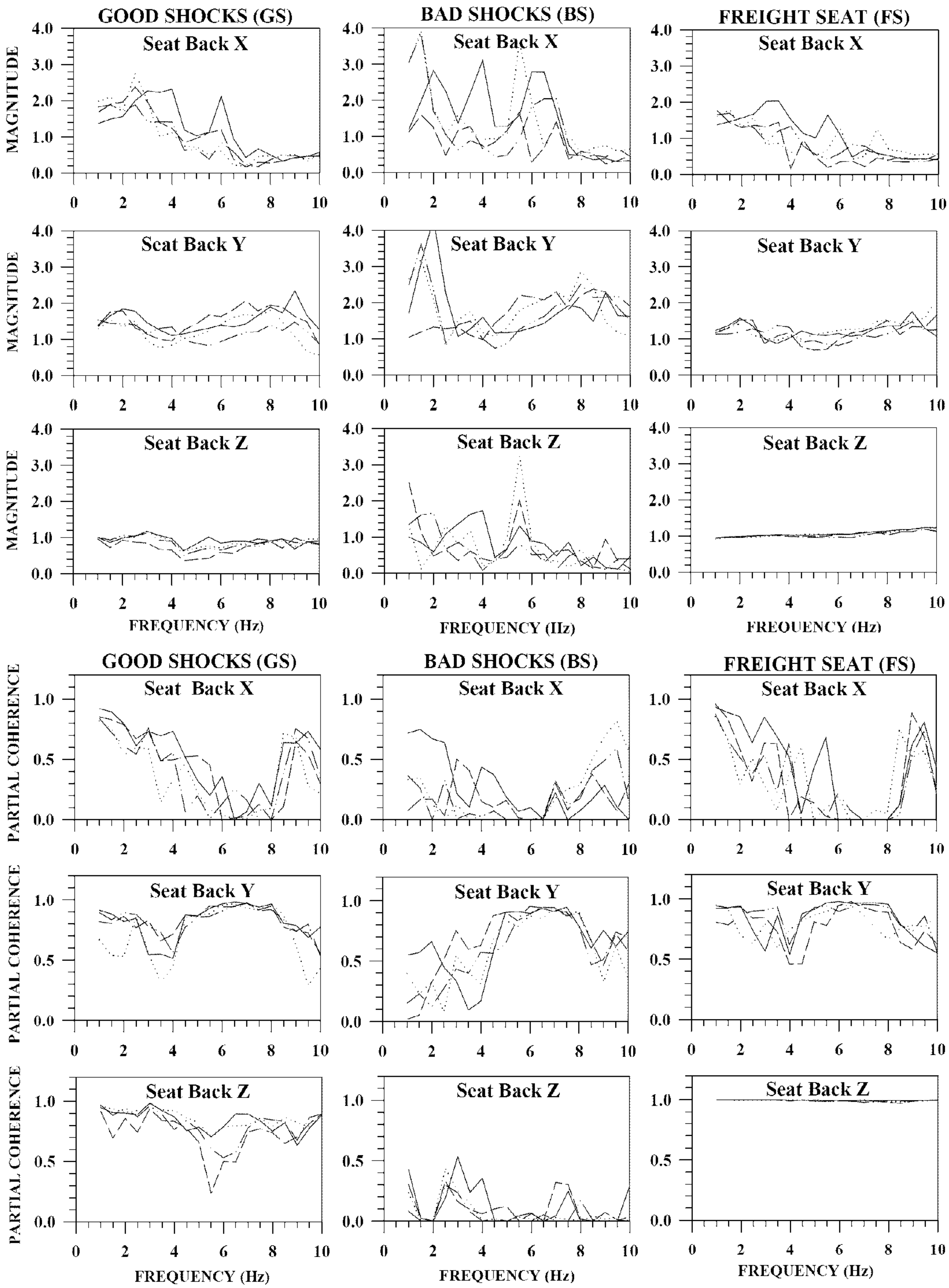


Figure C-8. Seat Back Transmissibilities and Partial Coherences for LOCO12 Exposure, Back-On

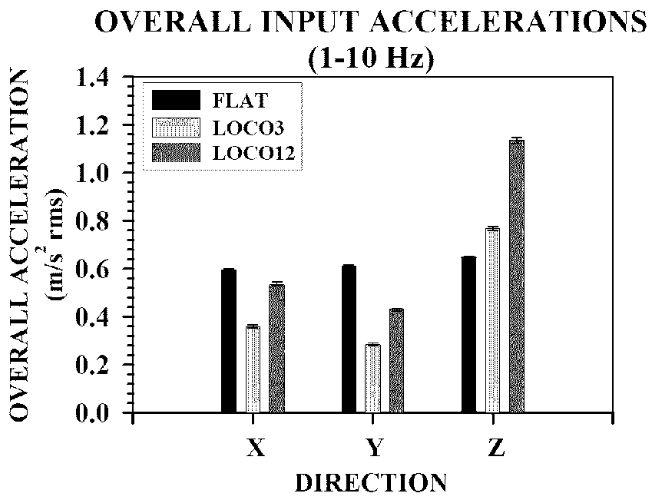


Figure C-9. Overall Floor (Input) Accelerations (1–10 Hz)

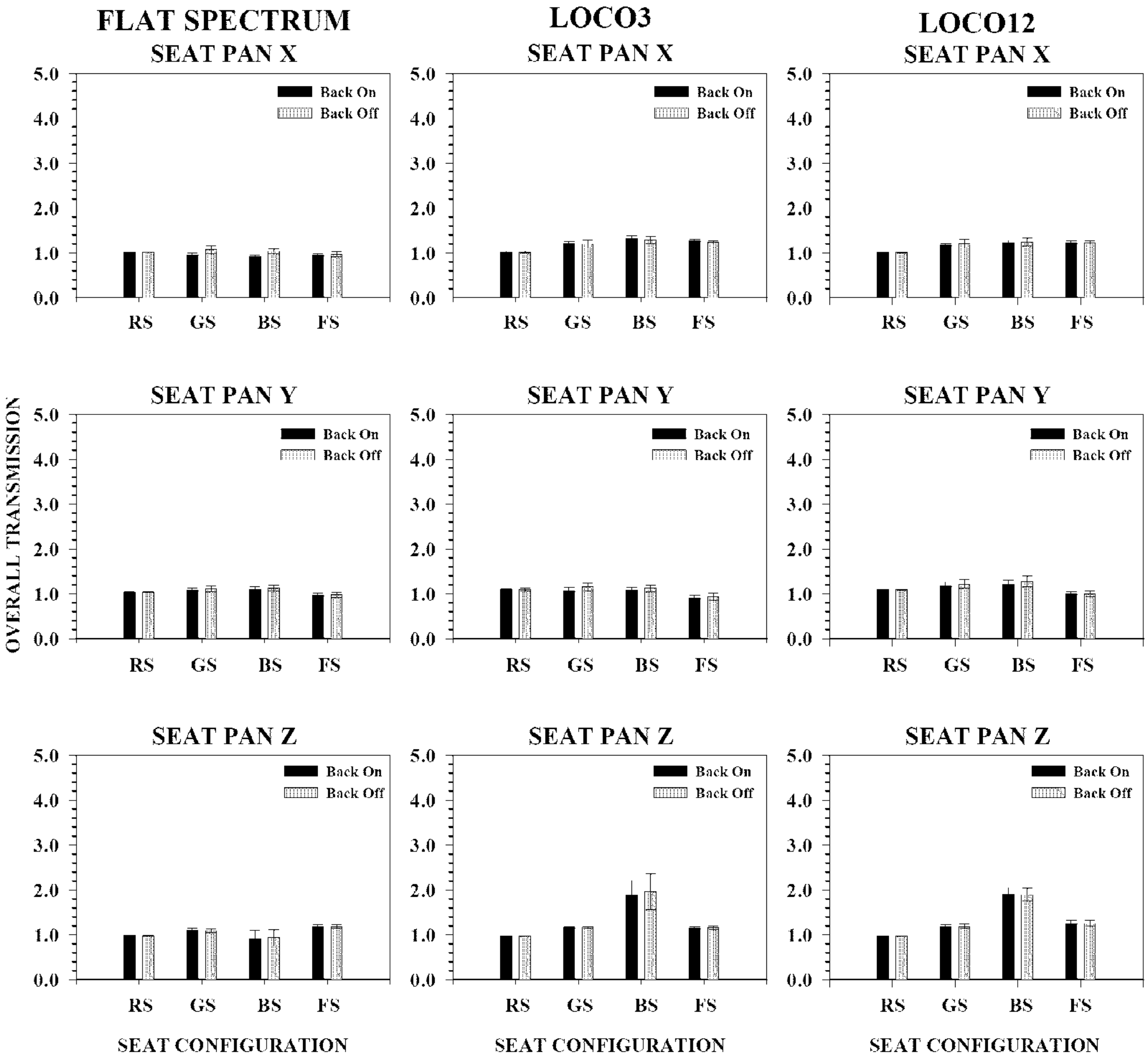


Figure C-10. Mean Overall Seat Pan Transmission (1-10 Hz) ± 1 Standard Deviation

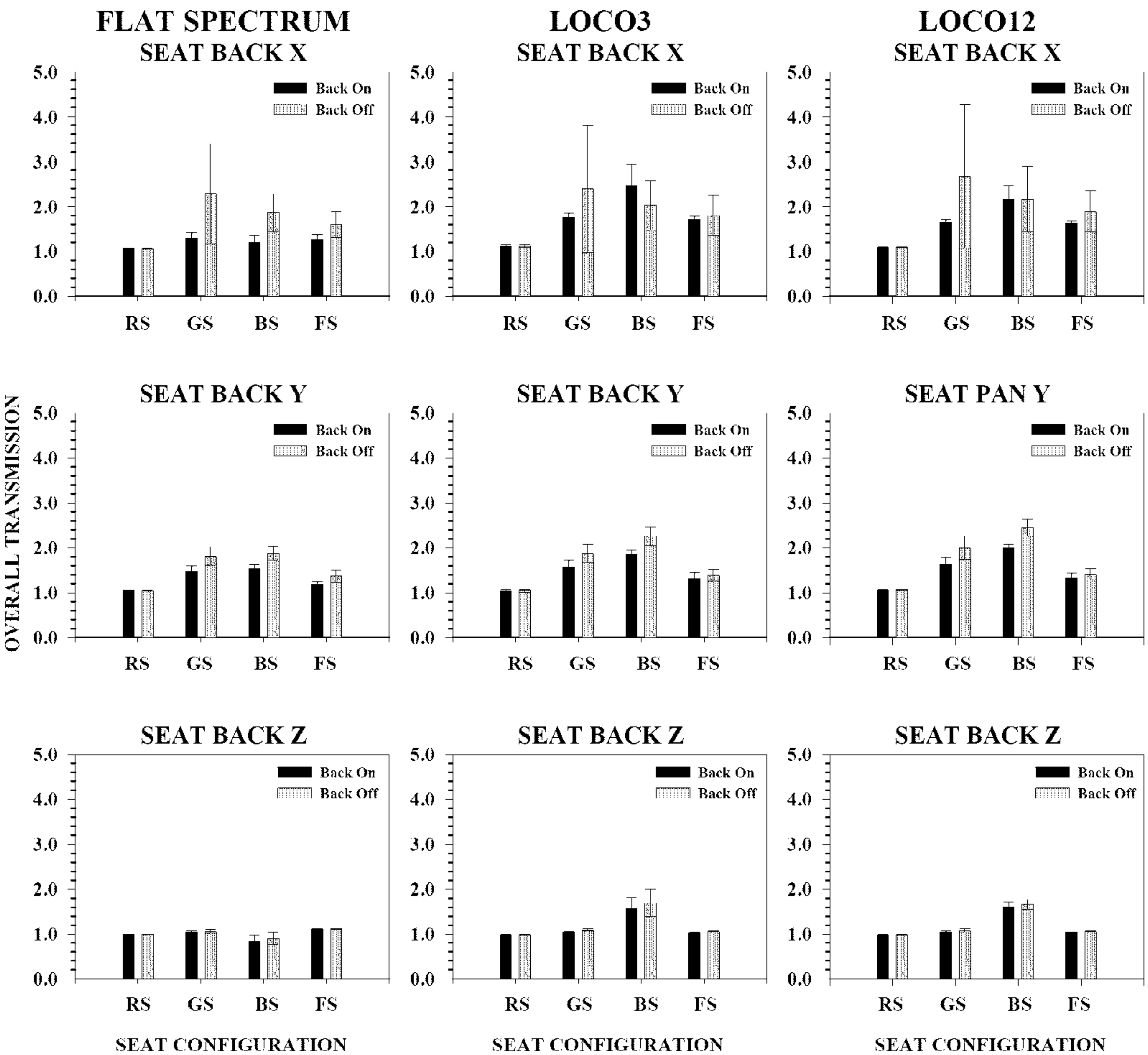


Figure C-11. Mean Overall Seat Back Transmission (1-10 Hz) ± 1 Standard Deviation

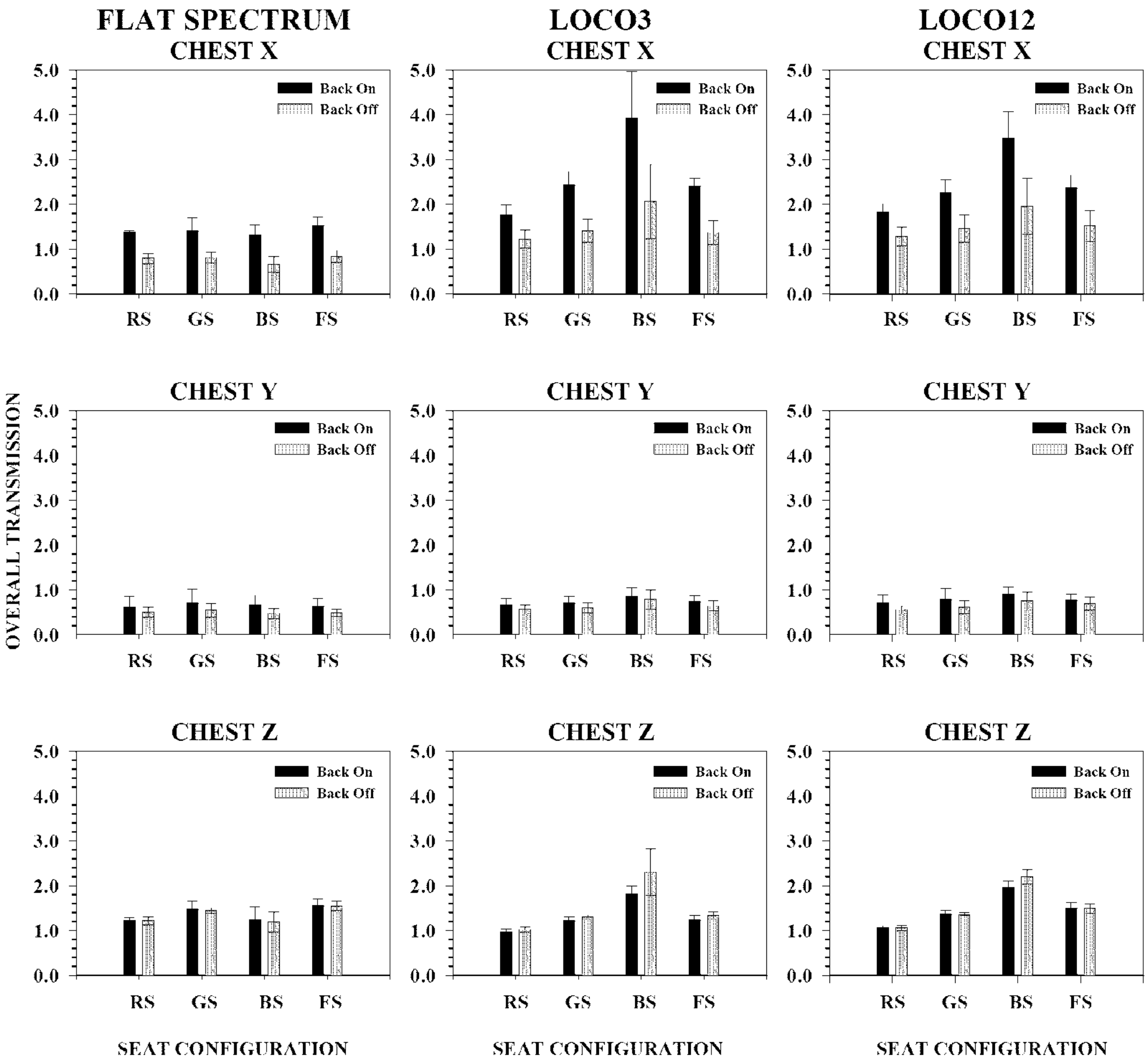


Figure C-12. Mean Overall Chest Transmission (1-10 Hz) ±1 Standard Deviation

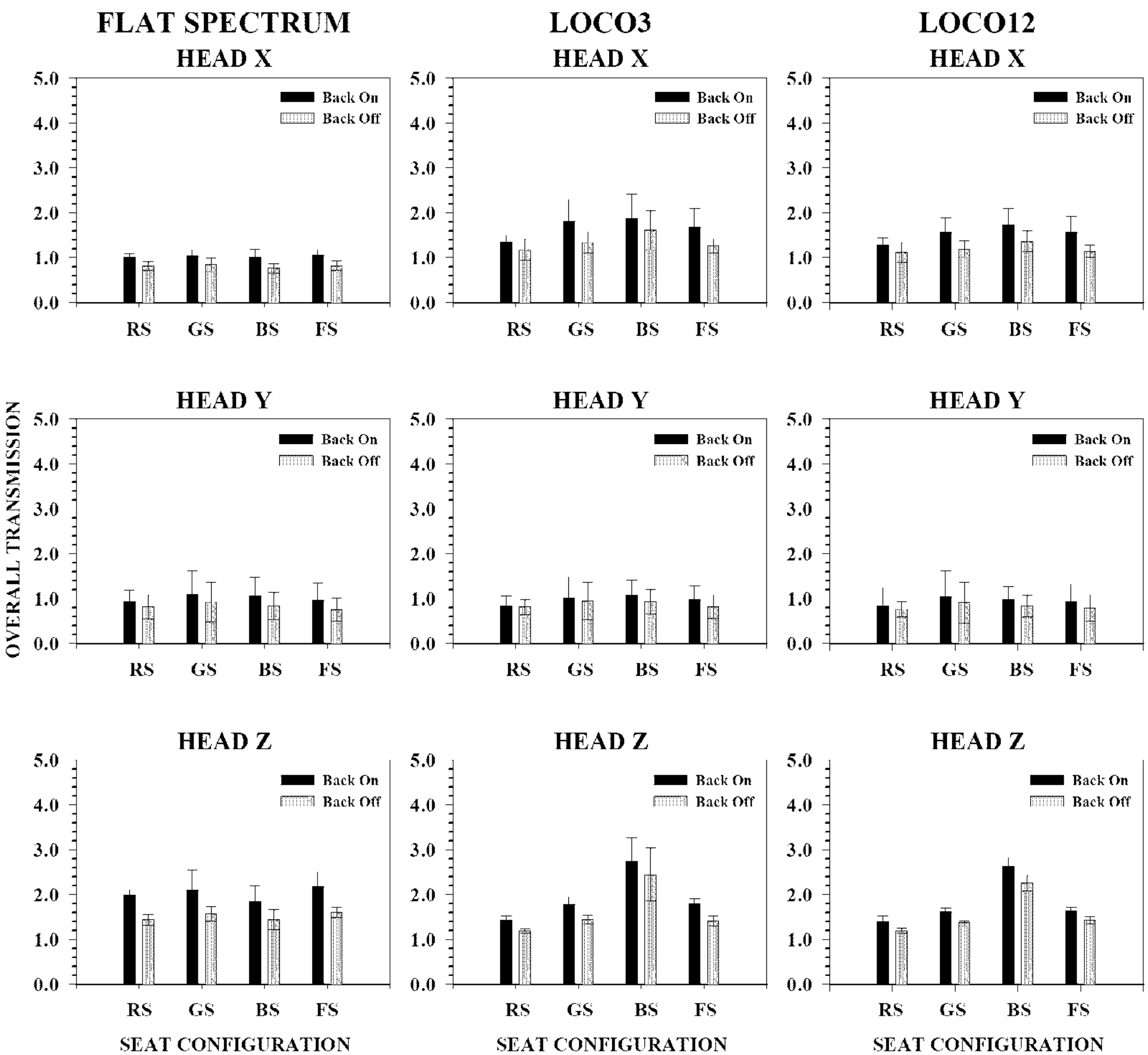


Figure C-13. Mean Overall Head Transmission (1-10 Hz) ± 1 Standard Deviation

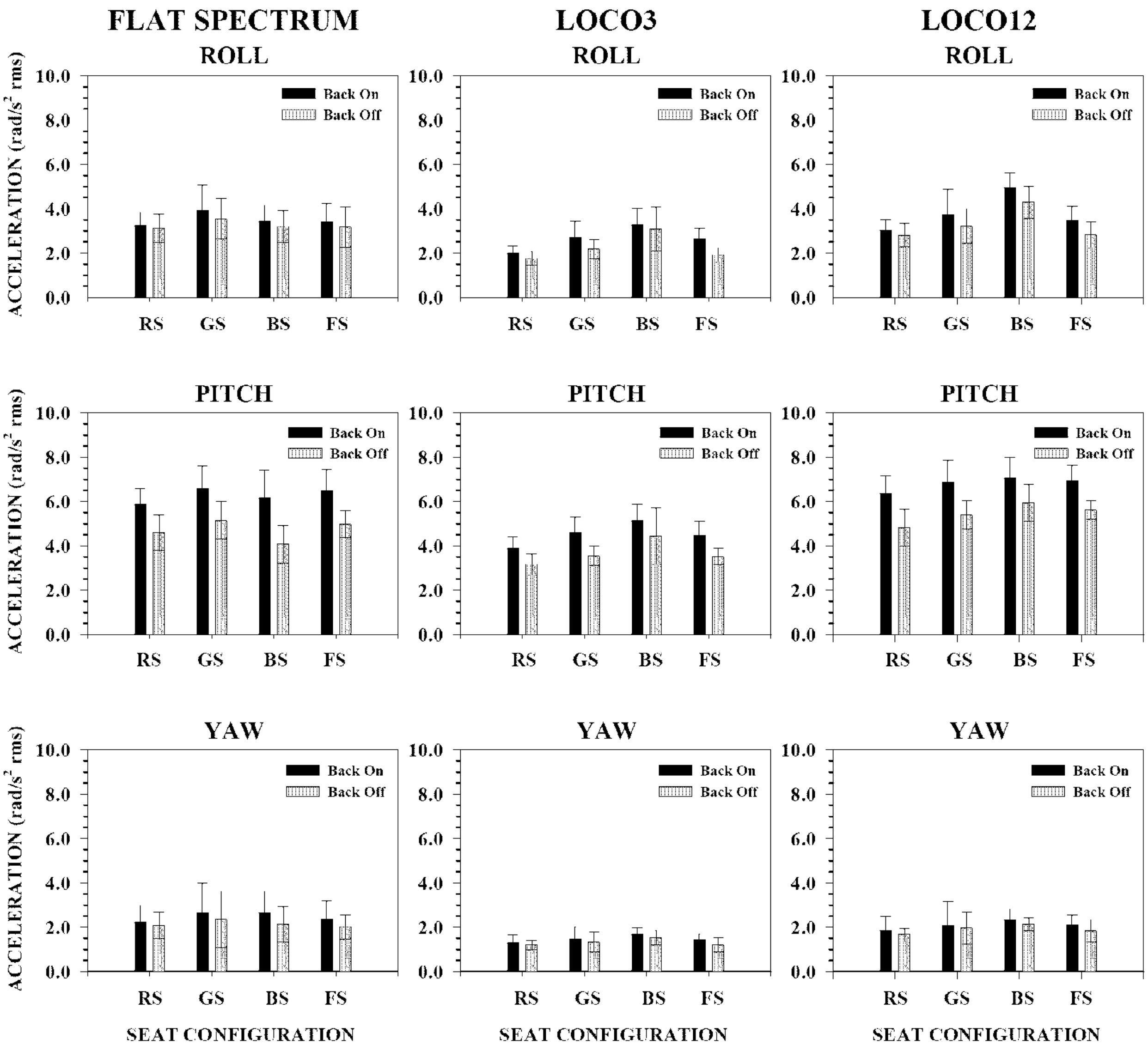
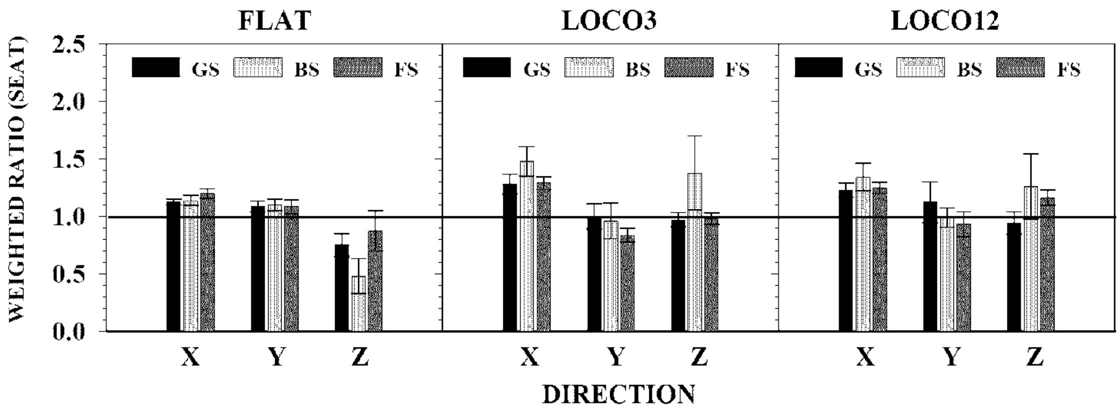
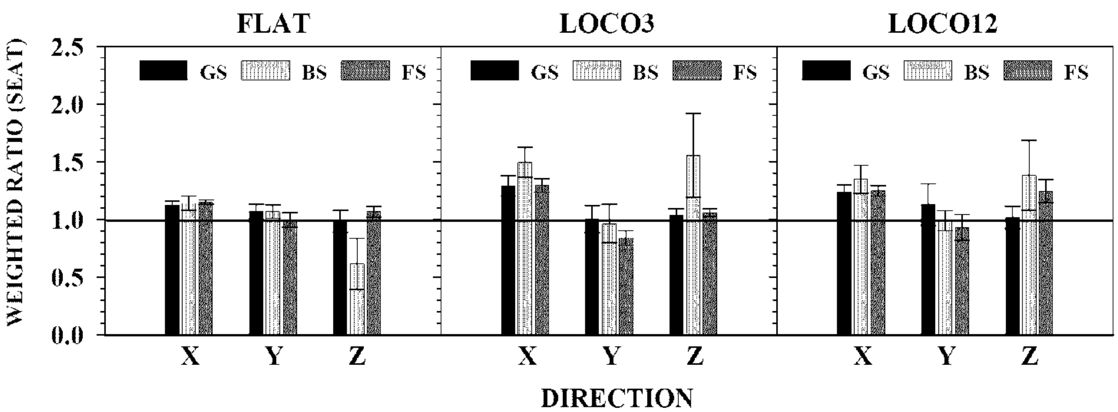


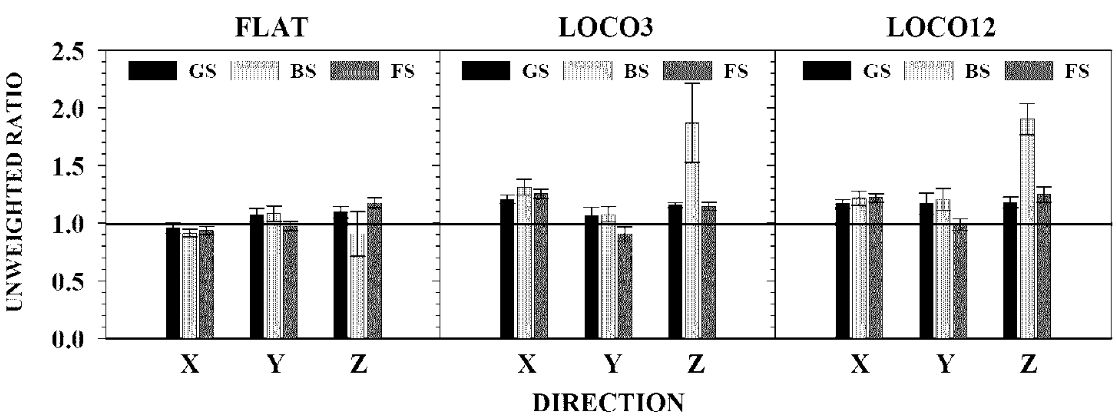
Figure C-14. Mean Overall (1-10 Hz) Head Rotation Accelerations ± 1 Standard Deviation



a. Weighted 1-80 Hz



b. Weighted 1-10 Hz



c. Unweighted 1-10 Hz

Figure C-15. Overall Weighted Transmission Ratios (SEAT) and Unweighted Ratios (Overall Transmissions)

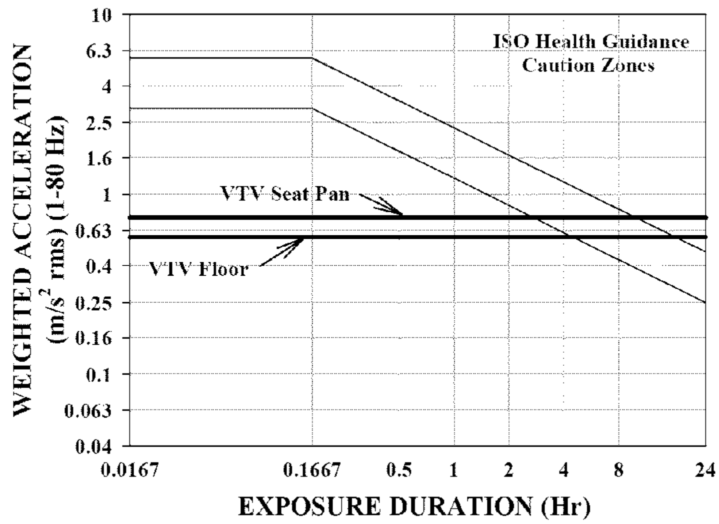


Figure C-16. Floor and Estimated Seat Pan Vibration Total Value for a 1-Hour Exposure to Locomotive Vibration

Table C-1. Mean Frequency, Transmissibility, and Coherence of Peak Response

		FR (Hz)	1 SD	TR	1 SD	PCOH	1 SD	MCOH	1 SD
GS	SUSPX	2.262	0.499	1.178	0.041	0.981	0.011	0.995	0.005
GS	PANX	2.440	0.614	1.308	0.058	0.982	0.009	0.988	0.007
GS	BACKX	2.548	0.525	2.013	0.368	0.917	0.030	0.947	0.015
GS	CHESTX	2.429	0.499	2.053	0.543	0.828	0.096	0.910	0.044
BS	SUSPX	2.238	0.827	1.171	0.050	0.958	0.022	0.982	0.012
BS	PANX	2.595	0.576	1.396	0.091	0.951	0.033	0.964	0.025
BS	BACKX	2.738	0.568	2.243	0.484	0.887	0.025	0.926	0.018
BS	CHESTX	2.595	0.407	2.334	0.583	0.744	0.101	0.863	0.037
FS	SUSPX	1.861	0.400	1.111	0.010	0.989	0.005	0.996	0.002
FS	PANX	2.286	0.369	1.370	0.028	0.972	0.012	0.981	0.012
FS	BACKX	2.500	0.192	2.093	0.188	0.933	0.021	0.951	0.015
FS	CHESTX	2.452	0.300	2.300	0.438	0.879	0.037	0.933	0.011
		FR (Hz)	1 SD	TR	1 SD	PCOH	1 SD	MCOH	1 SD
GS	SUSPY	6.833	0.650	1.229	0.050	0.982	0.007	0.991	0.003
GS	PANY	6.792	0.778	1.240	0.072	0.977	0.008	0.988	0.005
GS	BACKY	8.524	0.565	1.772	0.223	0.937	0.021	0.959	0.015
GS	CHESTY	1.893	0.664	1.381	0.471	0.848	0.059	0.910	0.030
BS	SUSPY	6.548	0.854	1.230	0.067	0.989	0.005	0.993	0.003
BS	PANY	7.095	0.860	1.311	0.112	0.979	0.010	0.986	0.005
BS	BACKY	7.952	0.516	2.048	0.198	0.937	0.022	0.957	0.017
BS	CHESTY	1.833	0.631	1.271	0.325	0.862	0.060	0.928	0.020
FS	SUSPY	7.750	0.397	1.086	0.030	0.984	0.006	0.995	0.001
FS	PANY	8.472	0.770	1.076	0.062	0.964	0.021	0.982	0.008
FS	BACKY	8.929	1.117	1.371	0.158	0.925	0.027	0.951	0.025
FS	CHESTY	2.119	0.599	1.164	0.304	0.877	0.048	0.920	0.034
		FR (Hz)	1 SD	TR	1 SD	PCOH	1 SD	MCOH	1 SD
GS	SUSPZ	3.310	0.244	1.416	0.047	0.980	0.006	0.986	0.006
GS	PANZ	3.476	0.063	1.671	0.081	0.964	0.014	0.972	0.014
GS	BACKZ	3.095	0.317	1.156	0.043	0.977	0.008	0.993	0.003
GS	CHESTZ	3.833	0.272	2.293	0.078	0.896	0.037	0.933	0.020
BS	SUSPZ	1.881	0.699	1.747	0.176	0.930	0.019	0.965	0.008
BS	PANZ	1.976	0.690	1.793	0.235	0.909	0.025	0.952	0.019
BS	BACKZ	1.881	0.699	1.529	0.146	0.925	0.027	0.968	0.009
BS	CHESTZ	2.452	0.756	1.789	0.367	0.762	0.181	0.904	0.041
FS	SUSPZ	3.500	0.000	1.111	0.006	0.999	0.000	0.999	0.000
FS	PANZ	3.500	0.000	2.029	0.268	0.951	0.022	0.968	0.013
FS	BACKZ	3.500	0.000	1.056	0.015	0.999	0.000	1.000	0.000
FS	CHESTZ	3.595	0.252	2.724	0.302	0.893	0.039	0.929	0.016

Table C-2. Mean Weighted Rms Accelerations and Overall VTV (1 - 80 Hz)

SIGNAL/DIRECTION	SEAT CONFIGURATION					
	GS	1 SD	BS	1 SD	FS	1 SD
LOCO3 ON X	0.32	0.02	0.38	0.02	0.33	0.02
LOCO 3 OFF X	0.30	0.01	0.36	0.06	0.30	0.01
LOCO12 ON X	0.47	0.02	0.52	0.05	0.48	0.02
LOCO12 OFF X	0.43	0.05	0.48	0.07	0.47	0.01
LOCO3 ON Y	0.14	0.01	0.13	0.02	0.11	0.01
LOCO3 OFF Y	0.14	0.02	0.13	0.01	0.12	0.01
LOCO12 ON Y	0.23	0.04	0.21	0.02	0.19	0.02
LOCO12 OFF Y	0.22	0.03	0.22	0.05	0.18	0.01
LOCO3 ON Z	0.60	0.03	0.84	0.20	0.59	0.04
LOCO3 OFF Z	0.58	0.03	0.87	0.23	0.62	0.01
LOCO12 ON Z	0.85	0.09	1.13	0.26	1.05	0.05
LOCO12 OFF Z	0.85	0.09	1.12	0.24	1.02	0.04
LOCO3 ON VTV	0.77	0.04	1.01	0.20	0.77	0.05
LOCO12 ON VTV	1.13	0.11	1.38	0.27	1.27	0.06

1 HOUR OPERATION	SEAT CONFIGURATION (UNKNOWN)
X	0.32
Y	0.09
Z	0.58
VTV (EST)	0.74

This page intentionally left blank.

Abbreviations and Acronyms

AFRL	Air Force Research Laboratory
AFRL/HE	Air Force Research Laboratory, Human Effectiveness Directorate
AFRL/HEPA	Air Force Research Laboratory, Human Effectiveness Directorate, Biosciences and Protection Division, Biomechanics Branch
BS	Bad Shocks Seat (shocks removed)
DOT	U.S. Department of Transportation
FLAT	Flat Acceleration Spectrum
FRA	Federal Railroad Administration
FS	Freight Seat
GS	Good Shocks Seat
ISO	International Organization for Standardization
LOCO3	Locomotive Vibration Signal
LOCO12	Locomotive Vibration Signal
PSD	Power Spectral Density
RS	Rigid Seat
SEAT	Seat Effective Amplitude Transmissibility
SIXMODE	Six Degree-of-Freedom Motion Simulator
USSC	United States Seating Company
VTV	Vibration Total Value
X	Fore-and-Aft (relative to seated occupant)
Y	Lateral (relative to seated occupant)
Z	Vertical (relative to seated occupant)