EVALUATION OF SEAT DESIGNS RELATIVE TO TRANSMITTED VEHICLE VIBRATION ON UNDERGROUND MINE TRANSPORT VEHICLES

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ABSTRACT

The National Institute for Occupational Safety and Health (NIOSH) researchers have investigated seat design issues for the occupants and operators of underground mine transport vehicles relative to whole-body vibration (WBV) and mechanical shock. Considering the ergonomic and engineering improvements made to underground mine shuttle car seats, this study has focused on reducing injury risk by improving seating on transport vehicles such as scoops, mantrips, personnel carriers, and rail-mounted locomotives. Similarly, proposed seat design improvements included layering of various types of viscoelastic foam padding to isolate vehicle occupants and operators from adverse health effects of jarring/jolting exposure. This paper discusses the results obtained from laboratory vibration testing of new seat padding materials in seven configurations at the NIOSH – Pittsburgh Research Laboratory (PRL) showing that careful use of configuration and materials can reduce the operator's exposure to WBV. In addition, results for four mine transport vehicles are presented from field data collection efforts at a Southwestern Pennsylvania mine showing that a NIOSH based design does reduce the operator's exposure to WBV. Finally, the authors discuss efforts to develop and field test seat padding interventions using new padding materials and configurations based on the laboratory test results [The findings and conclusions in this report are those of the author(s) and do not represent the views of the National Institute for Occupational Safety and Health.]

INTRODUCTION

Mobile mining equipment can expose workers to whole-body vibration (WBV) and mechanical shock. This exposure can adversely affect their health, safety, comfort, as well as, working efficiency and performance. Remington et al. (1984) documented WBV exposure for operators of underground mining equipment. For mining equipment, proper seat design is an important consideration in reducing the adverse effects of WBV exposure to vehicle operators.

Mayton et al. (1999, 2003, and 2005) reported on improved seat designs for underground mine shuttle cars. Current research is an extension of this work and focuses on seat designs for underground mine transport vehicles. NIOSH developed seat designs include padding with selected viscoelastic foams that have undergone extensive laboratory vibration experiments. During vibration exposure, the unique qualities of these foams provide responses similar to those found in a mechanical spring/damper suspension system and thus, isolation for the seated occupant or operator. In contrast, many existing transport vehicle seats, which typically include inexpensive foam padding commonly used in furniture, provide minimal isolation from vibration.

THESIS

Seat designs using viscoelastic foam padding offer better alternatives to existing seat designs for mine transport vehicles in isolating operators from vehicle jarring/jolting and for reducing discomfort. As demonstrated in prior mine shuttle car seat studies (Mayton et al. 1999, 2003, and 2005), researchers intend to show similar enhancements in isolating the seated vehicle operator/occupant from vehicle jarring/jolting and improving comfort. Seat padding improvements developed through NIOSH laboratory vibration testing are good interventions in reducing risk of back injuries on transport vehicles. This paper presents results of initial laboratory testing of seat padding options and configurations. It also presents results of field data collected on selected mining transport vehicles of vehicle vibration exposure for the seated occupants/operators.

METHODS

Laboratory vibration tests of different seat padding materials

In the laboratory, researchers conducted vibration testing with a MTS® shaker table [Mention of any company or product does not constitute endorsement by the National Institute for Occupational Safety and Health] and seven different seat/seat padding configurations (see Table 1). The objective was to ascertain which configuration provided the best damping of the seat/seat padding selections for the vibration test conditions. A SONY PC208 AX, 8-channel digital data recorder and PCB tri-axial accelerometers and signal conditioning amplifiers were used to measure and record accelerations on the shaker table, the seat/mass interface and on the mass itself. The seat designs included foam padding composites with different 1-in thick layers of

Table 1. Test seat configurations.

Seat Design	Bottom		→			Top
	Spring	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
1	Yes	XS	XS	XS	PU	XS
2	Yes	XS	XS	XS	XS	XS
3	No	XS	XS	XS	PU	XS
4	No	XS	XS	XS	XS	XS
5	No	YIM	XS	XS	PU	XS
6	No	YIM	XS	XS	XS	XS
7	No	BIM	XS	XS	PU	XS
Materials Used: XS – Extra Soft Sunmate, PU – Pudgee, YIM – Yellow Impact Material, and BIM – Blue Impact Material						

viscoelastic foams and viscoelastic polymer materials. The sequence of foams was altered for some designs, whereas, all designs were assembled into a total seat pad thickness of 127 mm (5 in) and incorporated into an off-the-shelf seat. Analysis of the data included calculating the ratio of the seat pad root-mean-square (RMS) acceleration to the shaker table RMS acceleration. This ratio is commonly referred to as transmissibility and is an established way of expressing how well the seat suspension is isolating the occupant from vehicle vibrations.

Researchers tested the seat/seat padding designs according to the ISO 5007 Standard section 10.1 that required a sinusoidal peak-to-peak amplitude vibration of ±15 mm (0.6 in) at a test frequency range from 0.5 to 2 Hz at 0.05 Hz intervals. The ISO 5007 Standard test procedure was modified to include the frequency range from 2 to 8 Hz at 0.25 Hz intervals and test masses (weights) of 40 and 80 kg (88 and 176 lbs). The latter frequency was added to aid in developing transmissibility curves for each seat/seat padding configuration, whereas the 40-kg (88-lb) and 80-kg (176-lb) weights were specified in ISO 5007 and used to approximate the upper torso weights of the seated 5th percentile female and 95th percentile male vehicle operators. After a few tests, the amplitude criteria was reduced by one-half to ± 7.5 mm (0.3 in) instead of the ± 15 (0.6 in) mm due to researchers' safety concerns. At certain test frequencies, the seat/mass system became extremely difficult to control because of forces generated by the shaker system. Subsequently, all tests were performed at the lower amplitude. This change from the ISO 5007 standard did appear to modify the results in the 0.5 Hz to 1 Hz range due to the low amplitudes in the acceleration data. For foam seat pads, the transmissibility in this range should be close to 1, but with the adverse signal to noise ratio in this range, the results in this range are inaccurate.

The test run procedures included the following steps:

1. With the loaded seat on the shaker table, researchers conducted the vibration tests in amplitude control mode with a displacement of ±7.5mm (0.3 in) loaded with 40 kg (88 lbs). The tests comprised frequencies from 0.5 Hz to 2 Hz in 0.05 Hz intervals and from 2 Hz to 8 Hz in 0.25 Hz intervals; each interval was recorded for 15 s.
2. Using the same test setup in step number 1, researchers reversed the frequency order (8 – 2 Hz in .25 Hz intervals and 2 to .5 Hz in .1 Hz intervals) as specified by the ISO 5007 standard and its modification for our use.
3. Again with the loaded seat on the shaker table, researchers conducted the vibration tests in amplitude control mode with a displacement of ±7.5mm (0.3 in) loaded with 80 kg (176 lbs). Similarly, the tests comprised frequencies from 0.5 Hz to 2 Hz in 0.05 Hz intervals and from 2 Hz to 8 Hz in 0.25 Hz intervals; each interval was recorded for 15 s.
4. Researchers ran the same test setup in step number 3 reversing the frequency order.

Mine field data collection

Underground mine field data were collected at a mine near the town of Washington in Southwestern Pennsylvania. The coal seam thickness and mining height for the mine averaged 183 cm (72 in) with a range of 152 to 244 cm (60 to 96 in) for seam thickness. Seam height averaged about 66 inches in the area in which tests were conducted. NIOSH researchers collected vibration data on three rail vehicles and a rubber tired scoop with the same instrumentation used for laboratory tests: a data recorder, tri-axial accelerometers, signal conditioning amplifiers and in-line 150-Hz, low-pass filters. Data were gathered on existing seat designs for two personnel carriers or "mantrips," a locomotive, and a mine scoop (Fig. 1). One mantrip (designated mantrip #1 in the results section) featured a NIOSH-based seat design supplied by a company collaborating with NIOSH research, while the

Figure 1– A scoop traveling along mine roadway.

other seat designs on the other mantrip and other vehicles were supplied by the original equipment manufacturer (OEM). Acceleration data were collected to determine the energy transmitted from the vehicle frame through the floor and entering the seat. Tri-axial accelerometers are typically placed on the floor of the operator 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 a higher portion of the vehicle's frame. Mine roadway and rail conditions were noted during data collection.

RESULTS

Laboratory Data

Researchers created graphs of transmissibility versus frequency to aid in analyzing the seat design response to vibration test conditions. Figures 2 and 3 show the results of laboratory tests for the seven seat/seat padding configurations using 40- and 80-kg masses (88- and 176-lb), respectively. The curves represent the average of the ascending and descending frequency order of testing. The horizontal straight line represents transmissibility (output acceleration/input acceleration) equal to 1.

Values greater than 1 demonstrate amplification of the transmitted vibration, whereas, transmissibility less than 1 indicates attenuation of vibration. Considering curves for the 40-kg (88-lb) mass, peak amplitudes of vibration for seat designs 1 and 2 occur between 3.5 and 4.0 Hz, whereas peak amplitudes for the remaining seat designs 3 through 7 occur between 5.0 and 6.0 Hz. Similarly, for the 80-kg (176-lb) mass, peak amplitudes of vibration for seat designs 1 and 2 occur between 3.25 and 3.5 Hz, whereas peak amplitudes for

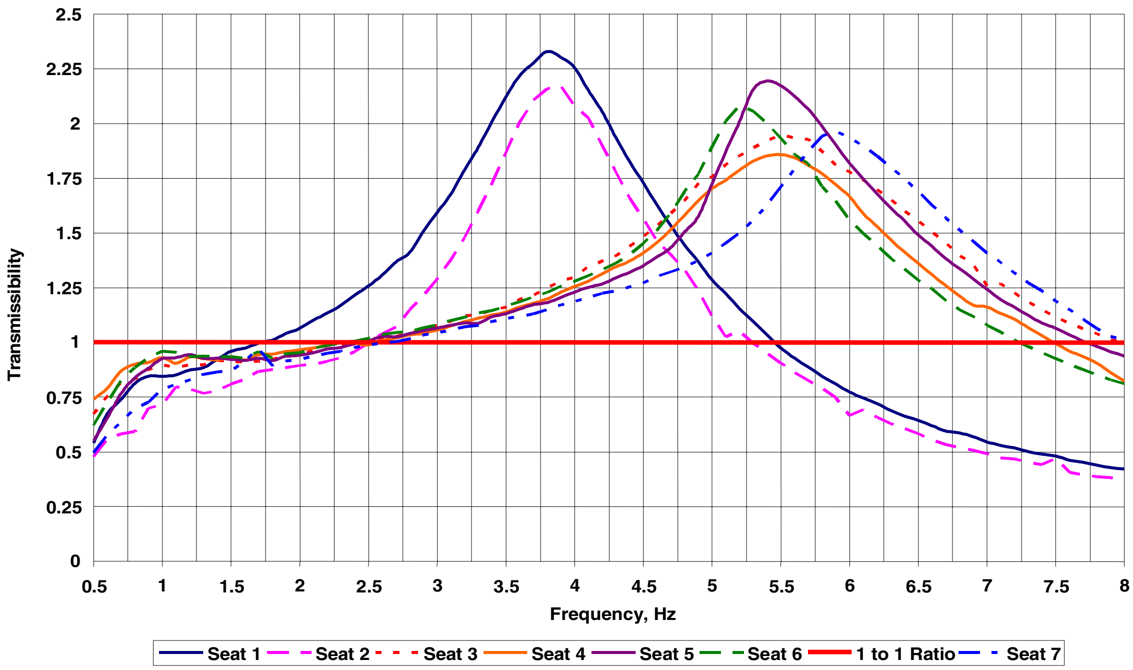

Figure 2 - Test results for the seat/seat padding configurations using the 40-kg (88-lb) mass.

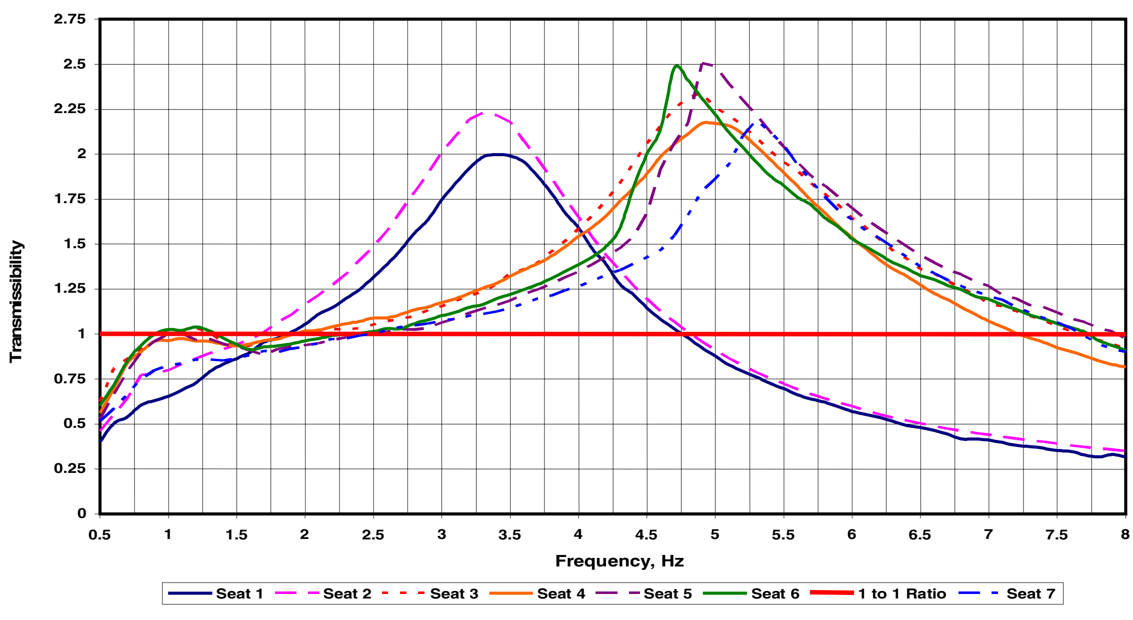

Figure 3 - Test results for the seat/seat padding configurations using the 80-kg (176-lb) mass.

seat designs 3 through 7 occur between 4.5 and 5.5 Hz. Seat designs 1 and 2 included an internal horizontal spring, typically included in automotive seats. Attenuation of vibration seat designs 1 and 2, using the 40-kg (88-lb) mass, occurs at a frequency below 2.5 Hz (for seat design 2) and below 1.75 Hz (for seat design 1) and above 5.25 Hz (for both designs). For designs 3 through 7, attenuation occurs below 2.5 and above 7.25 Hz. Attenuation of vibration for seat designs 1 and 2, using the 80-kg (176-lb) mass, occurs at a frequency below 2 Hz and above 4.75 Hz. For seat designs 3 through 7, attenuation occurs 1.25 and 2.0 Hz and above 7.25 Hz. Seat designs 1 and 2 show higher peak amplitudes or greater amplification that are just the reverse of each other when the 40-kg (88-lb) mass is used versus 80-kg (176-lb) mass.

Field Data

Table 2 presents the results of the measured data. The input acceleration data was obtained by a tri-axial accelerometer attached to the vehicle frame and was low-pass filtered at 150 Hz. The output acceleration data was obtained from a tri-axial accelerometer built into a seat pad upon which the operator sat and was also low-pass filtered at 150 Hz. The output to input ratios were obtained for both RMS and peak accelerations and the crest factor was generated as a ratio of the Peak to RMS accelerations. Several ISO metrics pertaining to the output acceleration data were also generated: *exposure limit (EL)*, *fatigue decreased proficiency limit (FDP)*, and *reduced comfort boundary (RCB)* as well as a vector sum generated using a total weighted RMS acceleration for all three axes according to ACGIH (2006).

The results show that the NIOSH based seat design exhibits greater attenuation of vehicle jarring/jolting levels for the seated operator/occupant. Of the rail vehicles tested (mantrips and locomotive), the NIOSH based design seat shows a performance in the peak and RMS transmissibility metrics almost an order of magnitude better than the OEM seat designs tested. Also, the vector sum (a measure of the operator's exposure to WBV) is significantly lower showing improved performance in isolating the operator from WBV.

DISCUSSION

The laboratory vibration tests were analyzed by plotting transmissibility against vibration frequency. The two left-most curves in Figures 1 and 2 represent data for seat designs that incorporated an internal horizontal spring upon which the foam padding rests. The presence of this spring in the seat shows a shift to the left or reduction in frequency for seats 1 and 2. Although all of the seat foam configurations show amplification for a large portion of the frequency range tested, the single seat foam showing the lowest amplitude was the foam used in seat design 3.

The foam padding configurations of all seven seat designs tested in the laboratory show amplification of vibration as indicated by transmissibility values greater than 1. Amplification of the vibration levels may or may not adversely affect health. The effect of vibration exposure on the seated vehicle occupant depends not only on the frequency, but also on the exposure time and magnitude of vibration. Thus, the authors, in view of the test results and past experience, conclude that any use of the tested seat foam padding configurations should not negatively affect the health of seated vehicle occupants. Nevertheless, PRL researchers are committed to determining the seat padding foam(s) and configuration(s) that would provide the best seat padding option for occupants and operators of mine transport vehicles in terms of attenuating vibration and comfort. Furthermore, the seats on the mine transport vehicles for which vibration levels were measured should also have no negative effects in view of the Threshold Limit Value (TLV) guidelines (ACGIH, 2006).

The quantitative levels of vehicle jarring/jolting for rail vehicles was generally larger than that of the rubber tired scoop being tested. In general, this is due to the floor conditions for the scoop (being soft and muddy without significant potholes) and the rail and switch conditions (typical of any mine) experienced by the man trips and the locomotive. The crest factor is designed to take this into account by dividing the peak ratios by the RMS ratios to generate a unit-less number which represents how well a seat design handles jolting/jarring. As can be seen from the data, the crest factors in all tests are comparable. There has been 9

Table 2. Overall averages of measured jarring/jolting levels for operators of various mine transport vehicles.

Equipment	RMS			Peak			Crest Factor			ISO Metrics			
	Frame (m/s^2)	Seat (m/s^2)	Ratio	Frame (m/s^2)	Seat (m/s^2)	Ratio	Frame (m/s^2)	Seat (m/s^2)	Ratio	EL (min.)	FDP (min.)	RCB (min.)	Vector Sum (m/s^2)
Mantrip #1	0.71	0.47	0.66	5.81	3.38	0.58	8.49	7.65	0.89	7680	2380	460	0.38
Scoop	1.94	1.08	0.56	47.14	22.93	0.49	24.26	21.19	0.87	2880	930	180	0.73
Locomotive	7.93	1.49	5.31	4.75	1.17	4.06	0.60	0.78	0.77	960	420	60	0.83
Mantrip #2	10.86	1.99	5.46	7.13	1.53	4.66	0.66	0.77	0.85	960	360	60	1.19

much discussion amongst researchers as to whether the crest factor is the best measure of jarring/jolting and many are now looking to the ISO criteria previously mentioned. The ACGIH (2006) using the ISO (1985)-based criteria indicate 6 as the value above which the effects of WBV will be underestimated. Moreover, this ISO criteria includes the use of third octave analysis of the seat acceleration experienced by the operator (typically in the vertical direction) over-plotted on an ISO-curves graph. The vector sum (the overall total weighted RMS acceleration) alternatively attempts to take into account the weighted RMS accelerations experienced by the operator in all three axes. The limiting value of crest factor has been updated to 9 in ISO (1997), which also recommends use of the fourth power vibration dose value procedure when the calculated crest factor exceeds 9. When considering the vector sum values computed for the recorded field data, the NIOSH-based seat design indicated the most positive result.

An example of a potential seat padding intervention for transport vehicles is the “throw pad” (Fig. 4) which was developed by RM Wilson Company in collaboration with management at the mine. It is a 35.6-cm (14-in) square and 6.4-cm (2-1/2-in) thick folding pad (covered in a black vinyl material) with a handle that workers could carry around with them. It was originally intended for maintenance workers, who needed the flexibility of a portable pad that can be used not only for sitting, but kneeling and lying down depending on the work task performed. NIOSH researchers are considering the “throw pad” as an intervention applicable for a variety of transport vehicles and optimizing the padding selection and configuration through laboratory vibration investigations.

Figure 2 - The portable “throw pad” features connected seat and backrest pads with loop handle. 0

Limitations

The ISO 5007 procedure was developed for testing mechanical seat suspension systems, thus demonstrating the need for researchers to modify the procedures for testing the different foam configurations. Field data was limited to only 4 vehicles and a small number of samples. A meaningful comparison of field test seat transmissibility and laboratory test transmissibility results isn’t feasible due to resolution issues inherent in the third octave analysis performed on the field test data.

Other limitations that may affect the results include, but are not limited to, the use of a solid weight instead of a human body during laboratory testing, and use of the sine wave excitation function instead of random vibration that would approximate vehicle jarring/jolting. Nonetheless, researchers believe the results of this work show careful selection of seat padding materials and configurations can provide greater vibration attenuation and positively effect mine workers that are exposed to vehicle jarring/jolting when riding or operating mine transport vehicles.

The testing of foam padding materials continues in order to determine the optimum padding and configuration. Future effort will include completing laboratory testing of the different and new seat padding foams and the selection of best configuration for use in the vibration environment of the aforementioned vehicles. The optimum foam padding will be incorporated in the “throw pad” or other intervention and tested in the field during actual coal mining operations.

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