Whole-body vibration exposure comparison of seat designs for low- and mid-seam shuttle cars in underground coal mines

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Abstract

In a systematic study, the National Institute for Occupational Safety and Health (NIOSH) evaluated seat designs in low- and mid-seam shuttle cars during production operations at two underground coal mines in southern West Virginia. The purpose was to support, with additional data, earlier findings that NIOSH ergonomic seat designs (featuring viscoelastic foam padding and lower-back support) may help reduce health risks to operators of coal mine shuttle cars. Eight shuttle car operators evaluated seven seat designs (one already in use in each vehicle and five NIOSH designs) relative to perceived and measured whole-body vibration (WBV) exposure (including vehicle jarring/jolting) and discomfort. Operators' perceptions using a visual analog scale (VAS) and questionnaire ratings were compared with International Standards Organization (ISO) 2631-1:1985 fatigue-decreased proficiency (FDP) limits and measured WBV levels on low- and mid-seam shuttle cars. Objective and subjective data results indicated that NIOSH seat designs (with added adjustability, lower-back support and improved seat padding) performed better to reduce vehicle jarring/jolting levels and that shuttle car operators favored them over existing seat designs. The NIOSH low- and mid-seam shuttle car seats showed 45 to 77 percent better performance in FDP and 9 to 60 percent better performance overall in operators' ratings. Considering the VAS results for low- and mid-seam shuttle cars under no-load conditions, operators rated the level of jarring/jolting 18 to 89 percent lower with the NIOSH seats. Reductions in measured vehicle jarring/jolting were 19 to 46 percent for the three-directional vector sum accelerations relative to the existing seats on the low- and mid-seam shuttle cars. Questionnaire responses indicated that operators for both shuttle car models rated NIOSH seat designs as more comfortable overall. Vehicle operators most frequently suggested adding armrests to improve the seats on the mid-seam shuttle car. A suggested improvement for the low-seam shuttle car was to make the seat a better fit for the operator compartment, which would enhance clearance between the operator and vehicle controls and allow for better seat adjustment and operator visibility.

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.,

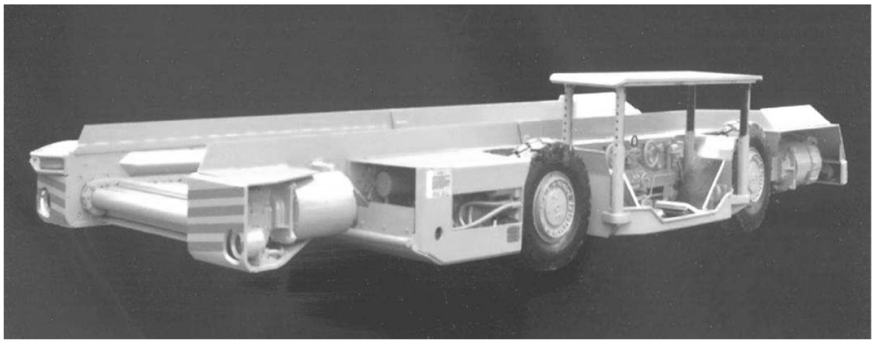


Figure 1 — JOY 21SC low-seam shuttle car (courtesy JOY Mining Machinery).

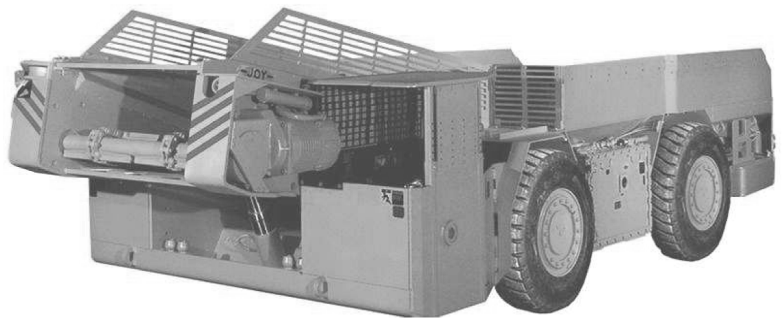


Figure 2 — JOY 10SC mid-seam shuttle car (courtesy JOY Mining Machinery).

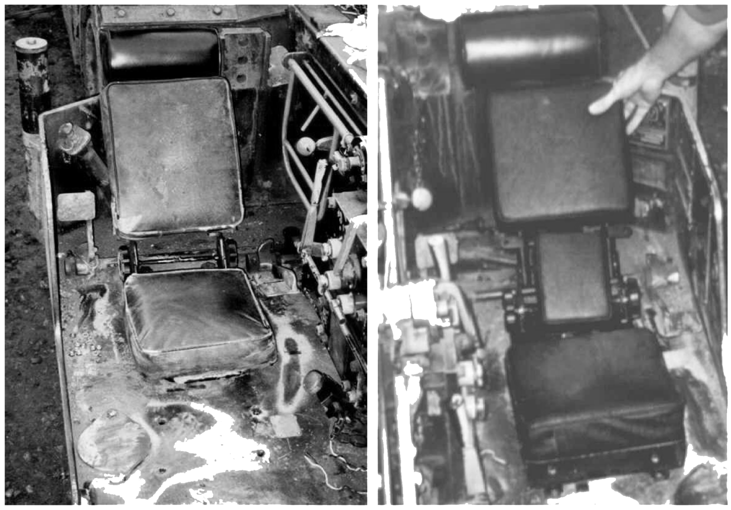
1997). This is especially true in the mining industry.

A study by Mayton et al. (1999) reported on a low-seam shuttle car seat design that underwent limited, yet positive, underground mine trials. 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 reports (narratives) from the Mine Safety and Health Administration (MSHA) database were analyzed for mobile mining equipment operators in association with vehicle jarring/jolting. These injuries can be described as acute and chronic musculoskeletal disorders affecting the back, neck and head. The trend for total back, neck and head from MSHA-reported injuries on underground mine shuttle cars showed a slight decline for the period 1999 - 2005. Nevertheless, vehicle jarring/jolting-related injuries averaged 75 % (253) per year of the total (338) 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; McPhee et al., 2001; Bernard and Fine, 1997; Wikström et al., 1994; Seidel and Heide, 1986; Hulshof and van Zanten, 1987).

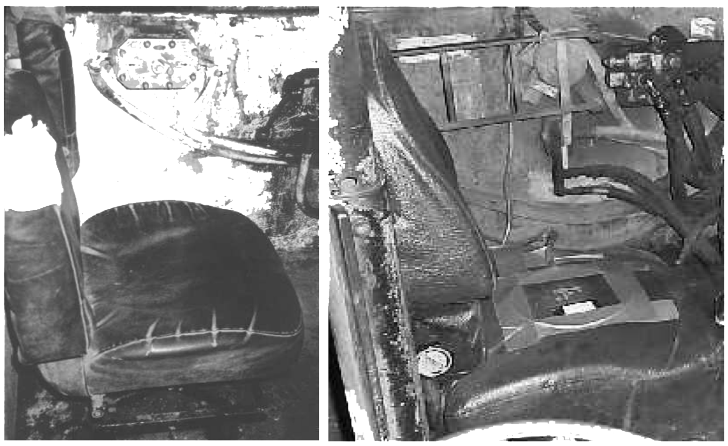
In an Australian study, Cross and Walters (1994) identified WBV and vehicle jarring as a contributing factor to back pain in the mining industry and as a significant concern to mobile equipment operators. They reviewed 28,306 compensation claims for a four-year period (July 1986 to March 1990), including 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.

The intent of this current study was to support earlier work with a more systematic evaluation of the low-seam shuttle car seat design and a second mid-seam shuttle car seat design. With additional information and a larger sample of shuttle car



(a) **(b)**

Figure 3 — Low-seam shuttle car seats: existing (a) and NIOSH (b).



(a) **(b)**

Figure 4 — Mid-seam shuttle car seats: example of existing (a) and NIOSH (b).

operators in this study, researchers affirmed earlier findings that NIOSH seat designs, with unique viscoelastic foam padding, were more effective than some existing seats in isolating shuttle car operators from jars and jolts. Moreover, the results of this study are relevant to the mining industry, since injury data and research studies have identified mine shuttle cars as major sources of adverse WBV exposure. Improving seat designs is important to reduce the adverse effects of WBV exposure and minimize health risks to vehicle operators.

Methodology

Seat design trials were conducted in two West Virginia mines on a JOY 21SC shuttle car (Fig. 1) operating at a low-seam mine, <122 cm (4 ft) and a JOY 10SC side-saddle-style shuttle car (Fig. 2) operating at a mid-seam mine, 122 to 144 cm (4 to 4.7 ft). Different seat designs were compared on each shuttle car. The existing seats, shown in Figs. 3a and 4a, were designated Seats L1 and M1 for trials with low- and mid-seam shuttle car models, respectively. The NIOSH seats shown in Figs. 3b and 4b featured viscoelastic foam padding, arranged as follows for the low-seam shuttle car (Fig. 5): Seat L2A included a combination of Pudgee (PU) and Sun-Mate Extra-Soft (XSS) foams, 7.6 cm (3 in.) thick; Seat L2B included XSS foam padding, 12.7 cm (5 in.) thick and Seat L2C included a combination of PU and XSS foams, 12.7 cm (5 in.) thick. The NIOSH seats for the mid-seam shuttle car featured viscoelastic foam padding arranged as follows (Fig. 6): Seat M2A's foams included XSS foam, 12.7 cm (5 in.) thick and Seat M2B included a combination of PU and XSS, 12.7 cm (5 in.) thick.

Figure 7 shows the instrumentation setup on the low- and mid-seam shuttle cars, respectively. Three low-seam shuttle car operators were tested on four seats: the existing seat, L1, and three NIOSH test seats, L2A, L2B and L2C. Five mid-seam shuttle car operators were tested on three seats: the existing seat, M1, and two NIOSH test seats, M2A and M2B. The data sets were divided into full-load and no-load conditions.

Subjects. Eight shuttle car operators participated in the

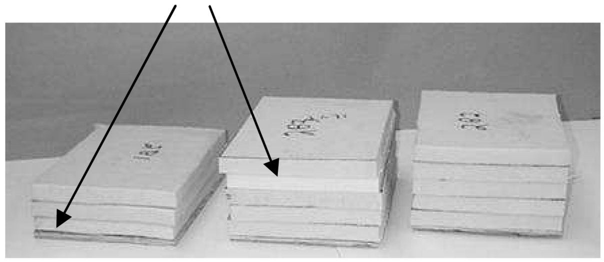


Figure 5 — Viscoelastic foam padding arrangements. L2A, 7.6 cm thick with two layers XSS and one PU; L2C, 12.7 cm thick with four layers XSS and one PU; L2B, 12.7 cm thick with five layers XSS and no PU.

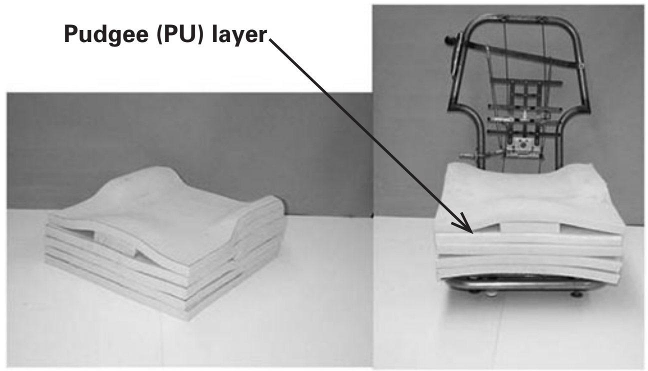


Figure 6 — Viscoelastic foam padding arrangements - 12.7 cm thick. M2A (no PU) and M2B (one PU).

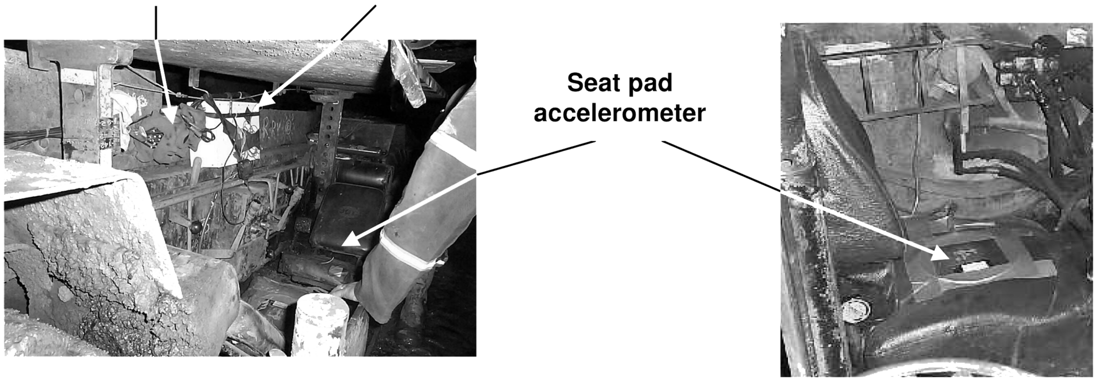


Figure 7 — Instrument setups on the low- (a) and mid- (b) seam shuttle car seats.

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 39 years. They ranged in height from 175 to 185 cm (69 to 73 in.), with an average height of 180 cm (71 in.) and they ranged in weight from 73 to 91 kg (161 to 201 lb), with an average weight of 87 kg (192 lb). The subjects' experience at operating a shuttle car varied from one-half to 24 years and averaged 9 years. Similarly, their underground mining experience varied from one-half to 37 years and averaged 14 years. Before participating, the shuttle car operators were briefed about the study and were asked to sign an informed consent and photo release forms.

Procedure for vibration data collection. Objective data were collected using accelerometers with pre-amplifiers and filters connected to a data recorder. Subjective data were gathered with a visual analog scale (VAS) and a questionnaire. An eight-channnel digital data recorder (model PC208Ax, Sony Manufacturing Systems America, Lake Forest, CA) used with instrumentation from PCB Piezotronics, Inc., Depew, NY. These included triaxial accelerometers (models 356B18 and 356B40), signal conditioning amplifiers (model 480E09) and in-line, 150-Hz low-pass filters (model 474M32). A floor- or frame-mounted accelerometer featured a frequency range of 0.3 Hz to 5 kHz and a charge sensitivity ranging from 949 to 1052 mV/g for the three directional axes. A seat pad accelerometer featured a frequency range of 0.5 Hz to 1 kHz and a charge sensitivity ranging from 97.4 to 105 mV/g for the three directional axes. One triaxial accelerometer was mounted on the frame of the shuttle car above the control panel (frame or chassis measurement) and one on the seat at the subject/seat interface (seat measurement). The frame accelerometers were ordinarily mounted on the floor of the operator's compartment near the base of the seat, but muddy conditions dictated the above mounting locations; this did not affect the data. Data were analyzed to determine the acceleration and transmissibility of energy entering the seat from the vehicle frame or chassis. During the field trials, roadway conditions were noted as smooth, pothole-riddled, debris strewn, rutted, dry, wet and/or water-filled.

Table 1 — Total average VAS ratings for low-seam JOY 21SC and mid-seam JOY 10SC shuttle car operators (lower value = better).

Low-seam JOY 21SC shuttle car seat	Mean of average operator ratings	Mid-seam JOY 10SC shuttle car seat	Mean of average operator ratings
	ID No.'s 1, 2 and 3		ID No.'s 1, 2, 3, 4 and 5
NO LOAD			
L1 - Existing seat:		M1 - Existing seat:	
Level of jar/jolt	0.395	Level of jar/jolt	0.742
Level of discomfort	0.372	Level of discomfort	0.738
L2A - NIOSH seat (3-in. XSS/PU):		M2A - NIOSH seat (5-in. XSS):	
Level of jar/jolt	0.325	Level of jar/jolt	0.085
Level of discomfort	0.438	Level of discomfort	0.093
L2B - NIOSH seat (5-in. XSS):		M2B - NIOSH seat (5-in. XSS/PU):	
Level of jar/jolt	0.170	Level of jar/jolt	0.432
Level of discomfort	0.396	Level of discomfort	0.334
L2C - NIOSH seat (5-in. XSS/PU):			
Level of jar/jolt	0.273		
Level of discomfort	0.301		
FULL LOAD			
L1 - Existing seat:		M1 - Existing seat:	
Level of jar/jolt	0.433	Level of jar/jolt	0.652
Level of discomfort	0.223	Level of discomfort	0.666
L2A - NIOSH seat (3-in. XSS/PU):		M2A - NIOSH seat (5-in. XSS):	
Level of jar/jolt	0.170	Level of jar/jolt	0.061
Level of discomfort	0.377	Level of discomfort	0.087
L2B - NIOSH seat (5-in. XSS):		M2B - NIOSH seat (5-in. XSS/PU):	
Level of jar/jolt	0.054	Level of jar/jolt	0.424
Level of discomfort	0.344	Level of discomfort	0.366
L2C - NIOSH seat (5-in. XSS/PU):			
Level of jar/jolt	0.189		
Level of discomfort	0.364		

Procedure for subjective data collection. The subjective data were gathered using a visual analog scale (VAS) form 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. The VAS consisted of a line approximately 10 cm (4 in.) long and terminated at each end by a vertical hash denoting the two limits of jarring/jolting level and level of discomfort, essentially "no" and "high or extreme." The rating scale was scored by measuring the distance (from left to right) from the beginning of the line to the operator's mark and dividing this value by the total length of the line. 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 the trials for each seat. 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. After the 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. 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.

Subjective data were also obtained using a short questionnaire (Appendix A) to interview shuttle car operators. The interview, lasting five to 10 minutes, occurred at the conclusion of each trial for each seat. The seven questions asked of the shuttle car operator to judge his exposure relative to comfort and vibration or shock, give his opinions on seat padding and lumbar support, indicate his likes, dislikes and suggested improvements concerning each seat and lastly, summarize comparisons of the seats. In order to quantify the responses, most of the questions included a 4- or 5-point scale to describe degrees of comfort

Table 2 — Pearson correlations from VAS ratings relating level of jarring/jolting to discomfort for low-seam JOY 21SC and mid-seam JOY 10SC shuttle car seats (P ≤ 0.05).

Low-seam JOY 21SC shuttle car seat	**Pearson correlation coefficient, *r***	**Mid-seam JOY 10SC shuttle car seat**	**Pearson correlation coefficient, *r***
	NO LOAD		
L1 - Existing seat:	0.29	M1 - Existing seat:	0.89
L2A - NIOSH seat (3-in. XSS/PU):	0.84	M2B - NIOSH seat (5-in. XSS)	0.71
L2B - NIOSH seat (5-in. XSS):	0.88	M2B - NIOSH seat (5-in. XSS/PU):	0.94
L2C - NIOSH seat (5-in. XSS/PU):	0.58		
	FULL LOAD		
L1 - Existing seat:	0.66	M1 - Existing seat:	0.93
L2A - NIOSH seat (3-in. XSS/PU):	0.88	M2B - NIOSH seat (5-in. XSS)	0.90
L2B - NIOSH seat (5-in. XSS):	0.69	M2B - NIOSH seat (5-in. XSS/PU):	0.97
L2C - NIOSH seat (5-in. XSS/PU):	0.73		

XSS Extra-soft Sun-Mate. PU Pudgee.

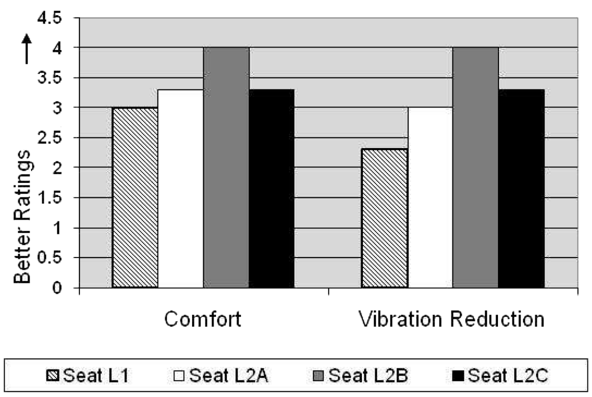


Figure 8 — Ratings of seat design for comfort and vibration reduction, based on questionnaire given to low-seam shuttle car operators.

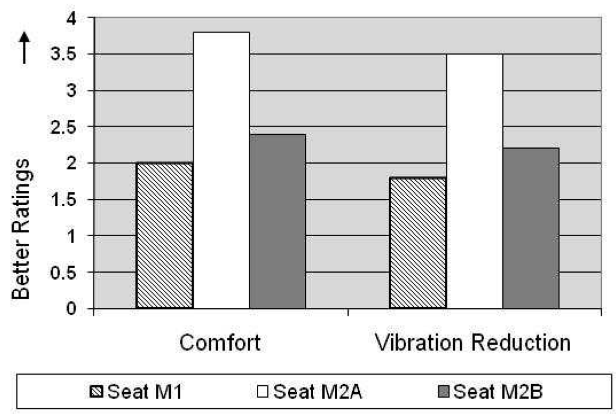


Figure 9 — Seat comfort and vibration reduction ratings based on questionnaire responses from mid-seam shuttle car operators.

and poor/good or worse/better seat performance.

Objective data were analyzed according to the American Conference of Governmental Industrial Hygienists (ACGIH) TLVs (threshold limit values), ACGIH (2006) and ISO 2631-1:1985 fatigue-decreased proficiency (FDP) methods. Subjective data were analyzed with simple statistics for frequency of occurrence and arithmetic mean. The Pearson correlation analysis was performed on the VAS data. Owing to the small sample sizes, the authors believed performing additional statistical analysis on the data would not yield any meaningful results.

The concepts of peak acceleration, root-mean-square (RMS) acceleration, crest factor and overall weighted total RMS acceleration were used in the data analysis as a means for assessing vehicle jarring/jolting exposure. These analytical parameters, presented in ISO 2631-1:1985 and by the American National Standards Institute (ANSI) (1979), were used by the ACGIH (2006) to develop the TLVs. 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, fatigue-decreased proficiency) and comfort (RCB, reduced-comfort boundary) (ISO, 1985, ANSI, 1979). The ACGIH (2006) points out that the TLVs may not be adequate for evaluating a vibration environment characterized by high-amplitude mechanical shocks (jars or jolts) and it may "underestimate the effects of WBV...when crest factors exceed 6." The ISO 2631–1:1997 recommends a crest factor of 9.0. The crest factor is a way of describing the rate of change in acceleration.

Some optional methods of analysis concerning the impact of jars and jolts on the body are presented in ISO 2631–1:1997 and ISO 2631–5:2004. ISO 2631–1:1997 offers health guid-

Table 3 — Performance comparison for no-load conditions using FDP limit values, crest factors and vehicle operator questionnaire ratings with percent better than existing seats L1 and M1.

Seat	Fatigue-decreased proficiency (FDP) (min)	Crest factor	Question #2 rating (Scale: 1.0 to 4.0)	Percent better than seat L1 or M1		
				Fatigue-decreased proficiency (FDP)	Crest factor	Question #2 rating
JOY 21SC (No-Load)						
L1	32	1.02	3	—	—	—
L2A	59	0.88	3.3	45	16	9
L2B	59	0.94	4	46	9	25
L2C	139	1.02	3.3	77	0	9
JOY 10SC (No-Load)						
M1	76	1.47	2.00	—	—	—
M2A	176	1.13	3.75	57	30	47
M2B	190	1.31	2.40	60	12	17

NOTE - Crest factor (peak acceleration/RMS acceleration) is dimensionless. Higher values for "questionnaire" and "fatigue decreased" indicate better results, whereas lower values for "crest factor" indicate better results.

ance 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 2631–5:2004 presents a method for evaluating vibration containing multiple shocks (jars and jolts) using the spinal response acceleration dose. Moreover, Griffin (1990, 1998) discusses the evolution of ISO 2631–1 from its inception and points out various shortcomings through the 1997 revision. Griffin suggests that ISO 2631–1:1997 may cause unneeded confusion relative to the measurement, evaluation and assessment of human shock and vibration exposures. These optional methods were not used for comparisons in this study, because researchers considered the FDP criteria (included as part of ISO 2631–1:1985) more relevant since they were utilized in the earlier study by Remington et al. (1984) and the TLVs of ACGIH (2006) were based on ISO 2631–1:1985 and ANSI S3.18:1979.

Results

Subjective evaluation - VAS. Table 1 illustrates the total average ratings for the shuttle car operators of the JOY 21SC low-seam and JOY 10SC mid-seam shuttle cars, respectively. The lower ratings from VAS responses indicate that the NIOSH-designed seats performed better than the existing seats used in the shuttle cars. Accordingly, the following observations were made:

- For both no-load and full-load conditions, mid-seam shuttle car operators observed lower levels of jarring/jolting and discomfort with the NIOSH seats (M2A and M2B), using two different 12.7-cm (5-in.) viscoelastic foam pad arrangements.
- The viscoelastic foam arrangement (M2A) with five 2.5-cm (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 seats (L2A, L2B and L2C), using three different viscoelastic foam arrangements. The viscoelastic foam arrangements, in order of operator preference, were the 12.7-cm (5-in.) XSS (L2B), 7.6-cm (3-in.) PU/XSS (L2A) and 12.7-cm (5-in.) PU/XSS (L2C) 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 (L1) versus the NIOSH seats (L2A, L2B and L2C) 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.

Pearson correlation values were calculated for the low- and mid-seam shuttle car seats and are displayed in Table 2. The following is a summary of the results obtained: a weak-to-strong positive correlation (for jar/jolt and discomfort) was realized for different seats tested on the low-seam JOY 21SC shuttle car ($P \leq 0.05$). 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. All correlation values for the mid-seam shuttle car showed a significant relationship between the variables of jarring/jolting and discomfort ($P \leq 0.05$).

Subjective evaluation - operator questionnaire. *JOY 21SC low-seam shuttle car* - Figure 8 shows seat ratings regarding comfort and shock/vibration reduction. 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

Table 4 — Perceived discomfort and jarring/jolting levels versus measured reductions in vector sum accelerations for operators of the JOY 21SC low- and JOY 10SC mid-seam shuttle cars (no load) (Mayton et al., 2003 and 2006).

Seat	Perceived reduction		Measured reduction
	Discomfort (%)	Jarring/ jolting (%)	Vector sum (%)
JOY 21SC (No-Load)			
L1 - Existing seat	—	—	—
L2A - NIOSH seat (3-in. XSS/PU)	[1]18	18	24
L2B - NIOSH seat (5-in. XSS)	[1]6	56	19
L2C - NIOSH seat (5-in. XSS/PU)	19	31	46
JOY 10SC (No-Load)			
M1 - Existing seat	—	—	—
M2A - NIOSH seat (5-in. XSS)	87	89	29
M2B - NIOSH seat (5-in. XSS/PU)	55	42	23

Vector sum (m/s^2) = Overall weighted total RMS acceleration for three directions (x, y and z axes).
[1]Increase instead of reduction.

liked the degree to which this seat reduced jars and jolts and one operator thought it was fairly comfortable. However, operators disliked its lack of durability and lack of lumbar support. 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.

Seats L2A and L2B ranked high 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 prototype seats were too close to the controls and did not adequately fit the available space of the shuttle car operator workstation.

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 support wider. One operator suggested improving the operators' control panel envelope to accommodate better seats, such as seat L2B.

Concerning seat L2C, operators liked the padding, how well it reduced jarring/jolting, how well the lumbar support took the strain off the back and the general comfort of the seat. Operators, however, did not like the lumbar width. Also, the seat seemed too large for the shuttle car operator workstation. Suggested improvements for seat L2C were to make the lumbar support and seat wider and to add a scaled-down seat (by reducing the padding) to better fit the control layout.

Ratings in Fig. 8 show seat L2C comparable to seat L2A in comfort, but better in reducing vibration. Seat L1 is the least favorite in all ratings. Seat padding, lumbar support and seat-pan tilt were rated better for seat L2B than any other seat. The reclining backrest, favored by one operator on seat L1, overall was better on seat L2B. Making the seat a better fit for the operator compartment (workstation) was a suggested improvement. This adjustment would improve clearance between the operator and the controls and allow for better operator adjustability and visibility.

*JOY 10SC mid-seam shuttle ca*r - Figure 9 displays the operators' responses to questions about reductions in vibration (jarring/jolting) and discomfort. Seat M2A was ranked highest in comfort and vibration reduction, as well as 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" highlighted the descriptions for seat M1. Suggested improvements to seat M1 included adding armrests and removing and replacing the seat with the one originally installed on the vehicle.

Seat M2A was ranked most favorable, in that operators liked the seat's apparent ability to absorb vibration and jars, as well as its good back support and comfort. The seat seemed to adversely affect visibility and was somewhat close to the control panel. Adding armrests and improved seat positioning relative to vehicle operator controls were primary suggestions for improving seat M2A.

Operators appreciated the comfort and firmness of seat M2B, but viewed its poor ability to absorb jars/jolts and stiff back support as shortcomings. Operators offered several suggestions to improve seat M2B, such as making the seat softer, adding armrests and improving the lumbar support.

Seat comparison rankings reflected how the operators viewed the seats relative to each other. Again, Seat M2A was the favorite. Seat padding rated well for both Seat M2A and Seat M2B. 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.

Measured vehicle jarring/jolting and questionnaire data compared to ISO 2631-1:1985 FDP limits. Data were collected on the JOY 21SC at the low-seam coal mine in West Virginia. 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.

Similarly, data were collected on the side-saddle-style shuttle car at the mid-seam mine. No information was collected from 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 results were distinguished by vehicle operation during full-load and no-load conditions.

FDP limits from the International Organization for Standardization (ISO) 2631-1:1985 were compared with the objective and subjective data discussed above. Griffin (1990) describes FDP as a concept created to define vibration exposure limits relative to exposure duration for working efficiency.

Considering 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

$$\omega_n = \sqrt{\frac{k}{m}} \qquad (1)$$

where:

ω_n = natural frequency;
k = spring constant and
m = mass.

FDP limits correlated with the results obtained from measured levels of vehicle jarring/jolting and questionnaire responses for the different vehicle operators and seat designs (Mayton et al., 2006). Table 3 provides data for the JOY 21SC and JOY 10SC shuttle cars when operating under no-load conditions. For the JOY 21SC, seat L2A showed 45% better performance in FDP, 16% better performance in the crest factor and 9% better performance overall when rated by the operators. Seat L2B showed 46% better performance in FDP, 9% better performance in the crest factor and 25% better overall performance when rated by the operators. Seat L2C showed 77% better performance in FDP, no change in the crest factor and 9% better overall performance when rated by the operators.

For the JOY 10SC, seat M2A showed 57% better performance in FDP, 30% better performance in the crest factor and 47% better overall performance when rated by the operators. Seat M2B showed 60% better performance in FDP, 12% better performance in the crest factor and 17% better overall performance when rated by the operators.

Comparison of VAS and Measured Data. Table 4 shows the results for the VAS and measured data using overall weighted total RMS acceleration or vector sum. The VAS ratings showed that vehicle operators overall (on average from three test trial ratings) rated the NIOSH-designed seats better than the existing seats. Regarding the low-seam shuttle car, under no-load conditions, operators rated the level of jarring/jolting 18 - 56% lower with the L2A, L2B and L2C seats. In addition, operators rated the level of discomfort 19% lower with seat L2C, but 6 - 18% higher with the L2A and L2B seats.

Regarding the mid-seam shuttle car, under no-load (worse case of two) conditions, operators rated the level of jarring/jolting 42 - 89% lower and level of discomfort 55 - 87% lower with the M2A and M2B seats. Reductions in measured vehicle jarring/jolting are shown in terms of vector sum accelerations relative to the existing seats L1 and M1. For the low-seam shuttle car, the percent reduction in the three-directional vector sum accelerations ranged from 19 - 46% and for the mid-seam shuttle car from 23 - 29%.

Discussion

No known studies of mine shuttle car seat design relative to WBV exposure have been reported aside from this NIOSH study. Eger et al. (2006) evaluated vibration exposure for operators of a variety of heavy surface and underground mining vehicles. Although none of the underground vehicles were mine shuttle cars, the study included LHDs (two 3.5-yd and one 7-yd) which are similar in function to shuttle cars, yet different in vehicle design. They analyzed WBV exposures relative to the ISO 2631-1:1997 Health Guidance Caution Zone (HGCZ) limits associated with an eight-hour daily exposure. The smaller capacity LHDs showed exposures above the HGCZ, whereas the higher capacity LHD exposures were within the HGCZ. Their results were comparable to exposures reported by Village et al. (1989). Furthermore, the Remington et al. (1984) study estimated that 30 to 40 percent of all underground mining machines may exceed the FDP criteria and cited that shuttle cars were a primary source of WBV exposure. Consequently, using the FDP criteria for comparison in this NIOSH study was deemed relevant.

Amirouche et al. (1991) and Tong et al. (1999a) reported on analytical computer models for optimizing the energy absorption during a human body's exposure to vibration and for evaluating the distribution of absorbed power and how the body reacts to roadway-induced vibration. Using their model to study energy absorption and work done by the 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.

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 and 1999b). The results concurred with the aforementioned analytical results of this study in showing lower energy absorption to the body.

Distinguishing the operational differences between traveling with a full load versus no load is again worth noting. 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 reduced mass under no-load conditions 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 under no-load conditions when comparing average values for peak acceleration, RMS acceleration and crest factor.

The use of seat foam padding alone is not the ultimate answer in providing optimum isolation for vehicle operators. Seat foam materials will amplify vibration at lower frequencies (1.7 to 5.5 Hz) as shown in investigations reported by Jobes and Mayton (2006). Nevertheless, the NIOSH seat designs showed definite improvements over the existing seat designs for the shuttle car models studied.

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. In terms of the U.S. market for low-seam shuttle cars, an estimated 51% of shuttle cars are now equipped with the improved seat design. Since 1999, it is estimated that the improved seat designs may have positively impacted the health and safety of nearly 1,980 shuttle car operators.

Limitations

This study provides useful results and information regarding shuttle car seat designs for two models of underground coal mine shuttle cars. 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 differences in driving technique among individual subjects, two underground coal mines and no non-coal mines, the inability to drive the same route on every trip (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 inability to measure the durability and reliability of the NIOSH seat designs over time.

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.

The results obtained from the analysis of quantitative (objective or measured) data, qualitative (subjective) data and the FDP analysis demonstrate that NIOSH-designed seats performed better than existing seats for both shuttle car models. This was particularly significant concerning vehicle jarring/jolting levels for the worse of the two operating conditions, no load. The quantitative levels of vehicle jarring/jolting for no-load conditions showed that the NIOSH L2A, L2B, L2C, M2A and M2B seats for the low- and mid-seam shuttle cars performed better than the existing seat in terms of overall weighted total RMS acceleration or vector sum acceleration and crest factor. The NIOSH seat designs show greater effectiveness in reducing levels of jarring/jolting and generally enhancing operator comfort, considering the limitations indicated with the NIOSH seat installations for the low-seam shuttle car. Questionnaire responses indicated that operators for both shuttle car models rated NIOSH seat designs as more comfortable overall. Future research should study the effects of combining viscoelastic foam seat padding with passive, semi-active or active seat suspension system, such as that described by Tong et al. (1999a, 1999b).

These results can provide the mining industry with additional evidence that NIOSH seat designs are improvements to existing designs for isolating operators from vehicle jarring/jolting. In addition, the results of this study have afforded the equipment manufacturer 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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Disclaimer

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Appendix A

Interview questions for shuttle car operators:

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

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

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 using the scale 1 = poor 2 = fair 3 = good 4 = very good 5 = excellent.

6. What would you do to improve this seat?

7. Compare seat No. 1 with seat Nos. 2 a, b and c using the scale 1 = much worse 2 = worse 3 = same 4 = better 5 = much better.