Comparison of seat designs for underground mine haulage vehicles using the absorbed power and ISO 2631-1(1985)-based ACGIH threshold limit methods

Alan G. Mayton

National Institute for Occupational Safety and Health,
Pittsburgh Research Laboratory,
P.O. Box 18070, PA 15236, Pittsburgh, USA
Fax: 412 386 6764 E-mail: amayton@cdc.gov

Farid Amirouche*

Department of Mechanical and Industrial Engineering,
University of Illinois at Chicago,
2027 Engineering Research Facility,
842 West Taylor St., IL 60607, Chicago, USA
Fax: 312 413 0447 E-mail: amirouch@uic.edu
*Corresponding author

Christopher C. Jobes

National Institute for Occupational Safety and Health,
Pittsburgh Research Laboratory,
P.O. Box 18070, PA 15236, Pittsburgh, USA
Fax: 412 386 6764 E-mail: cjobes@cdc.gov

Abstract: Based on prior mine vehicle studies of operators' exposure to whole-body vibration, researchers from the National Institute for Occupational Safety and Health (NIOSH) evaluated four seat designs on mine haulage vehicles, with regard to roadway-induced jarring/jolting and operator comfort. Investigators collected objective and subjective data from vehicle operators on two existing and two NIOSH seat designs. This study included time and frequency response data using accelerometers and a data recorder, operator perceptions of jarring/jolting and discomfort levels using a linear visual analogue scale, and data from a questionnaire developed for this study. Results from the analysis of subjective data show that operators generally favoured the NIOSH-designed seats over the existing seats. The results of analyses from the absorbed power method and the threshold limit method, based on ISO 2631-1 (ISO, 1985), support the premise that NIOSH seat designs are superior to the existing vehicle seat designs on both models of mine shuttle cars used in the study. The NIOSH seat designs, featuring viscoelastic foam padding, were more effective in reducing vibration energy for operators exposed to vehicle jarring/jolting. In this paper, the performances of the NIOSH and existing seat designs are compared relative to the operator's exposure to vehicle vibration (mainly jarring/jolting).

Keywords: seat designs; human body vibration; comfort analysis; absorbed power; mine operators.

Reference to this paper should be made as follows: Mayton, A.G., Amirouche, F. and Jobes, C.C. (2005) 'Comparison of seat designs for underground mine haulage vehicles using the absorbed power and ISO 2631-1(1985)-based ACGIH threshold limit methods', *Int. J. Heavy Vehicle Systems*, Vol. 12, No. 3, pp.225–238.

Biographical notes: Alan Mayton, a registered Professional Engineer, works as Mining Engineer in the Ergonomics and Machine Safety Groups at the NIOSH – Pittsburgh Research Laboratory, Pittsburgh, Pennsylvania. He received his BS degree in Mining Engineering from West Virginia University, Morgantown. His research interests include human body vibration control, ergonomic design of seats and operator compartments, and machine-mounted lighting systems. He has published papers in mining and illumination journals and a variety of conference proceedings. He serves on the International Minerals Association, Ergonomics Task Force, to provide technical expertise on human body vibration control and ergonomic seat design for heavy vehicle operators.

Farid Amirouche is a Professor, Mechanical and Bioengineering Department, College of Engineering and Adjunct Professor, Orthopedics Department, College of Medicine at the University of Illinois in Chicago (UIC). He is also Director, Biomechanics Research Laboratory and Director, Industrial Advisory Board, Mechanical Engineering Department, UIC. He received his PhD in Mechanical Engineering at the University of Cincinnati, Ohio. His research interests include biomechanics – human joints, spine modelling and osteoporosis, multi-body dynamics – rigid and flexible systems, human body vibration control. He has received several prestigious awards, is the author of several books, and also serves as Associate Editor for two journals.

Dr. Jobes is a Mechanical Engineer for the National Institute for Occupational Safety and Health Pittsburgh Research Centre. After receiving two Bachelor degrees from Geneva College, he worked as a Software Consultant for a year. During his graduate studies at West Virginia University he developed a variable speed robot controller for his Masters and a remotely controllable residential circuit breaker for his Doctorate. He worked in control and navigation of a computer-assisted mining machine from 1987 through 1997. Dr. Jobes has since been working in the fields of Programmable Electronic Systems Safety and Jolting and Jarring Abatement in Mining Machinery.

1 Introduction

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 whole-body vibration (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. Shuttle car haulage vehicles are among the major sources of exposure to WBV, which includes 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 not changed much since 1984. The evidence for this includes data from injury reports gathered by the Mine Safety and Health Administration and testimonials from operators of these vehicles. During the 7-year period from 1993 to 1999, 13% of 10,393 powered haulage injuries in coal mining were attributed to vehicle jarring/jolting. Sixty-seven percent of the total (1,330) powered haulage injuries concerned underground operations. The LHDs/scoops, shuttle car, and mantrip are consistently the top three machine types cited for powered haulage-related injuries and accounted for 95% of the powered haulage incidents attributed to jarring/jolting for this period.

Mayton et al. (1999) previously studied a low-coal mine shuttle car haulage seat design that included limited underground mine field trials. The current seat design comparison study was a more comprehensive evaluation of the low-coal shuttle car seat design and included the evaluation of seat designs for a mid-coal shuttle car. With a larger sample of shuttle car operators, researchers were able to support earlier findings that NIOSH seats, with unique viscoelastic foam padding, better isolate shuttle car operators from vehicle jarring/jolting (Mayton et al., 2003).

Griffin (1990) defines absorbed power as the “power dissipated in a mechanical system as a result of an applied force”. He continues that “the vibratory power dissipated in the human body has variously been advocated as an indicator of discomfort from whole-body vibration or injury from hand-transmitted vibration”. Pradko et al. (1965) first introduced the concept of absorbed power as a way to measure the human response to WBV. Lee and Pradko (1968) discussed the analytical use of absorbed power to determine how humans would respond to vibration in the time and frequency domains for periodic and random environments. They concluded that the method of absorbed power is important in that it has physical significance; it can be measured and computed analytically. Moreover, absorbed power is a scalar quantity and thus can be summed to assess the human response in complex systems with multiple degrees of freedom.

More recently, Amirouche et al. (1994) and Tong et al. (1999a) reported on analytical computer models for optimising the energy absorption during exposure to human body vibration and for evaluating the distribution of absorbed power and the reaction of the body to roadway-induced vibration. Furthermore, Tong et al. (1999b) discuss how energy is transmitted to different parts of the body and what happens when input conditions change. Their model was developed to study the energy absorption and work done by the human body’s muscles (represented as springs and dampers) during a rough ride. They assert that understanding the energy flow among the body’s parts can provide valuable input for the design of a seat and its suspension.

According to Griffin (1990), the standard ISO 2631 (ISO, 1985) does not define a precise analysis method and requires some judgement in defining the optimum procedure according to its content. In a more recent assessment, Griffin (1998) concludes that it is possible to interpret ISO 2631 (ISO, 1997) as consistent with BS 6841 (1987), but adds that other interpretations are possible. Moreover, the American Conference of Governmental Industrial Hygienists (ACGIH, 2002) points out that the ANSI/ISO standard is not adequate for evaluating a vibration environment characterised by high-amplitude mechanical shocks (jars or jolts). It will ‘underestimate the effects of WBV ... when crest factors exceed 6’. However, ISO 2631 (ISO, 1997) has revised the crest factor upwards to a value of 9.

2 Method

Time and frequency response data were gathered with a digital data recorder, triaxial accelerometers, signal conditioning amplifiers, and in-line, 150 Hz, low-pass filters. Researchers collected data to measure levels of vehicle jarring/jolting experienced by the seated operators of shuttle car haulage vehicles. Triaxial accelerometers (PCB models 356B18 and 356B40) were placed on the floor of the operator's 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 on to the frame of the shuttle car, above the control panel. During the field trials, mine roadway conditions were noted as smooth, pothole-riddled, debris-strewn, rutted, dry, wet, or water-filled.

In gathering subjective data, researchers interviewed shuttle car operators with an interview guide consisting of seven basic questions. It was administered at the end of each trial for each seat and took about 10 minutes to complete. The questions were concerned with rating the seat in terms of comfort and perceived level of shock and vibration, operator likes and dislikes about seat features, how to improve the seat, and comparing the seats with each other.

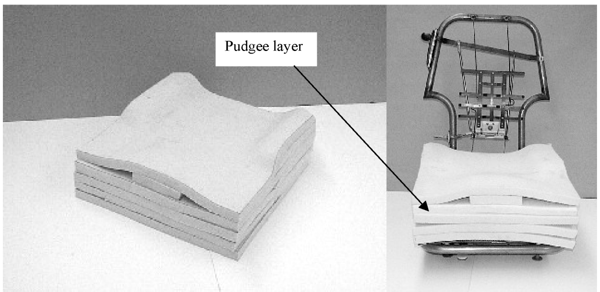
The remainder of the subjective data was collected using a linear visual analogue scale (VAS). It was used to obtain the operators' immediate impressions of shock, vibration, and discomfort levels for the vehicle ride on each of the seats. The VAS, a horizontal line about 10 cm long, was labelled 'zero or none' at one end and 'maximum' at the other end to indicate the extremes in levels of jarring/jolting and discomfort. Operators were asked to mark the line at a point that represented their discomfort and jarring/jolting levels. The shuttle car operator marked this scale after travelling with a full load of coal and with no load on the first, third, and sixth round trip of the trials for each seat. A round trip consisted of travelling to the coal face with no load and returning to the load discharge location with a full load of coal. The ratings were later translated into decimal values less than 1 and tabularised.

Field trials were conducted on shuttle car haulage vehicles operating at mid-coal seam and low-coal seam mines. Approximate specifications of the shuttle cars in the study included: weight – 13, 517 kg (29, 800 lb), overall length – 8.5 m (28 ft), width – 3 m (10 ft), wheel base – 2.7 m (9 ft), tire diameter – 0.8 m (2.7 ft), and travel speed – 8 km/hr (5 mph). Side-saddle style describes the mid-coal seam vehicle (the JOY 10SC) and how the vehicle operator is positioned in the vehicle cab. In this case, the operator remains in one seat and is perpendicular to, instead of facing, the direction of travel. The low-coal vehicle (the JOY 21SC) operator changed seats to face the direction of travel.

Four basic seat designs were compared on the shuttle cars. Mid-coal seam vehicle seats were designated as M1 (existing) and M2A and M2B (NIOSH) (Figure 1(a)). Low-coal seam vehicle seats, shown in Figure 2(a), were designated as L1 (existing) and L2A, L2B, and L2C (NIOSH). The viscoelastic foam padding arrangements distinguishing the different NIOSH seats are shown in Figures 1(b) and 2(b).

Figure 1 (a) Mid-coal seam shuttle car seats – existing (left) and NIOSH/Ergonomic (right): (b) Viscoelastic foam padding M2A (left – without pudgee) and M2B (right – with pudgee)

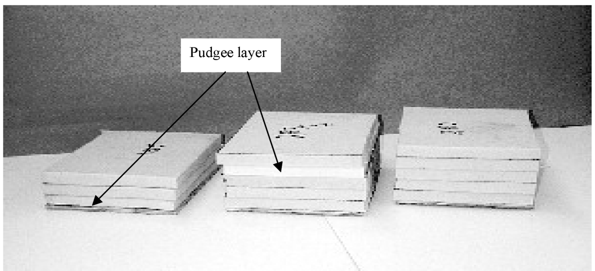
(a)



(b)

Figure 2 (a) Low-coal seam shuttle car seats – existing (left)and NIOSH/Ergonomic (right): (b) Viscoelastic foam padding arrangements from left to right, L2A, L2C, and L2B (without pudgee)

(a)



(b)

The existing seats were in service for some time and thus were more worn than the NIOSH seats, which were like new. The seats (after the NIOSH design) for the mid-coal seam shuttle cars were designated according to viscoelastic foam arrangements as follows:

- *seat M2A*: included a total thickness of 13 cm (5 in) of Sun-Mate Extra-Soft (XSS) foam padding
- *seat M2B*: included padding with a combination of Pudgee (PU) and XSS and a total thickness of 13 cm (5 in).

For the low-coal seam shuttle car, the seats (after the NIOSH design) were designated according to the viscoelastic foam arrangements as follows:

- *seat L2A*: included padding with a combination of PU and XSS and a total thickness of 8 cm (3 in)
- *seat L2B*: included a total thickness of 13 cm (5 in) of XSS foam padding
- *seat L2C*: included padding with a combination of PU and XSS and a total thickness of 13 cm (5 in).

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 old and averaged about 39 years. They ranged in height from 175 to 185 cm (69–73 in), an average of 180 cm or 71 in, and ranged in weight from 73 to 91 kg (160–200 lb), an average of about 87 kg or 191 lbs. The subjects' experience in operating a shuttle car varied from 2 to 24 years and averaged about nine years. Similarly, their underground mining experience varied from 2 to 37 years and averaged 14 years. Before participating in the study, the shuttle car operators were briefed and asked to sign informed consent and photo release forms.

3 Results

3.1 Subjective data

In summarising the results from the questionnaire data, the ratings reflect how the seats felt to the operator. For the mid-coal seam shuttle car, seat M2A is the favourite. Seat padding rated well for both seats M2A and M2B. Seat M1 is the least favourite in all ratings. Adding armrests is the improvement most often suggested for any of the seats.

For the low-coal seam shuttle car, seat L1 is the least favourite in all ratings. Seat padding, lumbar support, and seat-pan tilt are rated better in seat L2B than any other seat. The reclining back is better on seat L2B and surprisingly favoured on seat L1. Making the seat a better fit for the operator compartment is a suggested improvement. This could improve clearance between operator and controls and allow for better operator adjustability and visibility.

Average ratings from VAS responses indicated that the NIOSH-designed seats were superior to the existing shuttle car seats. For both no-load and full-load conditions, average ratings of mid-coal seam shuttle cars operators showed *lower* jarring/jolting and discomfort levels with the NIOSH seats using the two different 13-cm (5-in) viscoelastic foam padding arrangements. Seat M2A with 13 cm (5 in) of XSS foam padding was most preferred by operators of the mid-coal seam shuttle car. Similarly, for shuttle car no-load and full-load conditions, average ratings of low-coal seam shuttle car operators showed *lower* jarring/jolting levels with the NIOSH seat, using three different viscoelastic foam pad arrangements. The seats and viscoelastic foam padding arrangements, in order of operator preference, were seat L2B with 13 cm (5 in) of XSS foam, seat L2A with 8 cm (3 in) of PU/XSS foam, and seat L2C with 13 cm (5 in) of PU/XSS foam. Nevertheless, with regard to levels of discomfort, the average low-coal seam shuttle car operator rating favoured the existing seat slightly better than the NIOSH seat with the three different viscoelastic foam pad arrangements under full-load and no-load conditions. The explanation for this is that the closer proximity of the NIOSH seats to the control panel made the shuttle car operators feel awkward and slightly cramped. Researchers had to use existing bolt holes when mounting the NIOSH seats in the shuttle car. In addition, the NIOSH seats L2B and L2C with 13-cm (5-in) thick foam padding, elevated the operators higher, i.e. nearer to the canopy.

3.2 Objective data

Data segments showing greatest peak accelerations (most severe incidences of vehicle jarring/jolting) were selected from each vehicle operator data set for analysis. Figures 3 and 4 are examples of the frequency spectra for the operator/seat interface (output acceleration) and the frame (input acceleration) for the NIOSH seat 2C during full-load and no-load vehicle operation.

Figure 3 Frequency spectra input (frame) and output (operator/seat interface) for NIOSH Seat L2C when vehicle operated during full-load travel

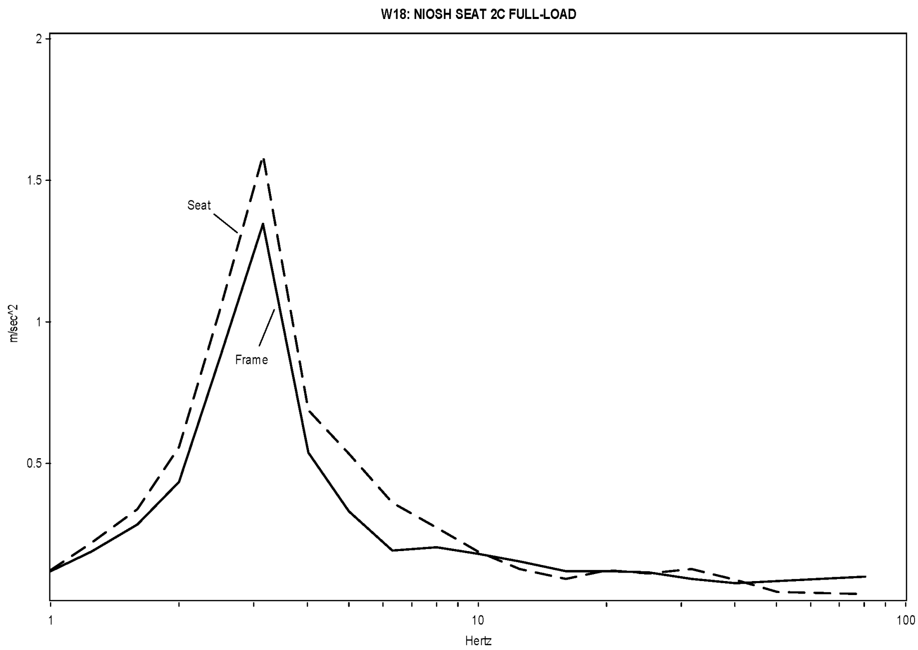
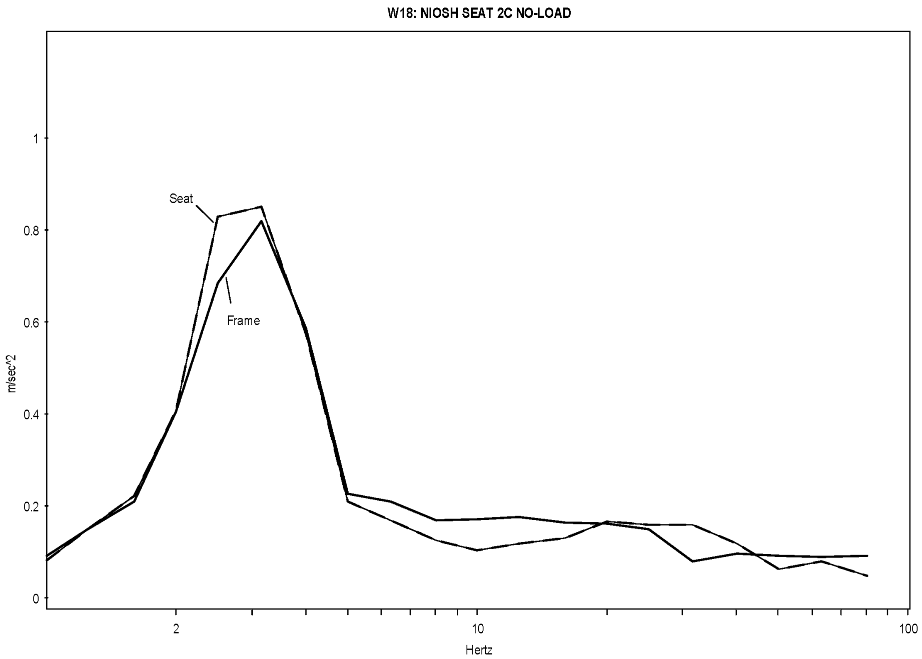


Figure 4 Frequency spectra input (frame) and output (operator/seat interface) for NIOSH Seat L2C when vehicle operated during no-load travel



3.3 Threshold limit method based on ISO 2631-1 (1985)

Exposure limits and total overall RMS accelerations (3-directions vector sum) for the low- and mid-coal shuttle cars are shown in Tables 1 and 2 with average values for each variable. The exposure limit times were computed from the daily exposure time-dependent curves, whereas total overall RMS accelerations were computed as the square root of the sum of the squares of the weighted accelerations for the x, y, and z axes (ACGIH, 2002). It should also be noted that higher exposure limit values indicate better isolation performance of the seat, whereas the reverse is true for the vector sum, i.e., the lower the value, the better the seat performance.

When comparing the average exposure limit values for the NIOSH seats L2A, L2B, and L2C, under full-load conditions their performance is 31–88% better (i.e., a worker can be safely exposed to the vehicle jarring/jolting environment measured for 61–175 additional minutes). Similarly, comparing the vector sum values, the NIOSH seats L2A, L2B, and L2C show a 15–19% reduction in total overall RMS accelerations.

The no-load conditions provided the more severe levels of jarring/jolting for the shuttle car operators. When comparing the average exposure limit values for the NIOSH seats L2A, L2B, and L2C, under no-load conditions their performance is 61–198% better than the existing L1 (i.e., a worker can be safely exposed to the vehicle jarring/jolting environment measured, for 77–249 additional minutes). Comparing the vector sum values, the NIOSH seats L2A, L2B, and L2C show a 19–46% reduction in total overall RMS accelerations.

Table 1 Exposure limits and total overall RMS accelerations (3-directions vector sum) for the low-coal seam shuttle car with average values according to seat and vehicle operator

Low-coal seam shuttle car					
		Full-load – ISO 2631		*No-load – ISO 2631*	
Seat	*Vehicle operator*	*Exposure limit,* min	*Vector sum,* m/sec^2	*Exposure limit,* min	*Vector sum,* m/sec^2
L1	1	240	1.81	138	2.55
	2	180	1.84	150	2.23
	3	180	2.16	90	3.35
	Average	*200*	*1.93*	*126*	*2.71*
L2A	1	243	1.73	144	2.51
	2	240	1.55	225	2.03
	3	300	1.64	240	1.68
	Average	*261*	*1.64*	*203*	*2.07*
L2B	1	360	1.45	150	2.63
	2	360	1.49	228	1.89
	3	330	1.74	240	2.09
	Average	*350*	*1.56*	*206*	*2.20*
L2C	1	ND	ND	ND	ND
	2	600	1.15	360	1.36
	3	150	2.12	390	1.59
	Average	*375*	*1.63*	*375*	*1.47*

ND: No data.

Table 2 Exposure limits and total overall RMS accelerations (3-directional vector sum) for the mid-coal seam shuttle car with average values according to seat and vehicle operator

Mid-coal seam shuttle car					
		Full-load – ISO 2631		*No-load – ISO 2631*	
Seat	*Vehicle operator*	*Exposure limit,* min	*Vector sum,* m/sec^2	*Exposure limit,* min	*Vector sum,* m/sec^2
M1	1	240	2.22	144	2.65
	2	540	1.37	300	0.92
	3	900	1.00	240	1.98
	4	450	1.48	180	2.20
	5	330	2.06	300	2.16
	Average	*492*	*1.62*	*233*	*1.98*
M2A	1	90	3.10	330	1.63
	2	440	1.49	660	1.13
	3	ND	ND	ND	ND
	4	200	2.06	400	1.48
	5	ND	ND	ND	ND
	Average	*243*	*2.21*	*463*	*1.41*

Table 2 Exposure limits and total overall RMS accelerations (3-directional vector sum) for the mid-coal seam shuttle car with average values according to seat and vehicle operator (continued)

Mid-coal seam shuttle car					
		Full-load – ISO 2631		*No-load – ISO 2631*	
Seat	*Vehicle operator*	*Exposure limit,* min	*Vector sum,* m/sec^2	*Exposure limit,* min	*Vector sum,* m/sec^2
M2B	1	180	2.44	147	2.43
	2	300	1.58	1140	0.97
	3	150	2.39	465	1.27
	4	210	2.06	420	1.48
	5	165	2.45	345	1.49
	Average	*201*	*2.19*	*503*	*1.53*

ND: No data.

For the mid-coal seam vehicle, Table 2 shows that the existing seat M1 performed better than the NIOSH seats for full-load conditions in terms of exposure limit and total overall RMS accelerations. Researchers suspect that this lower performance is attributable to a frame-mounted horizontal spring on which the viscoelastic foam padding rested in the NIOSH seats. This additional spring layer would increase accelerations at the operator/seat interface. However, under the more severe no-load conditions, the NIOSH seats performed better than the existing seat M1. When comparing the average exposure limit values for the NIOSH seats M2A and M2B under no-load conditions, their performance was 99–116% better (i.e., a worker can be safely be exposed to the vehicle jarring/jolting environment measured for 230–270 additional minutes). Comparing the vector sum values, the NIOSH seats M2A and M2B show a 23–29% reduction in total overall RMS accelerations.

Absorbed power

Lee and Pradko (1968) first introduced absorbed power as a way to measure the energy being transferred from the seat to the body. It is used to measure fatigue, endurance, and critical limits in human tolerance. The absorbed power, however, was never used in assessing the actual energy transferred between different body segments. Amirouche et al. (1994) introduced this concept by modelling the human driver as a lumped mass modelled with the muscles and inter-connective forces used as a combination of linear and nonlinear elastic springs and damping functions. The models are usually validated using accelerometers mounted on drivers' different body segments. In the model used to obtain the results presented in Tables 3 and 4, the human body is divided into five different body parts: legs, lower torso, middle torso, upper torso, and head. Each body part has its own mass and is connected to the corresponding body parts through springs and dampers. Each body part has only one degree of freedom, which is the vertical displacement. As input, the seat acceleration data about the z-axis were used to compute the results about the whole body. Absorbed power levels and RMS (vertical or z-direction) accelerations are for all vehicle operators using the different seats.

Table 3 Average absorbed power analysis for main body segments of vehicle operators driving a low-coal seam shuttle car. (The values below correspond to the average of the vertical accelerations obtained for each of five body parts: legs, lower torso, middle torso, upper torso and head)

		Low-coal seam shuttle car			
		Full-load		*No-load*	
Seat	*Vehicle operator*	*RMS vertical acceleration*, m/sec^2	*Absorbed power*, watts	*RMS vertical acceleration*, m/sec^2	*Absorbed power*, watts
L1	1	1.87	1.00	3.58	1.40
	2	0.52	0.30	1.85	0.95
	3	0.85	0.45	4.61	2.03
	Average	*1.08*	*0.58*	*3.35*	*1.46*
L2A	1	0.52	0.33	2.52	1.57
	2	0.30	0.22	1.75	1.04
	3	0.39	0.24	1.77	0.97
	Average	*0.40*	*0.26*	*2.01*	*1.19*
L2B	1	0.19	0.15	3.36	1.85
	2	0.30	0.15	2.01	1.07
	3	1.93	0.97	2.25	1.22
	Average	*0.80*	*0.42*	*2.54*	*1.38*
L2C	1	ND	ND	ND	ND
	2	0.23	0.13	1.31	0.69
	3	0.24	0.21	1.79	0.99
	Average	*0.24*	*0.17*	*1.55*	*0.84*

ND: No data.

Table 4 Average absorbed power analysis for main body segments of vehicle operators driving a mid-coal seam shuttle car. (The values below correspond to the average of the vertical accelerations obtained for each of five body parts: legs, lower torso, middle torso, upper torso and head)

		Mid-coal seam shuttle car			
		Full-load		*No-load*	
Seat	*Vehicle operator*	*RMS vertical acceleration*, m/sec^2	*Absorbed power*, watts	*RMS vertical acceleration*, m/sec^2	*Absorbed power*, watts
M1	1	0.36	0.17	0.32	0.32
	2	0.30	0.14	0.30	0.16
	3	0.08	0.07	0.49	0.14
	4	0.18	0.13	0.14	0.14
	5	0.25	0.15	0.37	0.17
	Average	*0.23*	*0.13*	*0.13*	*0.18*

Table 4 Average absorbed power analysis for main body segments of vehicle operators driving a mid-coal seam shuttle car. (The values below correspond to the average of the vertical accelerations obtained for each of five body parts: legs, lower torso, middle torso, upper torso and head) (continued)

		Mid-coal seam shuttle car			
		Full-load		*No-load*	
Seat	*Vehicle operator*	*RMS vertical acceleration*, m/sec^2	*Absorbed power*, watts	*RMS vertical acceleration*, m/sec^2	*Absorbed power*, watts
M2A	1	0.16	0.21	0.18	0.13
	2	5.04	0.10	36.35	0.10
	3	ND	ND	ND	ND
	4	1.34	ND	2.28	0.00
	5	ND	0.00	ND	ND
	Average	*5.04*	*0.10*	*12.94*	*0.08*
M2B	1	0.15	0.16	0.18	0.18
	2	0.09	0.11	0.08	0.07
	3	0.11	0.15	0.07	0.07
	4	0.11	0.14	0.13	0.10
	5	0.28	0.15	0.12	0.09
	Average	*0.15*	*0.14*	*0.12*	*0.10*

ND: No data.

As input, the vertical acceleration of the seat was used to compute its vertical displacement. Researchers supplied the displacements computed for the spring and damper connecting the seat to the lower torso. The programme, consequently, provides the acceleration of each body part which is used to compute the RMS acceleration for each body. Using the acceleration and the forces applied to each body part (the weight of the higher body parts), the labour is obtained. Integrating the labour with regard to time, the absorbed power is obtained for each body part. Next, the average absorbed power for each body part is computed with regard to the time. Using these averages, the average absorbed power representing the driver's body is computed. RMS acceleration is the sum of the RMS accelerations for each body part.

For both shuttle car models, the sum of the energy during the selected operator exposure times (absorbed power) varied from 0.00 to 1.00 watts during full-load travel and from 0.00 to 2.03 watts during no-load travel. In general, for the more severe no-load travel, the NIOSH seats showed lower levels of absorbed power, i.e., the vibration energy absorbed by the body. These seats, with the viscoelastic foam padding, exhibited higher damping and better energy dissipation during exposure to vibration, thus indicating better comfort. Indeed, absorbed power is the actual energy being circulated at the body level and is, in most cases, less than the actual energy transferred from the seat. This result occurs from the body's ability to dissipate the transmitted energy as a form of heat (sweat), perspiration, and muscle fatigue. What remains in the body is usually given back through the muscles (springs).

4 Discussion

The preceding results, using both the ISO 2631-1 (1985)-based threshold limit method from ACGIH (2002) and absorbed power method of analysis, support the notion that NIOSH seat designs are superior to the existing vehicle seat designs on both models of mine shuttle cars used in this study. The NIOSH seat designs, featuring viscoelastic foam padding, were more effective in reducing vibration energy for operators exposed to vehicle jarring/jolting.

Furthermore, the unique contribution of this paper stems from its in-depth analysis using experimental data and analytical tools such as the RMS acceleration, the ISO 2631-based protocol, and absorbed power to evaluate different seating designs and seats with different padding conditions. It is quite remarkable how the seats at low frequency favour the padding with high damping and viscoelastic materials more, whereas high accelerations with random jolting seem to be unresponsive to cushion and padding when the body is in an excited vibration mode, where much more human effort is expended to tolerate the energy, vibration, and exposure time. In most cases, the primary suspension of the seat must be designed to reduce the vibration so that the secondary suspension (the seat padding) can then play this critical role. This paper is a good illustration of such a development.

Acknowledgements

The authors thank Dean H. Ambrose, N. Kumar Kittusamy, Sc.D., and Timothy J. Matty for their contributions to this work. In addition, the authors thank the following engineering technicians at the NIOSH Pittsburgh Research Laboratory: Albert H. Cook, George F. Fischer, and Mary Ellen Nelson. The authors also express their gratitude to Wayne Persinger, Safety Director for the Laurel Alma and Black King Mines of Elk Run Coal Co. (an affiliate of A.T. Massey Corp.). Lastly, the authors thank Ron Dickey of JOY Mining Machinery, a subsidiary of Harnischfeger Industries, and Charles Yost of Dynamic Systems, Inc., for their help and support in this work.

References

ACGIH (2002) 'Threshold limit values (TLVs) for chemical substances and physical agents and biological exposure indices (BEIs)', *American Conference of Governmental Industrial Hygienists*, Cincinnati, OH, pp.124–131.

Amirouche, F., Xie, M. and Patwardhan, A. (1994) 'Energy minimization to human body vibration response for seating/standing postures', *Journal of Biomechanical Engineering*, Vol. 116, No. 4, pp.413–420.

Amirouche, F., Xu, P. and Alexa, E. (1997) *Evaluation of Dynamic Seat Comfort and Driver's Fatigue*, Technical Paper 971573, Society of Automotive Engineers, Warrendale, PA.

British Standards Institution BS 6841 (1987) Measurement and evaluation of human exposure to whole-body mechanical vibration.

Griffin, M.J. (1990) *Handbook of Human Vibration*, Academic Press Ltd., NY, pp.476, 799.

Griffin, M.J. (1998) 'A comparison of standardized methods for predicting the hazards of whole-body vibration and repeated shocks', *Journal of Sound and Vibration*, Vol. 215, No. 4, pp.883–914.

ISO (1985) '*ISO 2631/1 – Mechanical Shock and Vibration – Evaluation of Human Exposure to Whole-Body Vibration, Part 1*, International Organization for Standardization, Geneva, Switzerland.

ISO (1997) ISO 2631/1 – *mechanical Shock and Vibration – Evaluation of Human Exposure to Whole-Body Vibration, Part 1*, International Organization for Standardization, Geneva, Switzerland.

Lee, R.A. and Pradko, F. (1968) 'Analytical analysis of human response to vibration', *Technical Paper 680091*, Society of Automotive Engineers, Warrendale, PA.

Mayton, A.G., Ambrose, D.H., Jobes, C.C. and Kittusamy, N.K. (2003) 'Ergonomic and existing seat designs compared on underground mine haulage vehicles', *Proceedings of the Human Factors and Ergonomics Society 47th Annual Meeting*, Human Factors and Ergonomics Society, Santa Monica, CA, pp.1256–1260.

Mayton, A.G., Merkel, R. and Gallagher, S. (1999) 'Improved seat reduces jarring/jolting for operators of low-coal shuttle cars', *Mining Engineering*, Vol. 51, No. 12, pp.52–56.

Pradko, F., Orr, T.R. and Lee, R.A. (1965) 'Human vibration analysis', *Technical Paper 650426*, Society of Automotive Engineers, Warrendale, PA.

Remington, P.J., Andersen, D.A. and Alakel, M.N. (1984) '*Assessment of Whole Body Vibration Levels of Coal Miners, Volume II: Whole-Body Vibration Exposure of Underground Coal Mining Machine Operators*', Bolt, Beranek, and Newman, Inc., Cambridge, MA, US Bureau of Mines contract No. J0308045, NTIS No. PB 87-144-119.

Tong, R., Amirouche, F. and Nishiyama, S. (1999a) 'Analysis of absorbed power distribution in ride dynamics: evaluation of driver's comfort', *Proceedings of the ASME Symposium: Innovations in Vehicle Design and Development*, American Society of Mechanical Engineers, New York, NY, Vol. 101, pp.53–60.

Tong, R., Amirouche, F. and Palkovics, L. (1999b) 'Ride control: a two-state suspension design for cabs and seats', *Proceedings of the 16th Symposium of the International Association for Vehicle System Dynamics*, Pretoria, Republic of South Africa, Vol. 33, Suppl. 1, pp.578–589.