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Field Evaluation of Seat Designs for Underground Coal Mine Shuttle Cars

Department of Health and Human Services
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

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By Alan G. Mayton, Christopher C. Jobes, Ph.D., N. Kumar Kittusamy, Sc.D., and Dean H. Ambrose

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DEFINITION OF TERMS

Autopower spectrum: Distribution of the mean square value of a time history over a frequency range.

Crest factor: Ratio of peak acceleration divided by root-mean-square (RMS) acceleration.

Peak: Peak amplitude of a signal.

Transmissibility: Ratio of output/input for acceleration, velocities, displacements, forces.

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

Hz	hertz
in	inch
lb	pound
m/s^2	meter per second square
r	Pearson product moment correlation

FIELD EVALUATION OF SEAT DESIGNS FOR UNDERGROUND COAL MINE SHUTTLE CARS

By Alan G. Mayton,[1] Christopher C. Jobes, Ph.D.,[2] N. Kumar Kittusamy, Sc.D.,[3] and Dean H. Ambrose[4]

ABSTRACT

Researchers with the National Institute for Occupational Safety and Health (NIOSH) conducted a systematic study to evaluate seat designs on low- and mid-coal-seam shuttle cars. The purpose was to gather additional data to support earlier findings that NIOSH seats, with unique viscoelastic foam padding, are indeed improved designs for coal mine shuttle cars. This study included a larger sample of shuttle car operators than a prior NIOSH investigation.

Eight shuttle car operators participated in evaluating seat designs on the basis of perceived levels of vehicle jarring/jolting and discomfort. Researchers then compared the operators' perceptions with field-measured levels of vehicle jarring/jolting. Seven seat designs were evaluated on low- and mid-coal-seam shuttle cars during production operations at two underground coal mines in southern West Virginia. These seat designs comprised the one already in use on each vehicle and five NIOSH designs.

Experimental data were collected using accelerometers, signal conditioning amplifiers, and filters connected to a data recorder, whereas subjective data were gathered via a visual analog scale (VAS) and a questionnaire. Field trials included shuttle cars operating under full- and no-load conditions. VAS responses indicated that NIOSH-designed seats performed better relative to comfort and isolation from vehicle jarring/jolting than the existing seats used in the shuttle cars. Both mid- and low-coal-seam shuttle car operators, during no-load and full-load conditions, rated lower levels of jarring/jolting with the NIOSH seat design. Questionnaire responses indicated that shuttle car operators rated NIOSH seat designs as more comfortable. Vehicle operators most frequently suggested the addition of armrests as a way to improve the seats on the mid-seam shuttle car. The quantitative levels of vehicle jarring/jolting for the no-load condition (more severe condition for vehicle operation) showed that NIOSH seats for the mid-coal-seam shuttle car performed better than the existing seat in terms of peak acceleration and crest factor. Similarly, for the low-coal-seam shuttle car, NIOSH seats performed better than the existing seat in terms of peak acceleration, root-mean-square (RMS) acceleration, and crest factor.

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This research will provide the mining industry with better seat designs for isolating operators from vehicle jarring/jolting. Furthermore, equipment manufacturers are afforded the opportunity to refine and improve the NIOSH seat designs using information gathered from this research study.

INTRODUCTION

Modern transportation vehicles continually expose individuals to whole-body vibration (WBV) and mechanical shock. These include airplanes, ships, trains, and a variety of industrial and agricultural equipment. Exposing individuals to WBV and mechanical shock can negatively impact their health, safety, comfort, and working efficiency and performance.

In designing a comfortable seat, it is important to understand the vibration environment to which individuals are exposed and how well they can tolerate this environment. Moreover, human sensitivity to low-frequency WBV has pointed to ride quality as an important need in seat design [Amirouche et al. 1997]. This is especially true in the mining industry.

A study by Mayton et al. [1999] reported on a low-coal shuttle car seat design that underwent limited, yet successful underground mine trials. The intent of the seat design comparison study reported here was to build on earlier work by performing a more systematic evaluation of the low-coal shuttle car seat design and a second mid-coal shuttle car seat design. By gathering more information with a larger sample of shuttle car operators, researchers confirmed earlier findings that NIOSH seat designs, with unique viscoelastic foam padding, are more effective in isolating shuttle car operators from jars and jolts. The NIOSH seat designs include viscoelastic foam, which has properties similar to those found in a mechanical spring/damper suspension system. The seats also include an adjustable lumbar support and a fore-aft seat adjustment, whereas existing seats have little or no lumbar support and include inexpensive foam padding of the type commonly used in furniture. In view of the harshness of the mining environment and the space constraints of mining equipment, viscoelastic foam padding offers a viable alternative to passive mechanical seat suspensions that are difficult to use under these conditions.

BACKGROUND

Research has shown that underground coal mine equipment operators experience adverse levels of exposure to WBV and vehicle jarring/jolting (mechanical shock). This exposure is identified as the higher-amplitude, peak components of WBV. Shuttle car haulage vehicles are among the major sources of exposure to vehicle jarring/jolting in underground coal mines. Remington et al. [1984] showed that WBV was severe for these vehicles, as well as for load-haul-dumps (LHDs) or scoops. These circumstances have changed little since 1984, as evidenced by injury statistics and operator testimonials about these vehicles. Injury statistics for mobile mining equipment operators from the Mine Safety and Health Administration (MSHA) showed incidences of exposure to WBV and mechanical shock (vehicle jarring or jolting). These injuries can be described as acute and chronic musculoskeletal disorders affecting the back, neck, and head. The total MSHA-reported injuries involving the back, neck, and head showed a general decline for the period 1999–2003, although vehicle jarring/jolting-related injuries averaged 77% per year of the total back, neck, and head injuries for mine shuttle car operators.

Additional evidence exists to illustrate that serious health effects can result from prolonged exposure of vehicle operators to jarring and jolting. Critical surveys of the literature have concluded that exposure to long-term WBV and awkward postures can adversely affect the spine and can increase the risk of low-back pain [Kittusamy and Buchholz 2004; Bernard 1997; Wikström et al. 1994; Seidel and Heide 1986; Hulshof and van Zanten 1987].

In an Australian study, Cross and Walters [1994] identified WBV and vehicle jarring as a contributing factor to back pain in the mining industry and as a significant concern to mobile equipment operators. They reviewed 28,306 compensation claims for a 4-year period (July 1986 to March 1990), including surface and underground mining environments. Of the 8,961 claims relating to the head, back, and neck, 11% (986) were related to vehicular jarring. Underground transporters and shuttle cars accounted for 53% of all injuries attributed to vehicle jarring.

STUDY APPROACH

Through cooperative agreements, this study was carried out with the support of Joy Mining Machinery, the leading manufacturer and supplier of underground mine shuttle cars in the world (more than 90% market share of mine shuttle cars), and Dynamic Systems, Inc., Leicester, NC, a manufacturer and supplier of viscoelastic seating foams. The study was performed at the Laurel Alma and Black King underground coal mines (mid- and low-seam coal, respectively) in southern West Virginia. The mines are affiliates of Elk Run Coal Co. Their selection resulted from a referral by Joy Mining Machinery, the cooperator in the aforementioned agreement.

Seat design trials were conducted on a JOY 21SC low-coal-seam shuttle car (Figure 1) operating at the Black King Mine and a JOY 10SC mid-coal-seam, side-saddle-style[5] shuttle car (Figure 2) operating at the Laurel Alma Mine. Seven different seat designs were tested on the two shuttle cars. The existing seats were designated as “seat L1” (Figure 3) and “seat M1” for trials with low- and mid-coal-seam shuttle car models, respectively. The NIOSH seats were designated as follows according to the viscoelastic foam arrangement for the low-seam shuttle car:

- Seat L2A – included padding with a combination of Pudgee (PU) and Extra-soft SunMate (XSS) and a 3-in total thickness.
- Seat L2B – included a 5-in total thickness of XSS foam padding.
- Seat L2C – included padding with a combination of PU and XSS and a 5-in total thickness.

[5]The side-saddle-style refers to how the shuttle car operator is positioned in the vehicle cab. In this case, the operator is perpendicular to, instead of facing, the direction of travel.

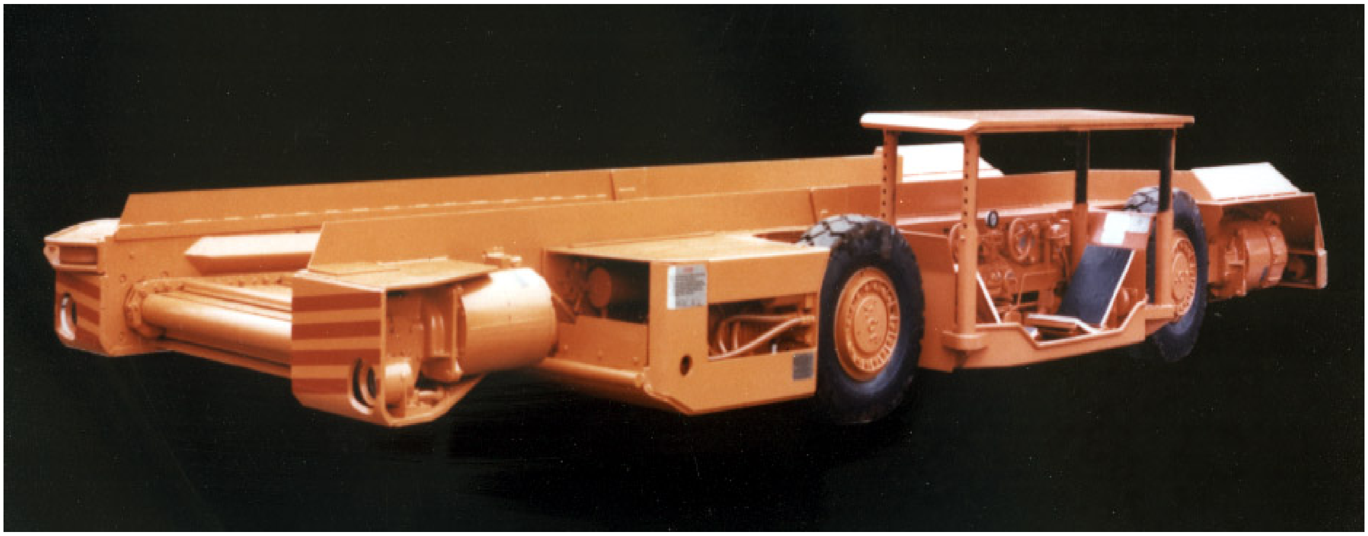

Figure 1.—JOY 21SC low-coal-seam shuttle car.

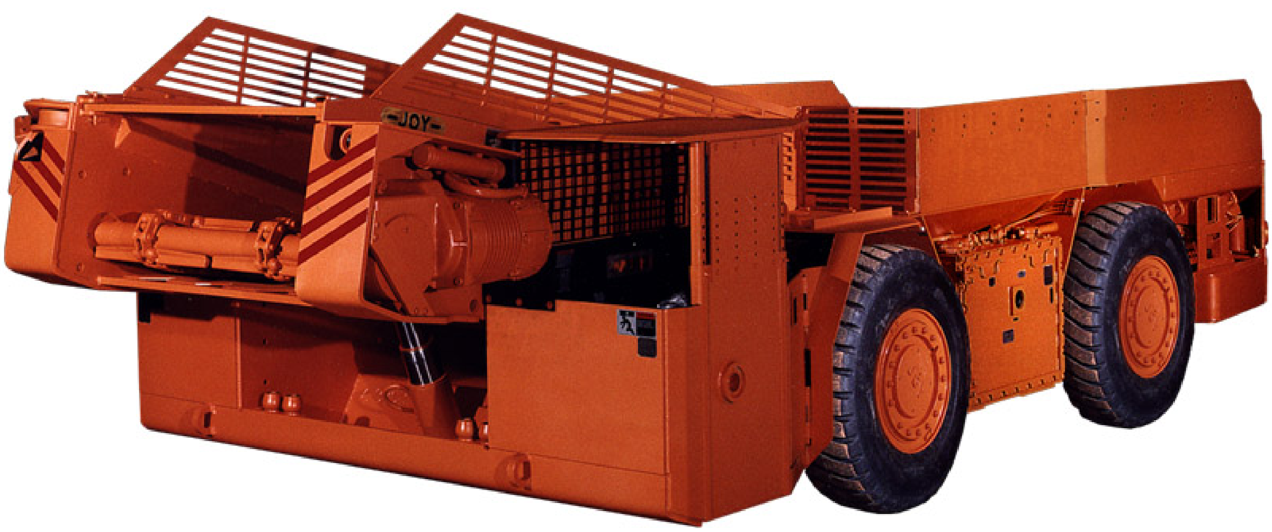

Figure 2.—JOY 10SC mid-coal-seam shuttle car.

Figure 3.—Existing low-coal-seam shuttle car seat.

Figures 4–5 show the NIOSH seat and the padding arrangements for the low-seam shuttle car. The NIOSH seats for the mid-seam shuttle car were designated as follows according to the viscoelastic foam arrangement:

- Seat M2A – included a 5-in total thickness of XSS foam padding.
- Seat M2B – included padding with a combination of PU and XSS and a 5-in total thickness.

Figures 6–7 show the NIOSH seat and the padding arrangements for the mid-seam shuttle car. The peak acceleration, root-mean-square (RMS) acceleration, and crest factor, in reference to the threshold limit values (TLVs) of the American Conference of Governmental Industrial Hygienists [ACGIH 2006], were used to quantitatively evaluate seat design performance relative to vehicle jarring/jolting.

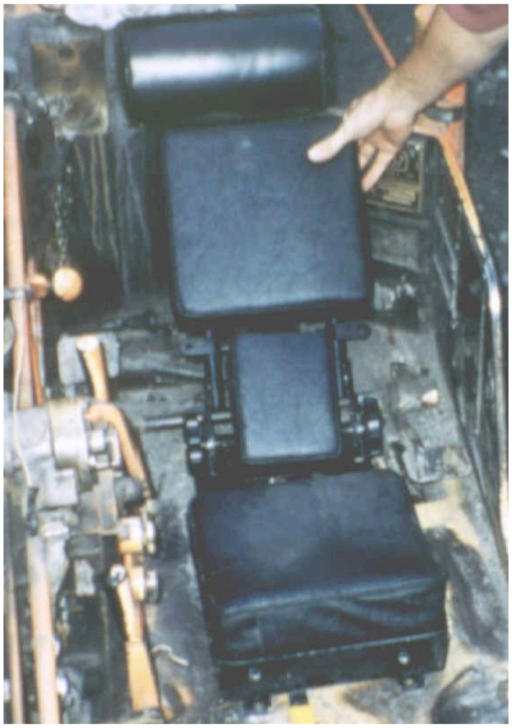

Figure 4.—NIOSH low-coal-seam shuttle car seat.

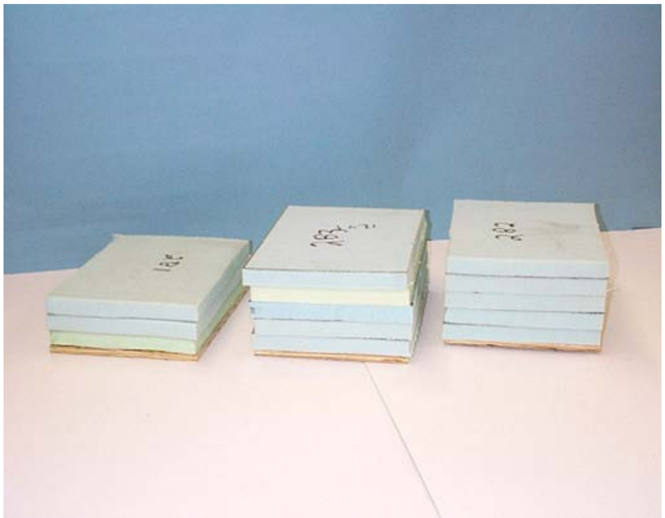

Figure 5.—Viscoelastic arrangements for the low-coal-seam shuttle car seat.

Figure 6.—NIOSH mid-coal-seam shuttle car seat.

Figure 7.—Viscoelastic arrangements for the mid-coal-seam shuttle car seat.

METHODOLOGY

Subjects

Eight shuttle car operators participated in the study; five operated the JOY 10SC and three operated the JOY 21SC. The operators were all males from 24 to 58 years of age and averaged about 39 years. They ranged in height from 69 to 73 inches (an average of 71 inches) and in weight from 160 to 200 lb (an average of about 191 lb). The subjects' experience in operating a shuttle car varied from to ½ to 24 years and averaged about 9 years. Similarly, their underground mining experience varied from ½ to 37 years and averaged 14 years. Moreover, before participating, the shuttle car operators were briefed about the study. Further, study participants were not coached, trained, or given practice sessions before the trials. They were briefly instructed about how to record their responses on the data forms and asked if they understood the instructions. Table 1 shows how the study was organized on the basis of seats, subjects, and test days.

Table 1.—Organization of seat trial days, seats, and subjects

Seat trials for low-coal-seam shuttle car: JOY 21SC					Seat trials for mid-coal-seam shuttle car: JOY 10SC						
Trial day No.	Seat design No.	Operator ID No., shift 1			Trial day No.	Seat design No.	Operator ID No., shift 1				
1	L1	O1	O2	O3	1.................	M1	O1	O2	O3	O4	O5
2	L2A	O1	O2	O3	2.................	M2A	O1	O2	O3	O4	O5
3	L2B	O1	O2	O3	3.................	M2B	O1	O2	O3	O4	O5
4	L2C	O1	O2	O3							

Procedure for Vibration Data Collection

Researchers gathered data to determine the acceleration and impact energy entering the shuttle car seats through the floor and vehicle frame. Data were gathered in operating sections at each mine using three different tools. Quantitative or objective data were collected using a Sony PC208Ax eight-channel digital recorder; PCB triaxial accelerometers – model Nos. 356B18 and 356B40; PCB 480E09 signal conditioning amplifiers; and PCB in-line, 150-Hz low-pass filters. The triaxial accelerometers were placed on the floor of the operators' compartment near the base of the seat (frame measurement) and on the seat at the subject/seat interface (seat measurement). Because of muddy conditions, the frame accelerometers were mounted to the frame of the shuttle car above the control panel. Mine roadway conditions during the field trials included areas that were deeply rutted and pothole-riddled, dry, wet and water-filled, and marginally "smooth."

Procedure for Subjective Data Collection

Half of the qualitative or subjective data were collected with the visual analog scale (VAS) (see Appendix A). This tool was used to obtain the operators' immediate impressions of shock, vibration, and discomfort levels for the vehicle ride on each of the seats and viscoelastic foam configurations. Operators were observed while tramming the shuttle cars when fully loaded with coal and when they were empty (en route to obtain a load). Each shuttle car operator made six round trips with each vehicle seat. The shuttle car operator marked this scale after traveling with and without a full load of coal on the first, third, and sixth round trips of each seat design trial. These round trip selections were deemed representative of typical roadway-induced vibration and lessened the influence of earlier ratings on the current rating. A round trip consisted of traveling to the coal face with no load and returning to the load discharge location with a full load of coal.

As such, the final ratings for each operator were the average of three out of the six round trips for each condition (of no-load and full-load). After each segment of the trip, participants were asked to rate the vehicle ride in terms of the level of jarring and jolting experienced through the selected seat.

The VAS consisted of a line about $3\frac{15}{16}$ inches long and terminated at each end by a vertical hash mark by two extremes of jarring/jolting level and level of discomfort. The two extremes were denoted as "zero or none" and "maximum." Operators were asked to make a vertical mark on the line that represents their level of perceived discomfort or jarring/jolting level. The rating scale was scored by measuring the distance (from left to right) from the beginning of the line to the operators' mark and dividing this value by the total length of the line. A decimal value was calculated for each rating and varied from 0.0 to 1.0. Each operator, unless otherwise indicated, rated levels of jarring and jolting and discomfort three times. These values were summed and averaged to obtain an average operator rating for the individual seats. In turn, the average operator ratings were summed and averaged to obtain a total average operator rating.

The remaining qualitative data were collected using a brief questionnaire administered through interviews with shuttle car operators. Researchers administered the questionnaire at the conclusion of each trial for each seat, which took approximately 5–10 minutes to complete. The questionnaire is shown in Appendix B.

RESULTS

Vehicle Jarring/Jolting Measurements

JOY 10SC Mid-coal-seam Shuttle Car

Data were taken on the side-saddle-style, mid-coal-seam shuttle car at the Laurel Alma mine in West Virginia. Figure 8 shows the instrumentation setup on this shuttle car. Five operators were tested on three seats (the existing seat (M1) and two test seats (M2A and M2B)) and the data sets were separated into full-load and no-load conditions. No information was collected for operator Nos. 3 and 5 on seat M2A due to other mining operation duties of these test subjects. Thus, from a possible 30 data sets, researchers obtained and analyzed a total of 26 data sets.

The data were initially examined according to RMS acceleration, peak acceleration, and crest factor. Ratios of input (frame) to output (seat) were used to normalize the data for different travel paths and operators. Averages were derived for each operator, load condition, and overall. Tables of these data are included in Appendix C.

Figure 8.—Instrument setup on the mid-coal-seam shuttle car seat.

The data from Table C–1 (see Appendix C) were further reduced by overall averaging of the operators for the no-load condition, with the results shown in Table C–2. Table 2 below compares each test seat with the existing seat under the no-load condition.

Table 2.—Existing seat versus NIOSH seats M2A and M2B: no-load comparison

Seat	Average ratio (output/input)			Seat comparison (1 vs. 2A or 2B)		
	Peak	RMS	Crest factor	Peak	RMS	Crest factor
M1..............	2.54	1.66	1.47	—	—	—
M2A	2.13	1.88	1.13	0.84	1.13	0.77
M2B	2.44	1.85	1.31	0.96	1.12	0.90

NOTE.—Peak and RMS are in m/s^2; crest factor is dimensionless.

Viewing the data and comparing with seat M1:

- Seat M2A showed a decrease in peak amplitude by 16% and crest factor by 23%, but an increase in RMS of 13%.
- Similarly, seat M2B showed a decrease in peak amplitude by 4% and crest factor by 10%, but an increase in RMS of 12%.

The data from Table C–1 were further reduced by overall averaging of the operators for the full-load condition, with the results shown in Table C–2. Table 3 compares each test seat with the existing seat under the full-load condition.

Table 3.—Existing seat versus NIOSH seats M2A and M2B: full-load comparison

Seat	Average ratio (output/input)			Seat comparison (1 vs. 2A or 2B)		
	Peak	RMS	Crest factor	Peak	RMS	Crest factor
M1	1.64	1.49	1.10	—	—	—
M2A	2.13	1.78	1.20	1.30	1.20	1.09
M2B	2.48	1.89	1.32	1.52	1.27	1.20

NOTE.—Peak and RMS are in m/s^2; crest factor is dimensionless.

Viewing the data and comparing with seat M1:

- Seat M2A showed increases in peak amplitude, RMS, and crest factor by 30%, 20%, and 9%, respectively.
- Similarly, seat M2B showed increases in peak amplitude, RMS, and crest factor by 52%, 27%, and 20%, respectively.

The data from Table C–1 were further reduced by averaging over all the operators for both load conditions, with the results shown in Table C–3. Table 4 below compares each test seat with the existing seat overall.

Table 4.—Existing seat versus NIOSH seats M2A and M2B: overall comparison

Seat	Average ratio (output/input)			Seat comparison (1 vs. 2A or 2B)		
	Peak	RMS	Crest factor	Peak	RMS	Crest factor
M1	2.09	1.57	1.28	—	—	—
M2A	2.13	1.83	1.17	1.02	1.16	0.91
M2B	2.46	1.87	1.32	1.18	1.19	1.03

NOTE.—Peak and RMS are in m/s^2; crest factor is dimensionless.

Viewing the data and comparing with seat M1:

- Seat M2A showed an increase in peak amplitude and RMS by 2% and 16%, respectively, but a decrease in the crest factor of 9%.
- Seat M2B showed increases in peak amplitude, RMS, and crest factor by 18%, 19%, and 3%, respectively.

JOY 21SC Low-coal-seam Shuttle Car

Data were taken on the JOY 21SC at the Black King Mine in West Virginia. Figure 9 shows the instrumentation setup on this low-coal shuttle car. Three operators were tested on four seats (the existing seat (L1) and three test seats (L2A, L2B, and L2C)), and the data sets were separated into full-load and no-load conditions. No information could be salvaged from operator 1 on seat L2C owing to excessive battery bounce in the data recorder caused by a very rough ride. Thus, from a possible 24 data sets, researchers obtained and analyzed a total of 22 data sets.

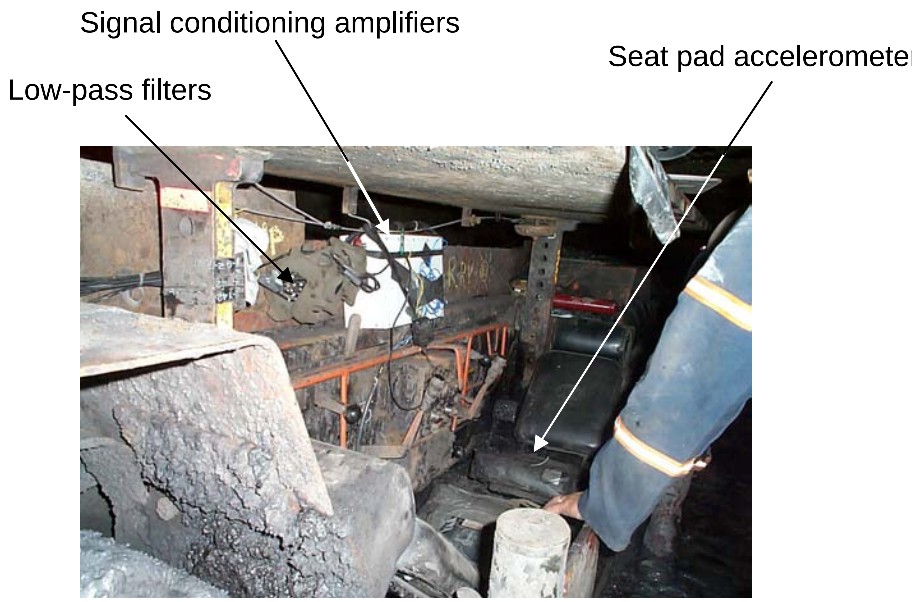

Figure 9.—Instrument setup on the low-coal-seam shuttle car seat.

The data were first examined by RMS acceleration, peak acceleration, and crest factor. Ratios of input (frame) to output (seat) were used to normalize the data for different travel paths and operators (see Table C–4 in Appendix C). The data were also examined using an autopower spectrum and transmissibility methods.

The data from Table C–4 were further reduced by overall averaging of the operators for the no-load condition, with the results shown in Table C–5. Table 5 below compares each test seat with the existing seat under the no-load condition.

Table 5.—Existing seat versus NIOSH seats L2A, L2B, and L2C: no-load comparison

Seat	Average ratio (output/input)			Seat comparison (1 vs. 2A, 2B, or 2C)		
	Peak	RMS	Crest factor	Peak	RMS	Crest factor
L1	1.29	1.27	1.02	—	—	—
L2A	1.00	1.14	0.88	0.77	0.90	0.86
L2B	1.11	1.18	0.94	0.86	0.93	0.92
L2C	1.19	1.16	1.02	0.92	0.92	1.00

NOTE.—Peak and RMS are in m/s^2; crest factor is dimensionless.

Viewing the data and comparing with seat L1:

- Seat L2A showed decreases in peak amplitude, RMS, and crest factor by 23%, 10%, and 14%, respectively.
- Seat L2B showed decreases in peak amplitude, RMS, and crest factor by 14%, 7%, and 8%, respectively.
- Seat L2C showed decreases in both peak amplitude and RMS by 8% and no change in the crest factor.

The data from Table C–4 were further reduced by overall averaging of the operators for the full-load condition, with the results shown in Table C–5. Table 6 below compares each test seat with the existing seat under the full-load condition.

Table 6.—Existing seat versus NIOSH seats L2A, L2B, and L2C: full-load comparison

Seat	Average ratio (output/input)			Seat comparison (1 vs. 2A, 2B, or 2C)		
	Peak	RMS	Crest factor	Peak	RMS	Crest factor
L1	1.21	1.13	1.06	—	—	—
L2A	1.17	1.14	1.03	0.97	1.00	0.97
L2B	1.43	1.32	1.08	1.18	1.16	1.02
L2C	1.31	1.25	1.04	1.08	1.10	0.99

NOTE.—Peak and RMS are in m/s^2; crest factor is dimensionless.

Viewing the data and comparing with seat L1:

- Seat L2A showed decreases in both peak amplitude and crest factor by 3% and no change in RMS.
- Seat L2B showed increases in peak amplitude, RMS, and crest factor by 18%, 16%, and 2%, respectively.
- Seat L2C showed increases in peak amplitude and RMS by 8% and 10%, respectively, but a decrease in the crest factor of 1%.

The data from Table C–4 were further reduced by overall averaging of the operators for both load conditions, with the results shown in Table C–6. Table 7 below compares each test seat with the existing seat overall.

Table 7.—Existing seat versus NIOSH seats L2A, L2B, and L2C: overall comparison

Seat	Average ratio (output/input)			Seat comparison (1 vs. 2A, 2B, or 2C)		
	Peak	RMS	Crest factor	Peak	RMS	Crest factor
L1	1.25	1.20	1.04	—	—	—
L2A	1.08	1.14	0.95	0.87	0.95	0.91
L2B	1.27	1.25	1.01	1.02	1.04	0.97
L2C	1.25	1.21	1.03	1.00	1.00	0.99

NOTE.—Peak and RMS are in m/s^2; crest factor is dimensionless.

Viewing the data and comparing with seat L1:

- Seat L2A showed decreases in peak amplitude, RMS, and crest factor by 13%, 5%, and 9%, respectively.
- Seat L2B showed increases in peak amplitude and RMS by 2% and 4%, respectively, but a decrease in the crest factor of 3%.
- Seat L2C showed no change in peak amplitude and RMS and a slight decrease in the crest factor of 1%.

Subjective Evaluation: VAS

Tables 8 and 9 illustrate the average and total average ratings for the shuttle car operators of the JOY 10SC mid-coal-seam and JOY 21SC low-coal-seam shuttle cars, respectively.

Table 8.—Total average ratings for mid-coal-seam JOY 10SC shuttle car operators

Seat	Average operator ratings					Total average value
	ID No. 1	ID No. 2	ID No. 3	ID No. 4	ID No. 5	
NO LOAD						
M1 - Existing seat:						
Level of jar/jolt	0.869	0.769	0.788	0.825	0.457	0.742
Level of discomfort	0.866	0.750	0.859	0.859	0.358	0.738
M2A - NIOSH seat (5-in XSS):						
Level of jar/jolt	0.093	0.115	ND	0.046	ND	0.085
Level of discomfort	0.112	0.140	ND	0.028	ND	0.093
M2B - NIOSH seat (5-in XSS/PU):						
Level of jar/jolt	0.648	0.068	0.922	0.062	0.461	0.432
Level of discomfort	0.632	0.031	0.601	0.021	0.383	0.334
FULL LOAD						
M1 - Existing seat:						
Level of jar/jolt	0.725	0.834	0.872	0.429	0.398	0.652
Level of discomfort	0.719	0.863	0.881	0.563	0.302	0.666
M2A - NIOSH seat (5-in XSS):						
Level of jar/jolt	0.037	0.133	ND	0.012	ND	0.061
Level of discomfort	0.031	0.205	ND	0.025	ND	0.087
M2B - NIOSH seat (5-in XSS/PU):						
Level of jar/jolt	0.598	0.115	0.934	0.050	0.423	0.424
Level of discomfort	0.595	0.034	0.810	0.009	0.380	0.366

XSS Extra-soft SunMate. PU Pudgee. ND No data.

Table 9.—Total average ratings for low-coal-seam JOY 21SC shuttle car operators

Seat	Average operator ratings			Total average value
	ID No. 1	ID No. 2	ID No. 3	
NO LOAD				
L1 - Existing seat:				
Level of jar/jolt	0.769	0.152	0.264	0.395
Level of discomfort	0.451	0.189	0.476	0.372
L2A - NIOSH seat (3-in XSS/PU):				
Level of jar/jolt	0.460	0.056	0.458	0.325
Level of discomfort	0.040	0.831	0.442	0.438
L2B - NIOSH seat (5-in XSS):				
Level of jar/jolt	0.274	0.012	0.224	0.170
Level of discomfort	0.009	0.959	0.221	0.396
L2C - NIOSH seat (5-in XSS/PU):				
Level of jar/jolt	0.619	0.025	0.174	0.273
Level of discomfort	0.056	0.657	0.189	0.301
FULL LOAD				
L1 - Existing seat:				
Level of jar/jolt	0.560	0.297	0.442	0.433
Level of discomfort	0.135	0.127	0.408	0.223
L2A - NIOSH seat (3-in XSS/PU):				
Level of jar/jolt	0.230	0.046	0.233	0.170
Level of discomfort	0.028	0.869	0.233	0.377
L2B - NIOSH seat (5-in XSS):				
Level of jar/jolt	0.068	0.025	0.068	0.054
Level of discomfort	0.012	0.968	0.053	0.344
L2C - NIOSH seat (5-in XSS/PU):				
Level of jar/jolt	0.407	0.031	0.130	0.189
Level of discomfort	0.025	0.959	0.108	0.364

XSS Extra-soft SunMate. PU Pudgee.

From Tables 8–9, the following observations were made:

Ratings from VAS responses indicate that the NIOSH-designed seats performed better than the existing seats used in the shuttle cars.

- For both no-load and full-load conditions, mid-coal-seam shuttle cars operators rated lower levels of jarring/jolting and discomfort with the NIOSH seat using two different 5-in viscoelastic foam pad arrangements.
- The viscoelastic foam arrangement with five 1-in layers of XSS foam padding was the most preferred by operators of the mid-seam shuttle car.
- Similarly, for no-load and full-load conditions, low-seam shuttle car operators rated jarring/jolting as lower with the NIOSH seat using three different viscoelastic foam pad arrangements. The viscoelastic foam arrangements, in order of operator preference, were the 5-in XSS, 3-in PU/XSS, and 5-in PU/XSS padding.
- However, under no-load and full-load conditions for the low-seam shuttle car, operators rated discomfort levels as lower with the existing seat versus the NIOSH seat using three different viscoelastic foam pad arrangements. Because researchers had to use existing bolt holes to install the NIOSH seat, the seat was closer to the control panel and made the shuttle car operators feel awkward and cramped.

Moreover, a strong positive correlation for jarring/jolting and discomfort was determined for the different seats tested on the mid-seam JOY 10SC shuttle car. The following results were obtained:

- A strong positive correlation (between jar/jolt and discomfort) was obtained for seat M1 (no load, $r = 0.89$; full load, $r = 0.93$).
- A strong positive correlation (between jar/jolt and discomfort) was obtained for seat M2A (no load, $r = 0.71$; full load, $r = 0.90$).
- A strong positive correlation (between jar/jolt and discomfort) was obtained for seat M2B (no load, $r = 0.94$; full load, $r = 0.97$).

All of the above correlations for the mid-seam shuttle car showed a significant relationship between the variables of jolting/jarring and discomfort ($P \leq 0.05$).

A weak-to-strong positive correlation (for jar/jolt and discomfort) was realized for the different seats tested on the low-seam JOY 21SC shuttle car ($P \leq 0.05$). The following results were obtained:

- A weak positive correlation (between jar/jolt and discomfort) was obtained for seat L1 (no load, $r = 0.29$; full load, $r = 0.66$).
- A strong positive correlation (between jar/jolt and discomfort) was obtained for seat L2A (no load, $r = 0.84$; full load, $r = 0.88$).
- A strong positive correlation (between jar/jolt and discomfort) was obtained for seat L2B (no load, $r = 0.88$; full load, $r = 0.69$).
- A moderate positive correlation (between jar/jolt and discomfort) was obtained for seat L2C (no load, $r = 0.58$; full load, $r = 0.73$).

Subjective Evaluation: Operator Questionnaire

Appendix B contains the questionnaire used to collect the data. The questions investigate the shuttle car operators' comfort in relation to vibration or shock; operators' opinions about seat padding and lumbar support; operators' likes, dislikes, and suggested improvements concerning each seat; and the operators' summary comparison of the seats. The questions are listed as follows:

1. How would you rate this seat in terms of comfort?
2. How would you rate this seat relative to reducing shock and vibration?
3. What do you like about this seat?
4. What don't you like about this seat?
5. Rate the following: seat padding, lumbar support, reclining seatback, seat-pan tilt, armrest, fore-aft adjustment
6. What would you do to improve this seat?
7. Compare seat No. 1 with seat No. 2.

Figures 10–15 present graphical displays of the operators' responses to these questions.

JOY 10SC Mid-coal-seam Shuttle Car

Figure 10 shows seat ratings regarding comfort and jarring/jolting (shock/vibration) reduction. Figure 11 shows seat ratings for seat padding and lumbar support. Both figures show that seat M2A was rated highest in comfort, vibration reduction, seat padding, and lumbar support.

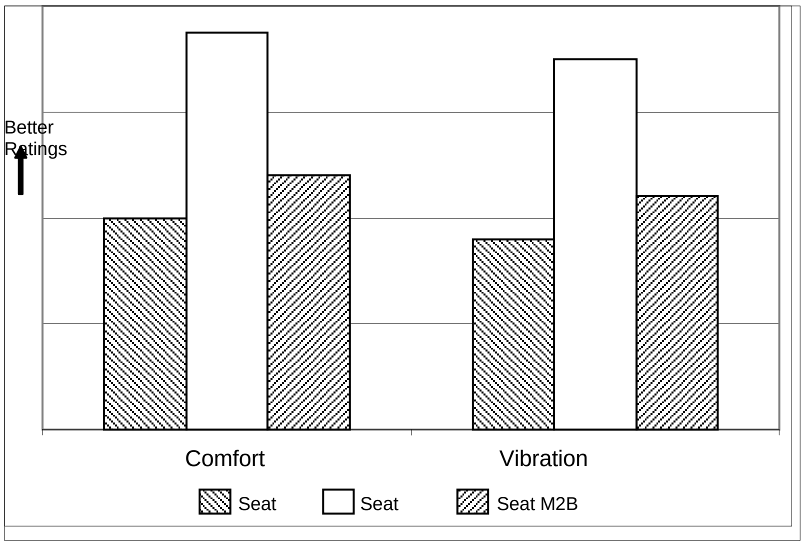

Figure 10.—Seat ratings of mid-coal-seam shuttle car operators on comfort and vibration reduction.

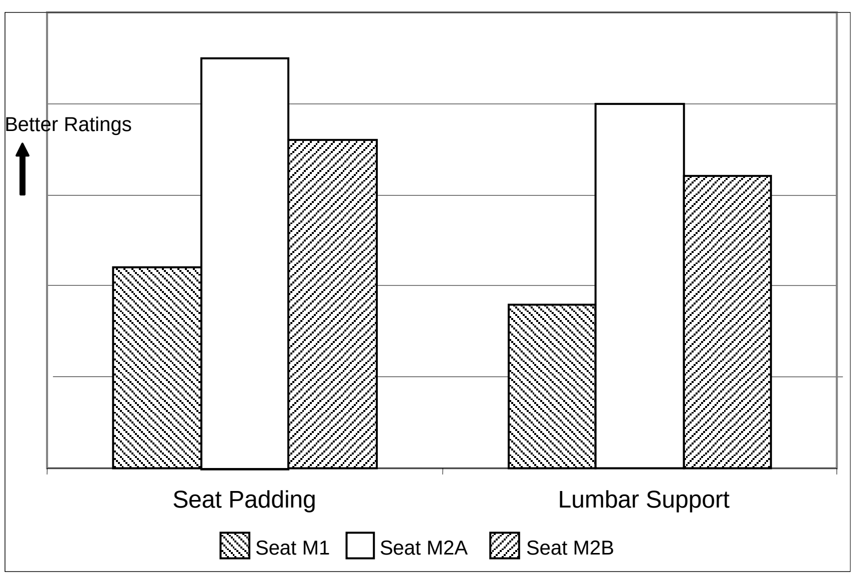

Figure 11.—Seat ratings of mid-coal seam shuttle car operators on seat padding and lumbar support.

Seat M1 ranked the lowest in comfort, vibration reduction, seat padding, and lumbar support; however, one operator liked its comfort and another liked the way the body fit the seat frame. "Partly broken," "weak," and "no comfort" were the leading dislikes expressed for seat M1. Suggested improvements to seat M1 included adding armrests and removing and replacing the seat with the original one.

Seat M2A was ranked most favorable. Operators liked the seats ability to absorb vibration/jars and its good support to the back, and the seat felt comfortable. The seat was apparently too low for good visibility, and seat placement caused the controls to be too close. Adding armrests and improved seat location were the major suggestion to improve seat M2A.

Seat M2B was ranked second (see Figures 10–11). Operators liked the seat comfort and firmness, but disliked the way it absorbed shock and found the back support too stiff. Operators offered several suggestions to improve seat M2B, such as making the seat softer, adding armrests, and improving the lumbar support.

Figure 12 shows the seat comparisons. The ratings reflect how the seats felt to the operator in comparison to each other. Seat M2A was the favorite. Seat padding rated well for both seats M2A and M2B. Individual ratings in Figures 10–11 compare favorably to the findings in Figure 12. Seat M1 (the existing seat) was the least favorite in all ratings. Adding armrests was the improvement most often suggested for all of the seats.

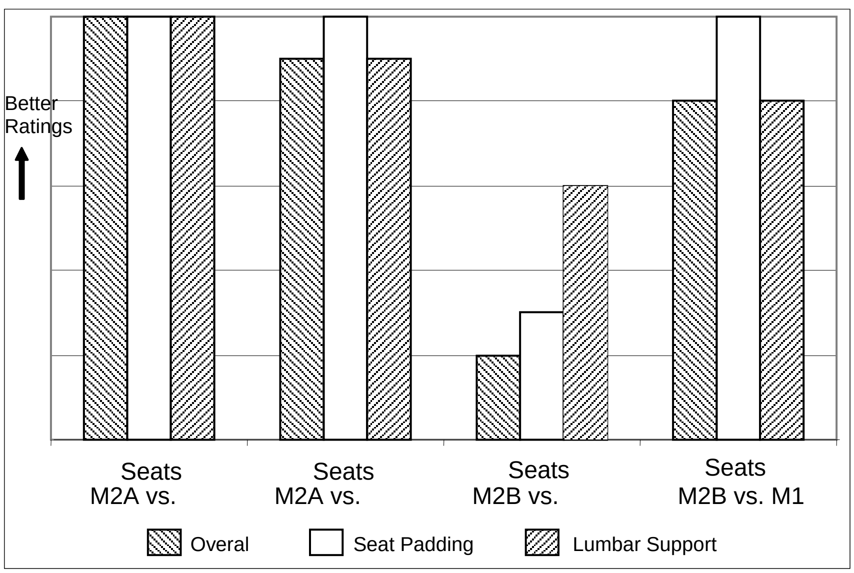

Figure 12.—Mid-coal-seam shuttle car operators' comparisons and ratings of seats for padding and lumbar support.

JOY 21SC Low-coal-seam Shuttle Car

Figure 13 shows seat ratings regarding comfort and shock/vibration reduction. Figure 14 shows seat ratings for seat padding and lumbar support. Both figures show that seat L2B was rated highest in comfort, vibration reduction, seat padding, lumbar support, and seat-pan tilt.

Seat L1 (the existing seat) ranked the lowest in seat comfort and vibration reduction. Operators liked how the seat reduced jars and jolts, and one operator thought it was fairly comfortable. However, operators disliked its durability and the lumbar was too thick. Suggestions to improve the seats were to make the back support better, improve adjustments for better visibility, and improve padding. Seat L1 did not have seat-pan tilt or fore-aft adjustment.

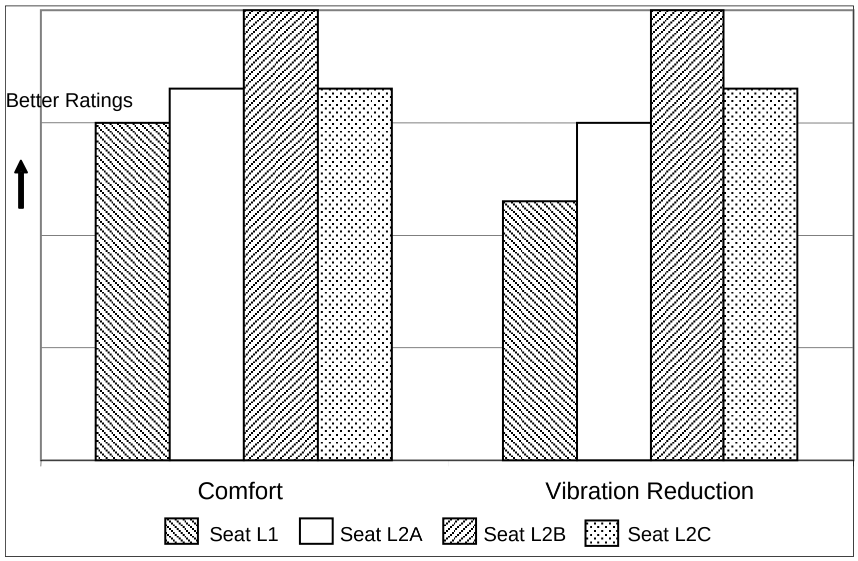

Figure 13.—Low-coal-seam shuttle car operators' ratings of seat designs for comfort and vibration reduction.

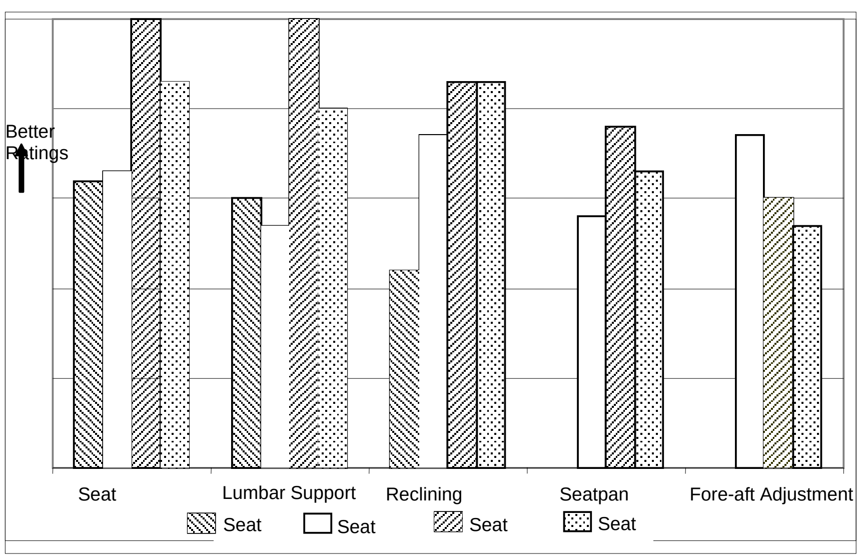

Figure 14.—Low-coal-seam shuttle car operators' ratings of seat designs for different seat features.

Seats L2A and L2B ranked well in comfort and vibration reduction. Operators liked how seat L2A took the strain off the lower back when the shuttle car traveled across large holes. Also, operators liked the thick cushion on seat L2A and how the seat adjusts to the body. For seat L2B, operators liked how comfortable it felt, how it reduced shocks, and its thick cushion. However, both seats were too close to the controls and did not fit the confined space of the shuttle car. Regarding seat L2B, operators found that they drove the shuttle car slower to avoid being bounced into the canopy. Suggested improvements for seats L2A and L2B were to make the lumbar seat wider. One operator suggested improving the operators' control panel envelope to accommodate better seats, such as seat L2B.

Seat L2C was the favorite. Operators liked the padding, how well it reduced shock, how well the lumbar support took the strain off the back, and how comfortable the seat was. However, operators did not like the lumbar width. Also, the seat was too large for the confined space of the shuttle car. Suggested improvements for seat L2C were to make the lumbar support and seat wider and to add a scaled-down seat to fit better behind the controls.

Figure 15 shows the seat comparisons. Individual ratings in Figures 13–14 favor seat L2C, while the comparison ratings favor seat L2B. Seat L1 is the least favorite in all ratings. Seat padding, lumbar support, and seat-pan tilt are rated better for seat L2B than any other seat. The reclining back is better on seat L2B and surprisingly favored on seat L1. Making the seat a better fit for the operator compartment is a suggested improvement. This could improve clearance between the operator and controls and allow for better operator adjustability and visibility.

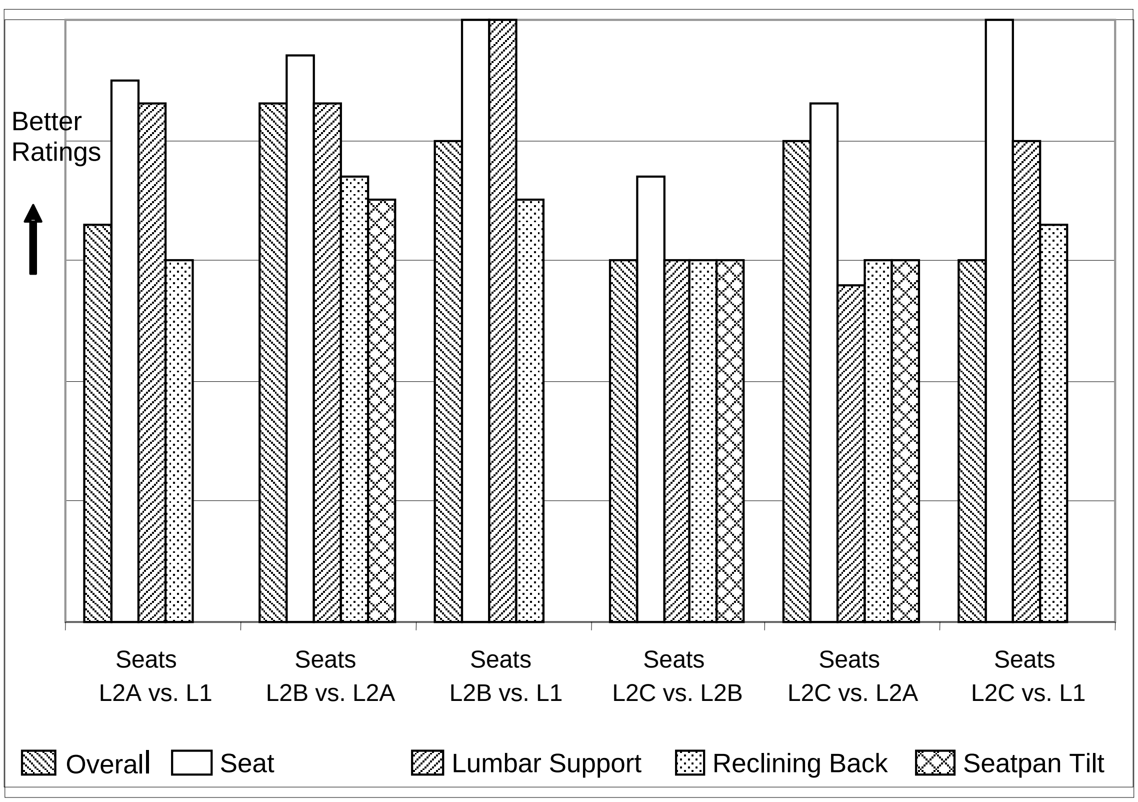

Figure 15.—Low-coal seam shuttle car operators' comparisons and ratings of seat designs for different seat features.

COMPARISON OF ISO 2631 FATIGUE-DECREASED PROFICIENCY LIMITS WITH RECORDED DATA AND QUESTIONNAIRE DATA

Researchers compared the International Organization for Standardization (ISO) 2631 fatigue-decreased proficiency (FDP) limits from the ACGIH [2006] for the objective and subjective data discussed above. Again, it is important to note that the shuttle car operator receives the roughest ride when traveling with no-load. Acceleration levels tend to be higher during no-load conditions since the shuttle car has less mass while maintaining the same spring rate and damping. The natural frequency of the vehicle shifts higher in the no-load condition and lower in the full-load condition, as shown by the equation—

$$\omega = \sqrt{k/m} \tag{1}$$

where ω = natural frequency;
k = spring constant;
and m = mass.

Researchers compiled Tables 10–12 to show how the FDP limits correlated with the results obtained from measured levels of vehicle jarring/jolting and questionnaire responses for the different vehicle operators and seats designs. Table 10 provides data for the JOY 10SC and JOY 21SC shuttle cars when operating under no-load conditions. For the JOY 10SC, seat M2A showed 57% better performance in FDP, 30% better performance in crest factor, and 47% better overall performance when rated by the operators. Seat M2B showed 60% better performance in FDP, 12% better performance in crest factor, and 17% better overall performance when rated by the operators. Figure 16 is an example of FDP curves for the JOY 10SC mid-coal-seam shuttle car during no-load operation with NIOSH seat M2B.

For the JOY 21SC, seat L2A showed 45% better performance in FDP, 16% better performance in crest factor, and 9% better performance overall when rated by the operators. Seat L2B showed 46% better performance in FDP, 9% better performance in crest factor, and 25% better overall performance when rated by the operators. Seat L2C showed 77% better performance in FDP, no change in crest factor, and 9% better overall performance when rated by the operators. Figure 17 is an example of FDP curves for the JOY 21SC low-coal-seam shuttle car during no-load operation with NIOSH seat L2C.

Table 11 lists data for the JOY 10SC and JOY 21SC shuttle cars when operating under full-load conditions. For the JOY 10SC, seat M2A showed 143% worse performance in FDP, 8% worse performance in crest factor, and 47% better overall performance when rated by the operators. Seat M2B showed 194% worse performance in FDP, 17% worse performance in crest factor, and 17% better overall performance when rated by the operators.

For the JOY 21SC, seat L2A showed 31% better performance in FDP, 3% better performance in crest factor, and 9% better overall performance when rated by the operators. Seat L2B showed 63% better performance in FDP, 2% worse performance in crest factor, and 25% better overall performance when rated by the operators. Seat L2C showed 57% better performance in FDP, 2% better performance in crest factor, and 9% better overall performance when rated by the operators.

Overall data for both full- and no-load conditions are shown in Table 12. For the JOY 10SC, seat M2A showed 4% worse performance in FDP, 9% better performance in crest factor, and 47% better overall performance when rated by the operators. Seat M2B showed 3% worse performance in FDP, 3% worse performance in crest factor, and 17% better overall performance when rated by the operators.

For the JOY 21SC, seat L2A showed 37% better performance in FDP, 9% better performance in crest factor, and 9% better overall performance when rated by the operators. Seat L2B showed 59% better performance in FDP, 3% better performance in crest factor, and 25% better overall performance when rated by the operators. Seat L2C showed 67% better performance in FDP, 1% better performance in crest factor, and 9% better overall performance when rated by the operators.

Table 10.—Comparison of FDP limit values with crest factor and vehicle operator questionnaire ratings relative to improved performance for no-load conditions

Seat	Fatigue decreased, min	Crest factor	Questionnaire (rating)
NO LOAD - JOY 10SC			
M1	76.00	1.47	2.00
M2A	175.67	1.13	3.75
M2B	190.40	1.31	2.40
NO LOAD - JOY 21SC			
L1	32.33	1.02	3
L2A	59	0.88	3.3
L2B	59.33	0.94	4
L2C	139.5	1.02	4.3
NO-LOAD COMPARISON - JOY 10SC (percent better than seat M1)			
M1	—	—	—
M2A	56.74	30.09	46.67
M2B	60.08	12.21	16.67
NO-LOAD COMPARISON - JOY 21SC (percent better than seat L1)			
L1	—	—	—
L2A	45.20	15.91	9.09
L2B	45.51	8.51	25.00
L2C	76.82	0.00	9.09

NOTE.—Crest factor is dimensionless. Higher values for "questionnaire" and "fatigue decreased" indicate better results, whereas lower values for "crest factor" indicate better results.

Table 11.—Comparison of FDP limit values with crest factor and vehicle operator questionnaire ratings relative to improved performance for full-load conditions

Seat	Fatigue decreased, min	Crest factor	Questionnaire (rating)
FULL LOAD - JOY 10SC			
M1...............	185	1.1	2
M2A	76	1.2	3.75
M2B	63	1.32	2.4
FULL LOAD - JOY 21SC			
L1................	60.33	1.06	3
L2A	88	1.03	3.3
L2B	165	1.08	4
L2C	139.5	1.04	3.3
FULL-LOAD COMPARISON - JOY 10SC (percent better than seat M1)			
M1...............	—	—	—
M2A	–143.42	–8.33	46.67
M2B	–193.65	–16.67	16.67
FULL-LOAD COMPARISON - JOY 21SC (percent better than seat L1)			
L1................	—	—	—
L2A	31.44	2.91	9.09
L2B	63.44	–1.85	25.00
L2C	56.75	1.92	9.09

NOTE.—Crest factor is dimensionless. Higher values for "questionnaire" and "fatigue decreased" indicate better results, whereas lower values for "crest factor" indicate better results.

Table 12.—Comparison of FDP limit values with crest factor and vehicle operator questionnaire ratings relative to improved performance for full- and no-load conditions combined

Seat	Fatigue decreased, min	Crest factor	Questionnaire (rating)
OVERALL - JOY 10SC			
M1	130.8	1.28	2
M2A	125.83	1.17	3.75
M2B	126.7	1.32	2.4
OVERALL - JOY 21SC			
L1	46.33	1.04	3
L2A	73.5	0.95	3.3
L2B	112.17	1.01	4
L2C	139.5	1.03	3.3
OVERALL COMPARISON - JOY 10SC (percent better than seat M1)			
M1	—	—	—
M2A	–3.95	9.40	46.67
M2B	–3.24	–3.03	16.67
OVERALL COMPARISON - JOY 21SC (percent better than seat L1)			
L1	—	—	—
L2A	36.97	9.47	9.09
L2B	58.70	2.97	25.00
L2C	66.79	0.97	9.09

NOTE.—Crest factor is dimensionless. Higher values for "questionnaire" and "fatigue decreased" indicate better results, whereas lower values for "crest factor" indicate better results.

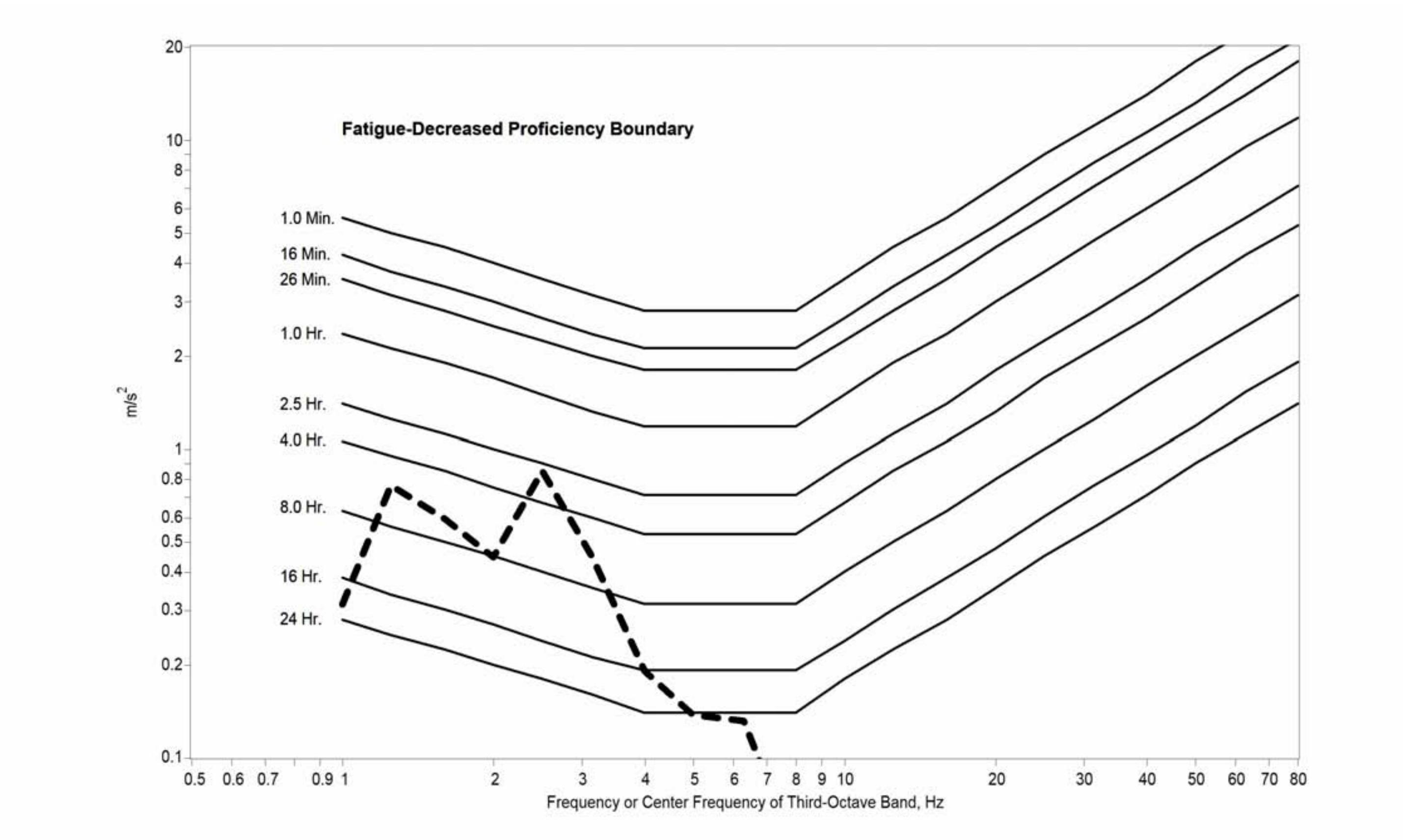

Figure 16.—Fatigue-decreased proficiency curves for mid-coal-seam shuttle car with NIOSH seat M2B during no-load vehicle operations.

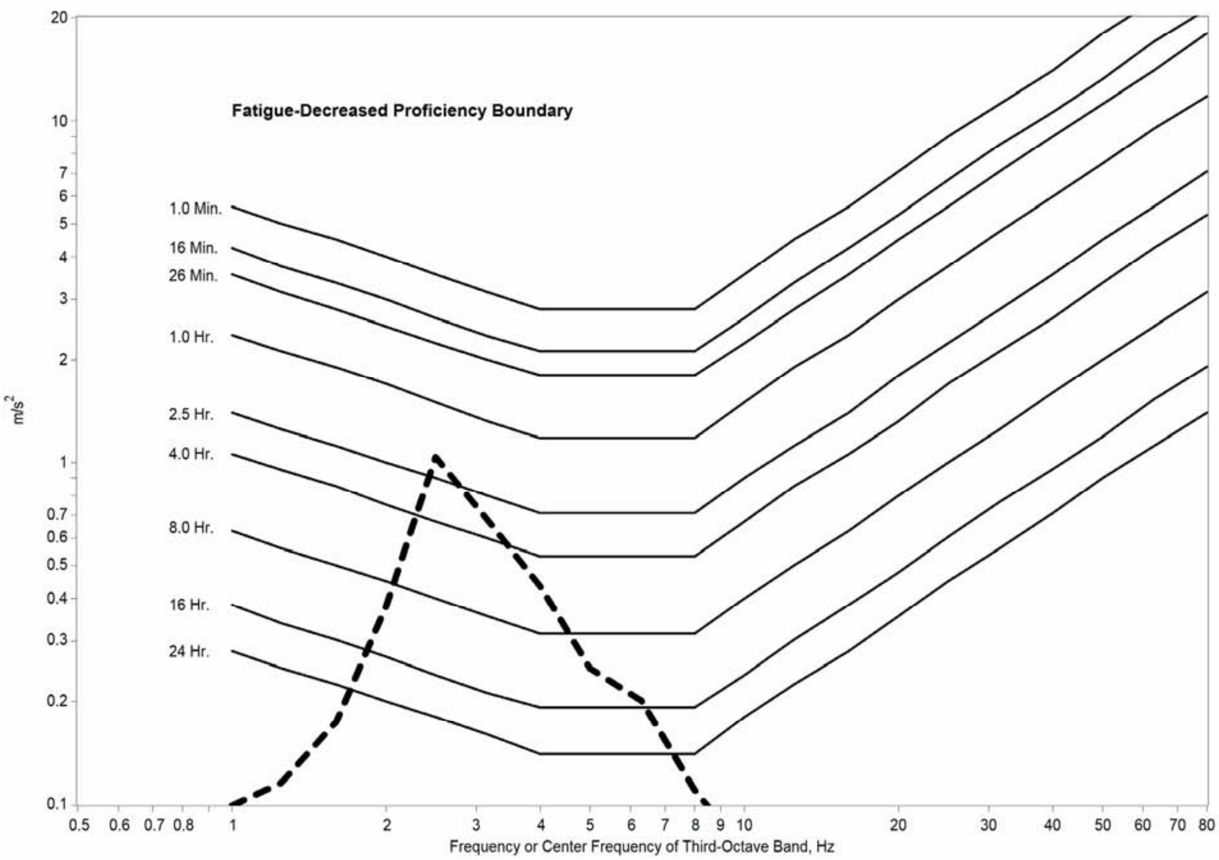

Figure 17.—Fatigue-decreased proficiency curves for low-coal-seam shuttle car with NIOSH seat L2C during no-load vehicle operations.

DISCUSSION

Average ratings from VAS responses indicated that the NIOSH-designed seats were superior to the existing seats used in the shuttle cars. For both no-load and full-load conditions, average ratings by operators of mid-coal-seam shuttle cars indicated lower levels of jarring/jolting and discomfort with the NIOSH seat using two different 5-in viscoelastic foam pad arrangements. The 5-in XSS viscoelastic foam arrangement (seat M2A) was most preferred by operators of the mid-coal-seam shuttle car.

Similarly, for no-load and full-load conditions, average ratings by low-coal-seam shuttle car operators showed lower jarring/jolting with the NIOSH seat using three different viscoelastic foam pad arrangements. The viscoelastic foam arrangements, in order of operator preference, were the 5-in XSS (seat L2B), 3-in PU/XSS (seat L2A), and 5-in PU/XSS foam padding (seat L2C). Nevertheless, with regard to overall levels of discomfort, the average operator rating favored the existing seat over the NIOSH seat with the three different viscoelastic foam pad arrangements under both full-load and no-load conditions. Researchers had to install the NIOSH seat using existing bolt holes, which caused the seat to be closer to the control panel and made the shuttle car operators feel awkward and cramped. Also, seats L2B and L2C (the 5-in foam pads) caused the operators to be closer to the canopy.

With regard to the mid-coal-seam vehicles, according to Table 13, NIOSH seat M2A showed 16% and 23% reductions in peak acceleration and crest factor, respectively. Seat M2A, however, showed a 13% increase for RMS acceleration. Similarly, seat M2B showed 4% and 11% reductions in peak acceleration and crest factor, respectively, and an 11% increase in RMS acceleration. Nevertheless, NIOSH researchers consider RMS acceleration the *least descriptive* of the three measurement parameters in terms of jarring/jolting events for vehicle operators. The reason is that RMS acceleration reflects a greater time period and includes acceleration levels far lower than those of peak acceleration, which includes a very short time period and a much higher level of energy. With its short time period and higher level, the peak acceleration (the jar/jolt) is perceived by vehicle operators as having a more profound impact on them in terms of comfort and health.

Better results were obtained with NIOSH-designed seats for the low-coal-seam vehicle. NIOSH seat L2A showed 22% and 14% reductions in peak acceleration and crest factor, respectively. Moreover, seat L2A reduced RMS acceleration by 10%. Similarly, seat L2B showed 14% and 8% reductions in peak acceleration and crest factor, respectively, and a 7% reduction for RMS acceleration. Finally, seat L2C showed 8% and 9% reductions in peak acceleration and RMS acceleration, respectively, with no change in crest factor.

With regard to the mid-coal-seam shuttle car, seat M2A showed 57% better performance in FDP, 30% better performance in crest factor, and 47% better overall performance when rated by the operators. Seat M2B showed 60% better performance in FDP, 12% better performance in crest factor, and 17% better overall performance when rated by the operators.

Similarly, with regard to the low-coal-seam shuttle car, seat L2A showed 31% better performance in FDP, 3% better performance in crest factor, and 9% better overall performance when rated by the operators. Seat L2B showed 63% better performance in FDP, 2% worse performance in crest factor, and 25% better overall performance when rated by the operators. Seat L2C showed 57% better performance in FDP, 2% better performance in crest factor, and 9% better overall performance when rated by the operators.

Tables 13–14 show the results of the analysis for VAS and unweighted measured data. The percentages in these tables were obtained from averages and, consequently, as in the case of the measured data, they may not necessarily result in the same values that are computed from a single set of the stated measured parameters. The VAS ratings showed that vehicle operators rated overall (on average from three test trial ratings) the NIOSH-designed seats better than the existing seats. For the mid-coal-seam shuttle car, under no-load (worse case of two) conditions, operators rated the level of jarring/jolting 31%–66% lower and level of discomfort 40%–65% lower with the M2A and M2B seats. For the low-coal-seam shuttle car, under no-load conditions, operators rated the level of jarring/jolting 7%–23% lower with the L2A, L2B, and L2C seats. In addition, operators rated the level of discomfort 7% lower with seat L2C, but 2%–7% higher with the L2A and L2B seats.

Table 13.—Perceived and measured reductions in discomfort and jarring/jolting levels for operators of the JOY 10SC mid-coal-seam shuttle car (no load)

Seat	Perceived reduction in—		Measured reduction in jarring/jolting		
	Discomfort, %	Jarring/ jolting, %	Peak *a*, %	RMS *a*, %	Crest factor, %
M1 - Existing seat	—	—	—	—	—
M2A - NIOSH seat (5-in XSS)................	65	66	16	[1]13	23
M2B - NIOSH seat (5-in XSS/PU)..........	40	31	4	[1]11	11

a = acceleration
[1]Increase instead of reduction.

Table 14.—Perceived and measured reductions in discomfort and jarring/jolting levels for operators of the JOY 21SC low-coal-seam shuttle car (no load)

Seat	Perceived reduction in—		Measured reduction in jarring/jolting		
	Discomfort, %	Jarring/ jolting, %	Peak *a*, %	RMS *a*, %	Crest factor, %
L1 - Existing seat	—	—	—	—	—
L2A - NIOSH seat (3-in XSS/PU)...........	[1]7	7	22	10	14
L2B - NIOSH seat (5-in XSS).................	[1]2	23	14	7	8
L2C - NIOSH seat (5-in XSS/PU)...........	7	12	8	9	0

a = acceleration
[1]Increase instead of reduction.

The quantitative levels of vehicle jarring/jolting for no-load conditions showed that the NIOSH M2A and M2B seats for the mid-coal-seam shuttle car performed better than the existing seat in terms of peak acceleration and crest factor, whereas the L2A, L2B, and L2C seats performed better than the existing seat in terms of peak acceleration, RMS acceleration, and crest factor. During full-load conditions, the foam- or air-filled tires provided primary damping or attenuation of jars/jolts as a result of the extra mass from the load of coal. The performance of the seat in providing this attenuation of jars/jolts is thus secondary. However, the extra mass is lacking under no-load conditions and allows for more severe levels of jarring/jolting for the shuttle car operators. Consequently, it is significant that the NIOSH-designed seats performed better than the existing seats when comparing average values for peak acceleration, RMS acceleration, and crest factor.

With the mid-coal-seam vehicles, NIOSH seat M2A showed 16% and 23% reductions in peak acceleration and crest factor, respectively. Seat M2A, however, showed a 13% increase for RMS acceleration. Similarly, seat M2B showed 4% and 11% reductions in peak acceleration and crest factor, respectively, and an 11% increase in RMS acceleration. Again, NIOSH researchers consider RMS acceleration the *least descriptive* of the three measurement parameters in terms of jarring/jolting events for vehicle operators. The reason is that RMS acceleration reflects a greater time period and includes acceleration levels far lower than those of peak acceleration, which includes a very short time period and a much higher level of energy. With its short time period and higher level, the peak acceleration (the jar/jolt) is perceived by vehicle operators as having a more profound impact on them in terms of comfort and health.

Even better results were obtained with the NIOSH-designed seats for the low-coal-seam vehicle. NIOSH seat L2A showed 22% and 14% reductions in peak acceleration and crest factor, respectively. Moreover, seat L2A reduced RMS acceleration by 10%. Similarly, seat L2B showed 14% and 8% reductions in peak acceleration and crest factor, respectively, and also a 7% reduction for RMS acceleration. Finally, seat L2C showed 8% and 9% reductions in peak acceleration and RMS acceleration, respectively, with no change in crest factor.

The concepts of peak acceleration, RMS acceleration, and crest factor as a means for assessing vehicle jarring/jolting exposure were used in the data analysis. These analytical parameters, although descriptive as presented in ISO 2631 (1985)- and American National Standards Institute (ANSI) (1979)-based TLVs of the ACGIH [2006], do not seem to completely address the true impact on the body sustained by seated vehicle operators when they are subjected to vehicle jarring and jolting. The method assesses the effects of environmental vibration on the human body relative to health, efficiency, and comfort. Human exposure to vibration is described relative to three broad criteria: health and safety (exposure limit), working efficiency (FDP), and comfort (reduced-comfort boundary) (ISO 2631–1 [ISO 1985], ANSI S3.18 [ANSI 1979]). The ACGIH [2006] points out that the TLVs are not adequate for evaluating a vibration environment characterized by high-amplitude mechanical shocks (jars or jolts) and it will "underestimate the effects of WBV...when crest factors exceed 6."

Some optional methods of analysis concerning the impact of jars and jolts on the body are worth considering and include those presented in ISO 2631–1 [ISO 1997] and ISO 2631–5 [ISO 2004]. The ISO [1997], which stipulates a crest factor of 9 as compared to 6 noted above, no longer includes exposure boundaries or limits and FDP. The standard cites that exposure duration of various effects on people (assumed to be the same for different effects—health, working proficiency, and comfort) was not supported by laboratory research. ISO 2631–1 [ISO 1997] offers health guidance caution zones based on the RMS value of the frequency-weighted acceleration. In cases where the crest factor exceeds 9, the running RMS method featuring the maximum transient vibration value and the fourth-power vibration dose value method are suggested. On the other hand, ISO 2631–5 [ISO 2004] presents a method for evaluating vibration containing multiple shocks (jars and jolts) using the spinal response acceleration dose. This is determined by calculating the human response of the spine, counting the number and magnitudes of peak accelerations, and calculating acceleration dose using a dose model that applies the Palmgren-Miner fatigue theory.

Griffin [1990, 1998] discusses the evolution of ISO 2631–1 from its inception and points out its various shortcomings through the 1997 revision. Griffin suggests that ISO 2631–1 [ISO 1997] may cause unneeded confusion relative to the measurement, evaluation, and assessment of human shock and vibration exposures.

Another method of analysis is the absorbed power method investigated by Pradko et al. [1965]. Lee and Pradko [1968] discussed the analytical use of absorbed power to determine how humans would respond to vibration in periodic and random environments. They described this method in the time and frequency domains. According to Lee and Pradko [1968], the method of absorbed power is important in that it has physical significance; it can be measured and computed analytically. In addition, absorbed power is a scalar quantity and thus can be summed to assess the human response in complex systems with multidegrees of freedom.

More recently, Amirouche et al. [1991] and Tong et al. [1999a] reported on analytical computer models for optimizing the energy absorption during exposure to human body vibration and for evaluating the distribution of absorbed power and how the body reacts to roadway-induced vibration. Using their model to study the energy absorption and work done by the human body's muscles (represented as springs and dampers) during a rough ride, Tong et al. [1999a] discussed how energy is transmitted to different parts of the body and what happens when input conditions change. Understanding the energy flow among the body's parts can provide valuable input for the design of a seat and its suspension. The application of this approach to mining vehicle seats requires further study.

As Mayton et al. [2003] reported relative to Tables 13–14, quantitative levels of vehicle jarring/jolting for no-load conditions showed that NIOSH seats M2A and M2B for the mid-coal-seam performed better than the existing seat (M1) in terms of peak acceleration and crest factor, whereas L2A, L2B, and L2C seats performed better than the existing seat (L1) in terms of peak acceleration, RMS acceleration, and crest factor. Furthermore, Mayton et al. [2005] compared the NIOSH seat designs according to the absorbed power method discussed by Amirouche et al. [1991] and Tong et al. [1999a,b]. The results concurred with the aforementioned analytical results of this NIOSH study in showing lower energy absorption to the body.

Joy Mining Machinery has been marketing the NIOSH seat designs and includes the improved seat design in its current product line. The company independently tested the new design and affirmed the results of the NIOSH studies. Between two shuttle car models, Joy has sold more than 510 of the newly designed seats from 1999 to 2005 and estimates that about 2,600 shuttle cars are in operation worldwide (about 1,500 in the United States). This translates to approximately 15% of the global population of shuttle cars that are equipped with the new seat design or padding design. In terms of the U.S. market for low-seam shuttle cars, 26% of shuttle cars are equipped with the improved seat design. Extrapolating further, the new seat design is positively impacting the health and safety of approximately 1,140 shuttle car operators.[6]

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[6]Assumptions include: one operator per shuttle car per shift, three shifts per day; 380 shuttle cars with new seat designs – 130 low-seam models (two seats per vehicle) and 250 mid- to high-seam models (one seat per vehicle); and 500 total shuttle cars in U.S. low-seam operations in 2005.

LIMITATIONS

This study provides useful results and information regarding shuttle car seat designs for two models of underground coal mine shuttle cars. Nevertheless, it was limited in various ways. The primary limitations of the study included: the small sample size of eight subject shuttle car operators, the constraints of conducting field trials during coal mining production operations, the driving differences among individual subjects, two underground coal mines and no noncoal mines, the exact same driving route was not possible although the same roadway was used, the worn existing seat versus the virtually new NIOSH seats, the short period of time that subjects used the NIOSH seats, and the durability and the reliability of the NIOSH seat designs could not be determined within the test period.

CONCLUSIONS

The objective of this study was to gather additional data to support earlier findings that NIOSH seats, with unique viscoelastic foam padding, are indeed improved designs for coal mine shuttle cars. A larger sample of shuttle car operators was included in this work compared to a prior NIOSH investigation.

Both objective and subjective data from this study indicate that NIOSH seat designs are more effective in reducing levels of jarring and jolting and generally enhancing operator comfort, considering the limitations indicated with the seat installations for the low-coal-seam shuttle car. The researchers realize that the use of seat foam padding alone is not the ultimate answer in providing optimum isolation for vehicle operators. Nevertheless, the NIOSH seat designs showed definite improvements over the existing seat designs for the shuttle car models studied. Future research should study the effects of combining viscoelastic foam seat padding with passive, semiactive, or active seat suspension system, such as that described by Tong et al. [1999a,b].

These results can provide the mining industry with additional evidence that NIOSH seat designs are improvements relative to existing designs for isolating operators from vehicle jarring/jolting. Moreover, the equipment manufacturer with these study results has the opportunity to further refine and improve the NIOSH seat designs from the added input of shuttle car operators. Furthermore, the results of this study may have potential application for the seats of other heavy off-road vehicles used in surface mining, construction, and agriculture.

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APPENDIX A.—VISUAL ANALOG SCALE FORM

Shuttle Car Model:

Operation: No Load

Jarring/Jolting Level:
Instructions: For the travel that you just completed, please rate the amount of jarring and jolting you felt from the vehicle through the seat by placing a straight line on the rating scale.

|____|

No Jarring/Jolting — High Jarring/Jolting

Jarring/Jolting Discomfort:

Instructions: For the travel that you just completed, please rate the amount of jarring and jolting you felt from the vehicle through the seat by placing a straight line on the rating scale.

|____|

No Discomfort — Extreme Discomfort

****

Operation: Full Load

Jarring/Jolting Level:
Instructions: For the travel that you just completed, please rate the amount of jarring and jolting you felt from the vehicle through the seat by placing a straight line on the rating scale.

|____|

No Jarring/Jolting — High Jarring/Jolting

Jarring/Jolting Discomfort:
Instructions: For the travel that you just completed, please rate the amount of jarring and jolting you felt from the vehicle through the seat by placing a straight line on the rating scale.

|____|

No Discomfort — Extreme Discomfort

APPENDIX B.—OPERATOR QUESTIONNAIRE TO COMPARE SEATS ON SHUTTLE CARS IN UNDERGROUND COAL MINES

Date:

Study ID No.:

Name:

Gender: Male _______ Female ______

Age: (yrs) __________

Height: Ft __________ In __________

Weight: ____________ Lbs

Experience as Shuttle Car Operator (yrs):

Underground Mining Experience (yrs):

Underground Experience At This Mine (yrs):

1. How would you rate this seat in terms of comfort?
   1 = very comfortable   2 = comfortable   3 = uncomfortable
   4 = very uncomfortable   Comments:

2. How would you rate this seat relative to reducing shock and vibration?
   1 = very good   2 = good   3 = fair   4 = poor   Comments:

3. What do you like about this seat?

4. What don't you like about this seat?

5. On a scale from 1 to 5, where 1 = poor, 2 = fair, 3 = good, 4 = very good, and 5 = excellent, rate the following:
   - o seat padding ______
   - o lumbar support ______
   - o reclining seatback ______
   - o seatpan tilt ______
   - o armrest ______
   - o fore-aft adjustment ______

6. What would you do to improve this seat?

7. Compare Seat No. 1 with Seat No. 2 for the items below using this scale:
   1 = much worse, 2 = worse, 3 = same, 4 = better, 5 = much better.

   a. Overall ___________________
      Explain ____
      ____
      ____

   b. Seat padding _______________
      Explain ____
      ____
      ____

c. Lumbar support ___________
Explain ____
____
____

d. Reclining seatback _________
Explain ____
____
____

e. Seatpan tilt _______________
Explain ____
____
____

f. Armrest _________________
Explain ____
____
____

APPENDIX C.—MEASURED JARRING/JOLTING DATA

Table C–1.—Output/input ratios, peak/RMS accelerations for different seats and operators of the JOY 10SC mid-coal-seam shuttle car

Seat	Input (frame)			Output (seat)			Ratio (output/input)		
	Peak	RMS	Crest factor	Peak	RMS	Crest factor	Peak	RMS	Crest factor
FULL LOAD									
Seat M1:									
ID No. 1	10.88	1.79	6.09	17.96	2.70	6.64	1.65	1.51	1.09
ID No. 2	5.37	1.03	5.20	9.09	1.57	5.79	1.69	1.52	1.11
ID No. 3	4.04	0.80	5.08	7.00	1.18	5.94	1.73	1.48	1.17
ID No. 4	3.93	1.14	3.44	7.20	1.90	3.79	1.83	1.66	1.10
ID No. 5	14.00	1.60	8.74	17.83	2.01	8.87	1.27	1.25	1.02
Seat M2A:									
ID No. 1	10.76	2.26	4.76	23.27	3.97	5.86	2.16	1.76	1.23
ID No. 2	4.35	0.98	4.44	9.03	1.77	5.11	2.08	1.80	1.15
ID No. 3	ND	ND	ND	ND	ND	ND	ND	ND	ND
ID No. 4	5.66	1.22	4.64	12.12	2.17	5.59	2.14	1.78	1.20
ID No. 5	ND	ND	ND	ND	ND	ND	ND	ND	ND
Seat M2B:									
ID No. 1	7.39	1.54	4.79	18.98	3.07	6.18	3.07	1.99	1.29
ID No. 2	5.41	1.09	4.97	11.13	2.03	5.48	2.06	1.87	1.10
ID No. 3	7.10	1.38	5.16	16.05	2.64	6.08	2.26	1.92	1.18
ID No. 4	5.65	1.40	4.04	11.23	2.60	4.32	1.99	1.86	1.07
ID No. 5	7.54	1.65	4.56	26.64	2.97	8.97	3.53	1.80	1.97
NO LOAD									
Seat M1:									
ID No. 1	7.31	1.81	7.31	37.04	3.88	37.04	3.88	2.14	2.36
ID No. 2	9.96	1.49	6.68	17.54	2.27	7.72	1.76	1.53	1.16
ID No. 3	7.61	1.53	4.98	18.47	2.33	7.94	2.43	1.52	1.59
ID No. 4	5.99	1.64	3.66	11.57	2.85	4.07	1.93	1.74	1.11
ID No. 5	8.54	1.56	5.48	13.00	2.13	6.09	1.52	1.37	1.11
Seat M2A:									
ID No. 1	5.45	1.08	5.06	11.84	2.00	5.91	2.17	1.86	1.17
ID No. 2	2.62	0.66	3.94	5.43	1.28	4.24	2.08	1.93	1.08
ID No. 3	ND	ND	ND	ND	ND	ND	ND	ND	ND
ID No. 4	5.58	1.36	4.11	11.97	2.51	4.77	2.14	1.85	1.16
ID No. 5	ND	ND	ND	ND	ND	ND	ND	ND	ND
Seat M2B:									
ID No. 1	8.19	1.31	6.27	22.66	2.71	8.37	2.71	2.07	1.34
ID No. 2	2.61	0.60	4.36	6.05	1.09	5.53	2.31	1.82	1.27
ID No. 3	3.43	0.80	4.26	10.17	1.52	6.71	2.97	1.88	1.57
ID No. 4	5.94	0.91	6.56	12.91	1.73	7.48	2.18	1.91	1.14
ID No. 5	5.91	1.05	5.62	11.65	1.65	7.04	1.97	1.57	1.25

ND No data.

NOTE.—Peak and RMS are in m/s^2; crest factor is dimensionless.

Table C–2.—Average ratios, peak/RMS accelerations for different seats and conditions on the JOY 10SC mid-coal-seam shuttle car

Seat	Input (frame)			Output (seat)			Ratio (output/input)		
	Peak	RMS	Crest factor	Peak	RMS	Crest factor	Peak	RMS	Crest factor
Seat M1:									
Full load	7.64	1.27	5.71	11.81	1.87	6.21	1.64	1.49	1.10
No load............	7.88	1.60	4.97	19.53	2.69	7.07	2.54	1.66	1.47
Seat M2A:									
Full load	6.92	1.49	4.61	14.81	2.64	5.52	2.13	1.78	1.20
No load............	4.55	1.03	4.37	9.75	1.93	4.97	2.13	1.88	1.13
Seat M2B:									
Full load	6.62	1.41	4.71	16.80	2.66	6.21	2.48	1.89	1.32
No load............	5.22	0.93	5.41	12.69	1.74	7.03	2.44	1.85	1.31

NOTE.—Peak and RMS are in m/s^2; crest factor is dimensionless.

Table C–3.—Total average ratios, peak/RMS accelerations for different seats and conditions on the JOY 10SC mid-coal-seam shuttle car

Seat	RMS			Peak			Crest factor		
	Input	Output	Ratio	Input	Output	Ratio	Input	Output	Ratio
Seat M1.............	1.44	2.28	1.57	7.76	15.67	2.09	5.34	6.64	1.28
Seat M2A	1.26	2.28	1.83	5.74	12.28	2.13	4.49	5.25	1.17
Seat M2B	1.17	2.20	1.87	5.92	14.75	2.46	5.06	6.62	1.32

NOTE.—Peak and RMS are in m/s^2; crest factor is dimensionless.

Table C–4.—Output/input ratios, peak/RMS accelerations for different seats and operators of the JOY 21SC low-coal-seam shuttle car

Seat	Input (frame)			Output (seat)			Ratio (output/input)		
	Peak	RMS	Crest factor	Peak	RMS	Crest factor	Peak	RMS	Crest factor
FULL LOAD									
Seat L1:									
ID No. 1	10.08	2.07	4.87	10.30	2.12	4.87	1.02	1.02	1.00
ID No. 2	8.14	1.58	2.00	10.54	1.92	2.00	10.54	1.92	2.00
ID No. 3	9.58	1.92	4.99	12.44	2.23	5.57	1.30	1.16	1.12
Seat L2A:									
ID No. 1	7.42	1.56	4.76	8.69	1.77	4.92	1.17	1.13	1.03
ID No. 2	7.07	1.44	4.90	8.40	1.63	5.14	1.19	1.13	1.05
ID No. 3	10.35	1.49	6.96	11.91	1.71	6.95	1.15	1.15	1.00
Seat L2B:									
ID No. 1	7.30	1.18	6.21	10.17	1.50	6.79	1.39	1.27	1.09
ID No. 2	7.46	1.15	6.46	11.86	1.55	7.67	1.59	1.34	1.19
ID No. 3	13.43	1.58	8.49	17.34	2.11	8.22	1.29	1.33	0.97
Seat L2C:									
ID No. 1	ND	ND	ND	ND	ND	ND	ND	ND	ND
ID No. 2	4.18	0.86	4.88	5.92	1.10	5.39	1.10	1.28	1.10
ID No. 3	9.68	1.61	6.02	11.57	1.95	5.93	1.20	1.21	0.98
NO LOAD									
Seat L1:									
ID No. 1	7.89	1.82	4.35	9.99	2.34	4.27	1.27	1.29	0.98
ID No. 2	11.19	1.68	2.00	13.72	2.18	2.00	13.72	2.18	2.00
ID No. 3	13.47	2.79	4.83	18.69	3.40	5.50	1.39	1.22	1.14
Seat L2A:									
ID No. 1	13.21	1.91	6.90	12.38	2.11	5.87	0.94	1.10	0.85
ID No. 2	14.11	1.73	8.18	15.99	2.11	7.59	1.13	1.22	0.93
ID No. 3	7.34	1.56	4.70	6.75	1.69	3.99	0.92	1.08	0.85
Seat L2B:									
ID No. 1	8.78	2.12	4.14	9.33	2.60	3.58	1.06	1.23	0.86
ID No. 2	6.45	1.47	4.40	8.57	1.98	4.33	1.33	1.35	0.98
ID No. 3	10.09	1.97	5.11	9.59	1.93	4.98	0.95	0.98	0.97
Seat L2C:									
ID No. 1	ND	ND	ND	ND	ND	ND	ND	ND	ND
ID No. 2	7.92	1.36	5.83	10.59	1.73	6.13	1.34	1.27	1.05
ID No. 3	7.67	1.36	5.63	8.02	1.44	5.57	1.05	1.06	0.99

ND No data.

NOTE.—Peak and RMS are in m/s^2; crest factor is dimensionless.

Table C–5.—Average ratios, peak/RMS accelerations for different seats and conditions on the JOY 21SC low-coal-seam shuttle car

Seat	Input (frame)			Output (seat)			Ratio (output/input)		
	Peak	RMS	Crest factor	Peak	RMS	Crest factor	Peak	RMS	Crest factor
Seat L1:									
Full load	9.27	1.86	5.01	11.09	2.09	5.31	1.21	1.13	1.06
No load............	10.85	2.10	5.27	14.13	2.64	5.35	1.29	1.27	1.02
Seat L2A:									
Full load	8.28	1.50	5.54	9.67	1.71	5.67	1.17	1.14	1.03
No load............	11.55	1.73	6.59	11.71	1.97	5.82	1.00	1.14	0.88
Seat L2B:									
Full load	9.40	1.30	7.05	13.12	1.72	7.56	1.43	1.32	1.08
No load............	8.44	1.85	4.55	9.16	2.17	4.30	1.11	1.18	0.94
Seat L2C:									
Full load	6.93	1.23	5.45	8.75	1.53	5.66	1.31	1.25	1.04
No load............	7.80	1.36	5.73	9.31	1.58	5.85	1.19	1.16	1.02

NOTE.—Peak and RMS are in m/s^2; crest factor is dimensionless.

Table C–6.—Total average ratios, peak/RMS accelerations for different seats and conditions on the JOY 21SC low-coal-seam shuttle car

Seat	RMS			Peak			Crest factor		
	Input	Output	Ratio	Input	Output	Ratio	Input	Output	Ratio
Seat L1..............	1.98	2.37	1.20	10.06	12.61	1.25	5.14	5.33	1.04
Seat L2A	1.62	1.84	1.14	9.92	10.69	1.08	6.07	5.74	0.95
Seat L2B	1.58	1.94	1.25	8.92	11.14	1.27	5.80	5.93	1.01
Seat L2C	1.30	1.55	1.21	7.36	9.03	1.25	5.59	5.75	1.03

NOTE.—Peak and RMS are in m/s^2; crest factor is dimensionless.

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