COMPARISON OF WHOLE-BODY VIBRATION EXPOSURES ON OLDER AND NEWER HAULAGE TRUCKS AT AN AGGREGATE STONE QUARRY OPERATION

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ABSTRACT

Exposure to whole-body vibration (WBV) and the postural requirements of the job have been identified as important risk factors in the development of musculoskeletal disorders of the back among workers exposed to a vibratory environment. This paper focuses on preliminary results of WBV data collected for two groups of haulage trucks – four older trucks from manufacturer A (MFR-A) and two newer trucks from manufacturer B (MFR-B).

All of the trucks and their respective seats were considered to be in good working order during the study. Measurement periods for the truck groups had similarities, but varied from 2 to 58 minutes. Sampling times for the older trucks included a mean of 19.5 minutes and a standard deviation (STD) of 6.5 minutes compared to a mean of 40.8 minutes and a STD of 12.1 minutes for the newer trucks. Data collection coincided with the approximate delivery and first operation of the new trucks, and occurred approximately 12 months apart under similar weather and road conditions, and with the same drivers except an additional driver was included with the older trucks. Truck routes were somewhat different in that quarry production had changed location in the time between data collection activities. Overall, the results suggest that the newer trucks may provide better overall isolation to drivers/operators from WBV exposure compared to the older trucks operating at the quarry; although, this will need to be confirmed with additional measurements. Considering the higher variability and shorter sampling times for the older trucks, the results should be viewed with caution. For two of seven trials, the older trucks showed that seats amplified vibration, i.e., a transmissibility (T) >1.0. Seat T for the older trucks ranged from 0.31 to 1.17 with a mean of 0.77 and STD of 0.32. This contrasted with the newer haulage trucks where seats amplified vibration in 3 of 8 trials. In this case, T did not vary greatly and ranged from 0.87 to 1.05 with a mean of 0.97 and STD of 0.07. Regarding older trucks, in five of seven trials, the seat (output) data of weighted root-mean square (RMS) acceleration ($wRMS_Z$) for the dominant z-axis exceeded the action level of 0.5 m/s^2 action level recommended by the European Union Good Practice Guide for WBV (EUGPG) and levels exceeded the recommended exposure limit of 1.15 m/s^2 in two of the seven trials. The $wRMS_Z$ values for the older trucks varied from 0.41 to 1.83 m/s^2 with a mean of 0.99 and STD of 0.57. Similarly, newer trucks indicated a narrower range of $wRMS_Z$ from 0.38 to 0.95 m/s^2. The mean $wRMS_Z$ was lower for the newer trucks at 0.58 m/s^2 with a STD of 0.23 m/s^2. Similarly, newer trucks indicated $wRMS_Z$ reached or exceeded the action level in four of eight trials. None of the trials with the new trucks showed $wRMS_Z$ levels that reached or exceeded the recommended 1.15 m/s^2 exposure limit. As an indicator of driver/operator discomfort, overall weighted total RMS acceleration (vector sum) values seem to show a "rougher" ride for the older trucks. The vector sum values for these trucks ranged widely from 0.70 to 2.59 m/s^2 and, in four of seven trials, showed levels greater than 1.40 m/s^2. The mean vector sum was 1.44 m/s^2 with a STD of 0.75 m/s^2. Comparatively, the newer trucks exhibited less variation with a range from 0.69 to 1.59 m/s^2. The mean vector sum was 1.02 m/s^2 with a STD of 0.35 m/s^2. Vibration dose values for the dominant z-axis (VDV_Z), gave a sense of vehicle jarring/jolting conditions. All trials with the older trucks were within the recommended EUGPG action level of 9.1 m/s$^{1.75}$. On the other hand, in three of eight trials, both newer trucks exceeded this action level with values of 9.18, 12.58, and 13.21 m/s$^{1.75}$. Neither truck group showed VDV_Z that exceeded the exposure limit of 21 m/s$^{1.75}$. A statistical analysis was not conducted, since the differences reported between truck groups may not be statistically significant owing to the relatively small sample size. Road conditions, changes in the truck routes, and driver/operator differences (e.g., stopping and turning) are possible factors in the higher VDV for the newer trucks.

1 INTRODUCTION

Operation of earth-moving equipment contributes to some of the most common, prolonged, and severe occupational exposures of vehicle vibration among equipment operators. Whole-body vibration (WBV) is mechanical vibration or shock transmitted to the body as a whole [1]. The recognition of potential hazards has resulted in standards that address vibration transmitted by seats and the vibration exposure of vehicle operators [1-3].

Exposure to whole-body vibration (WBV) and the postural requirements of the job have been identified as important risk factors in the development of musculoskeletal disorders of the spine among workers exposed to a vibration environment [4-10]. Acute health effects from WBV exposure include loss of visual acuity, postural stability and manual control; whereas chronic health effects include low back pain, early degeneration of the spine, herniated discs, and digestive and circulatory disorders. Moreover, WBV may also contribute to the development of noise-induced hearing loss [11].

2 BACKGROUND

An assessment of WBV exposure was conducted at a U.S. eastern mid-Atlantic crushed stone operation. Company management had received a number of verbal and written responses from haulage truck drivers about back symptoms and vibration issues while performing their regular work cycles. As part of their ergonomics training, risk factor report cards submitted by employees indicated low back discomfort was the most frequently reported at one quarry, and exposure to bouncing and jarring was reported on a high percentage of cards. In some cases, employees indicated that the discomfort was associated with the seating in vehicles. Consequently, company managers were interested in evaluating seating and operator exposure to WBV at the driver/seat interface for older and newer model haulage trucks. Managers were also interested in establishing a baseline of data for new trucks brought into service to compare with data collected later at 6-month intervals. The purpose of the repeated measures was to monitor the performance of older and newer truck models relative to WBV exposures as a means for determining when vehicle (e.g., suspension system) and seats required maintenance or replacement.

3 METHODS

National Institute for Occupational Safety and Health (NIOSH) researchers collected data related to WBV exposure, global positioning system (GPS), and seat vibration transmissibility. WBV exposure data was collected on four older and two newer haulage trucks, (Table 1). Although the older haulage trucks were rear-dump style vehicles, they differed from the newer trucks by year of manufacturer, age, and capacity. Vibration measurements were recorded with an 8-channnel, digital data recorder (model PC208Ax, Sony Manufacturing Systems America, Lake Forest, CA). Other instrumentation (PCB Piezotronics, Inc. Depew, NY) included tri-axial accelerometers (models 356B18, 356B40), signal conditioning amplifiers (model 480E09), and in-line, 150-Hz low-pass filters (model 474M32). The floor or frame mounted accelerometer featured

Table 1. Description of equipment for newer and older haulage trucks evaluated at aggregate stone quarry.

MFR - A - Older Trucks			
Truck	*Year*	*Age (Yrs)*	*Capacity, Tons*
A1	1986	21	50
A2	1978	29	50
A3	1986	21	50
A4	1992	15	50
MFR - B - Newer Trucks			
B1	2007	0	70
B2	2007	0	70

NOTE: Manufacturer (MFR); Capacity is nominal rated value. Age is computed from vehicle year to date of latest data collection – 2007.

a frequency range of 0.3 Hz to 5 kHz and a charge sensitivity ranging from 949 to 1052 mV/g for the three orthogonal axes. The 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 orthogonal axes. Vibration data were collected using accelerometers with pre-amplifiers and filters connected to a digital data recorder. Installation (Figure 1) was

Figure 1. Instrumentation installed to collect WBV exposures for haulage truck operators. Tri-axial accelerometers are placed on the seat (seat pad) and on the vehicle frame next to the cab window.

done at the maintenance shop and vehicle parking area for both truck groups. Two tri-axial accelerometers were installed, one on the frame of the haul truck or loader next to the cab window (frame measurement) and one (encased in a disk-shaped, rigid black pad) on the seat at the operator/seat interface (seat measurement). Frame accelerometers were ordinarily mounted on the floor of the operator's compartment near the base of the seat, but space and setup constraints within the truck cab necessitated mounting the frame accelerometers on small ledges on the cab walls that were rigid and structurally connected to the floor. Measurement periods ranged from 2 to 58 minutes with a mean of 29 and standard deviation (STD) of 20 minutes. The relatively large deviation in sampling time is attributed to 2-, 3-, 6-, and 8-minute periods where random vehicle bouncing caused the battery to prematurely disconnect from the terminals in the recorder and resulted in recorder shutdown. Measures for the cyclical nature of load-haul-dump activities were considered representative of exposures for the shift. Given cab constraints and the setup of data collecting instrumentation, it was not feasible for researchers to ride along in the vehicles to observe truck operation.

Truck routes began and ended at the maintenance shop in the earlier study with the older truck group. Instrumentation were switched on just prior to the truck departing this area and returned to the same area at the end of the measurement period for uninstalling the instrumentation. The older truck group included some data collected for hauling material activities from surge/loading bins to large storage piles located in the plant area. Seats in the older trucks were not the original equipment, but had been replaced since the vehicles started operation. Vehicle suspensions, on the other hand, were maintained but included the original design. The drivers, ages 23, 57, and 59 weighed from 91 to 109 kg, respectively. Two of three truck drivers for the older truck group were the same two drivers for the newer group. Weather conditions during both studies were dry, warm and sunny to partly cloudy. The roadways were dusty and required constant watering for dust abatement. All of the trucks and their respective seats were considered to be in good working order.

ISO 1997 [3] was used to evaluate the WBV exposures for haulage truck drivers. For the x, y, and z directions (Figure 2), weighted RMS accelerations (wRMS) and vibration dose values (VDV) with overall totals of wRMS and VDV were used to evaluate driver/operator exposure. Considering an eight-hour exposure period, the European Union Good Practice Guide for WBV [12] (EUGPG) recommends, for the worst-case axis, wRMS accelerations of 0.5 m/s^2 as the action level and 1.15 m/s^2 as the exposure limit. Similarly, EUGPG recommends VDV of 9.1 $m/s^{1.75}$ as the action level and 21 $m/s^{1.75}$ as the dose limit for an eight-hour exposure. Moreover, the EUGPG recommends measurement periods totaling a minimum of 20 minutes or longer, and if shorter periods are unavoidable, measurement periods should be at least 3 minutes long and repeated if possible, for a total time of more than 20 minutes.

Vibration transmitted through the seat was determined by the ratio – transmissibility (T) – of vibration level at the vehicle frame or chassis to the vibration level at the seat. A value greater than 1.0 (times 100%) would indicate a higher vibration level at the seat and that the seat is amplifying rather than attenuating the vehicle ride vibration. Griffin [1] points out that comparing the accelerations on the seat with that at the seat base is the most direct method of obtaining accelerations. Impedance methods offer another means for measuring or predicting transmissibility. The seat effective amplitude transmissibility (SEAT) is given by the equation:

$$SEAT\,\% = \left[\left[\int G_{ss}(f) W_i\text{^}2(f)df\right] / \left[G_{ff}(f) W_i\text{^}2(f)df\right]\right]\text{^}0.5 \qquad (1)$$

where G_{ss} (f) and G_{ff} (f) are the seat and floor acceleration

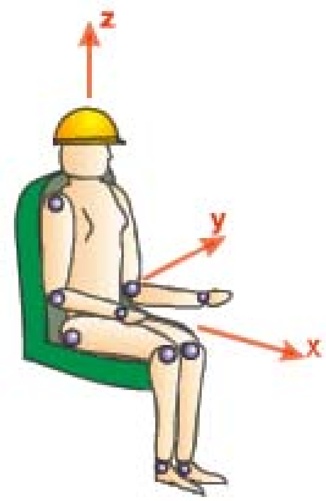

Figure 2. Vibrations levels are measured along the orthogonal x, y and z axes or vectors.

power spectra and W_i (f) is the frequency weighting of the human response to vibration [1]. In this study, the authors simply used the $wRMS_z$ for the seat and frame of the truck cab to approximate T values in Table 2.

GPS data were also collected and synchronized with vibration data to note when vibration accelerations were significant and roadway maintenance was required. This information was documented in an effort to identify areas of the quarry that required road maintenance. Significant vibrations were noted in Figure 3 with flags overlaid on an aerial photographic image of the quarry. The flags indicate locations where vibration levels exceeded 10 m/s^2.

4 RESULTS AND DISCUSSION

Table 2 shows the results from WBV exposure measurements collected for the newer and older haulage trucks at the aggregate stone operation. The data show that the vertical z-direction was the dominant axis of vibration and T, in column 3, was computed using $wRMS_Z$ for the output (seat) and input (frame or chassis). The seats in the older trucks showed amplification of vibration, T >1.0, in 2 of 7 trials. The range was from 0.31 to 1.17 with mean of 0.77 and STD of 0.32. This compared with the newer haulage trucks where amplification occurred for 3 of 8 trials, where T ranged from 0.87 to 1.05 with mean of 0.97 and STD of 0.07. Thus, the mean T for the newer trucks, showed less variation with a lower STD, but was higher than the mean for the older trucks.

Regarding older trucks, in five of seven trials, $wRMS_Z$ for the dominant z-axis exceeded the action level of 0.5 m/s^2 action level recommended by the European Union Good Practice Guide for WBV (EUGPG). In two of seven trials, levels reached or exceeded the recommended exposure limit of 1.15 m/s^2. The $wRMS_Z$ values varied from 0.41 to 1.83 m/s^2 with a mean of 0.99 and STD of 0.57. Similarly, newer trucks indicated $wRMS_Z$ with a narrower range from 0.38 to 0.95 m/s^2

Table 2. Assessment of WBV exposure levels includes seat transmissibility, weighted RMS acceleration and VDV for each orthogonal axis, overall weighted total RMS acceleration (vector sum), and overall VDV according to ISO 2631-1:1997.

Description	*ID*	*T (z-axis)*	*Seat - Output (Dominant Axis Shaded)*							
			$wRMS_X$	*$wRMS_Y$*	*$wRMS_Z$*	*Vector Sum*	*VDV*	*VDV_X*	*VDV_Y*	*VDV_Z*
Older										
MFR-A	A1	1.08	0.48	0.56	1.00	1.44	5.21	1.97	2.06	4.36
		0.87	0.28	0.25	0.46	0.70	2.91	1.47	1.01	2.25
	A2	1.17	0.73	0.74	1.83	2.34	8.28	3.07	3.31	6.94
		0.81	0.28	0.34	0.60	0.86	3.04	1.21	1.42	2.40
	A3	0.31	0.45	0.48	0.98	1.34	4.86	1.80	1.80	4.15
		0.39	0.91	1.08	1.68	2.59	8.63	3.59	4.13	6.67
	A4	0.75	0.30	0.43	0.41	0.84	3.31	1.64	1.93	2.13
Newer										
MFR-B	B1	0.98	0.52	0.75	0.93	1.58	17.82	7.03	9.68	13.21
		0.87	0.25	0.33	0.38	0.69	6.93	3.11	4.02	4.71
		1.02	0.26	0.43	0.43	0.82	9.05	3.64	5.97	5.74
		0.97	0.30	0.42	0.48	0.87	7.19	2.95	4.15	5.07
	B2	0.96	0.33	0.42	0.52	0.91	13.37	8.06	5.34	9.18
		1.05	0.30	0.43	0.43	0.85	5.03	2.03	2.68	3.73
		1.03	0.55	0.73	0.95	1.59	17.01	7.08	8.80	12.58
		0.87	0.28	0.42	0.50	0.87	9.96	3.64	5.16	7.71

NOTE: Manufacturer (MFR); Vector Sum accelerations are in m/s^2; VDVs are in $m/s^{1.75}$; T (Transmissibility = weighted output-a_{RMS}/weighted input-a_{RMS}) is dimensionless.

and that reached or exceeded the action level in four of eight trials. The mean $wRMS_Z$ was lower for the newer trucks at 0.58 m/s^2 with a STD of 0.23 m/s^2. No trials with the new trucks showed $wRMS_Z$ levels that exceeded the recommended 1.15 m/s^2 exposure limit. In assessing vehicle jarring/jolting conditions, vibration dose values for the dominant z-axis (VDV_Z) for the older trucks were generally lower than those for the newer trucks and less than the recommended EUGPG action level of 9.1 $m/s^{1.75}$. VDV_Z varied from 2.13 to 6.94 $m/s^{1.75}$ for the older trucks with a mean of 4.13 $m/s^{1.75}$and a STD of 2.04 $m/s^{1.75}$. This contrasted with the newer trucks whose VDV_Z values varied much more broadly than those for the older trucks from 3.73 to 13.21 $m/s^{1.75}$ with a mean of 7.74 $m/s^{1.75}$and a STD of 3.62 $m/s^{1.75}$. Moreover, in three of eight trials, both newer trucks exceeded this action level with values of 9.18, 12.58, and 13.21 $m/s^{1.75}$. Neither truck group showed VDV_Z exceeded the exposure limit of 21 $m/s^{1.75}$. The routes, road conditions, stopping, turning, and inadequate seat adjustment to different size drivers/operators are possible factors in the higher VDV for the newer trucks.

Overall weighted total RMS acceleration (vector sum) values can be used as an indicator of driver/operator comfort [3]. Vector sum values give the general sense of a "rougher" ride for the older trucks. The vector sum values for these trucks ranged widely from 0.70 to 2.59 m/s^2 and four of seven trials showed levels greater than 1.40 m/s^2. The mean vector sum was 1.44 m/s^2 with a STD of 0.75 m/s^2. Comparatively, the newer trucks exhibited less variation ranging from 0.69 to 1.59 m/s^2. The mean vector sum value was 1.02 m/s^2 with a STD of 0.35 m/s^2.

Eger et al. examined WBV exposure on a variety of mining equipment, including haulage trucks used in surface operations [13]. The trucks, however, were 150-ton trucks – about 2/3 greater in size (considering rated haulage capacity) than those in the NIOSH studies. In comparing the NIOSH and Eger et al. studies, the mean $wRMS_Z$ and vector sum accelerations, for the newer haulage trucks in the NIOSH study were higher than those in the Eger et al study by about 2 to 3 times, respectively. Similarly, the mean $wRMS_Z$ and vector sum accelerations for the older haulage trucks in the NIOSH study were much higher than those in the Eger et al. study, approximately 3.5 to 4 times, respectively. Aside from truck capacity differences, fewer controls (e.g. sampling time variability and shorter durations, particularly for the older trucks) may account for differences in results between the NIOSH and Eger et al. studies.

Review of the GPS data for the older trucks showed instances of jarring/jolting for haulage trucks traveling into the pit with no load. The GPS data also indicated episodes of jarring/jolting occurring at the loading tower for trucks operating

Figure 3. Marker flags overlaid on aerial photograph of aggregate stone quarry derived from GPS data. The numbered flags show locations where peak accelerations exceeded 10 m/s^2.

in the plant area. Other instances of jarring or "bouncing" of truck also occurred from driver/operator braking. Considering the GPS data collected for the newer trucks, the majority of the shocks (jars/jolts) occurred at the loader, dump, and the wash out just below the entrance to the pit road, and the corner approaching the loader that the trucks took at a fairly high speed. Drivers entered this turn with no load (truck empty of material) and were traveling downhill. The data showed the average ride was "rougher" after the road was graded and there were fewer incidences of shocks over 1g. So, the inference is that the washouts were filled in, but that the road surface itself had been roughed up by the grader. According to quarry personnel and management, a wheel dozer was typically used to maintain roadways and did a better job in smoothing the road surface. However, at the time of data collection, this dozer was undergoing needed maintenance and was not in operation. Finally, results of this study are preliminary and should be viewed with caution because of the small sample size and limitations in study controls. Additional measurements are required before conclusive statements can be made about older versus newer truck performance relative to driver/operator exposures to WBV.

5 LIMITATIONS

The obvious limitations were the changes in the working environment (pit and bench location changes for loading operations) and truck driving routes over the 12-month period. Although the data were collected for both truck groups during dry summer conditions, the newer haulage trucks had a shorter travel route (roundtrips from pit to dump hopper). The older trucks travel began at the maintenance shop, approximately 0.25 miles from the dump hopper. Sampling times for the older trucks (mean of 19.5 minutes and a STD of 6.5 minutes) varied more and were shorter than the newer trucks sampling times (mean of 40.8 minutes and a STD of 12.1 minutes). The larger newer truck size, greater haulage capacity, shorter route, and inadequate driver/operator seat adjustment may explain the higher concentration of vehicle jarring incidents in the WBV data from the newer trucks.

6 CONCLUSIONS

The results suggest that the newer trucks and associated seats may provide lower levels of WBV exposure when considering mean $wRMS_Z$ for drivers/operators compared to the older trucks and seats previously studied at the quarry. The lower mean vector sum values seem to indicate a "smoother" rather than "rougher" ride for newer truck drivers/operators than for the older truck drivers/operators. Even though the overall WBV was less, the newer trucks had a somewhat higher number of jarring incidents than the older trucks as evidenced by the greater variability in and higher mean VDV_Z values. The reasons are not completely clear why the better overall results were achieved by the newer trucks, although contributing factors would include; differences by manufacturer and model, and improved wheel suspension designs for newer vehicles resulting from technological advances in these areas. Based on information from the quarry Maintenance Chief, the authors believe the newer and improved vehicle suspensions and isolated cab on the newer haulage trucks may be factors in providing better vibration isolation for the newer versus older trucks, although this can only be verified with additional data and, where possible, adding more study controls. Due to the small sample size and limited controls, results of this study are preliminary and are not to be viewed as definitive. Additional measurements are required before conclusive statements can be made about older versus newer truck performance relative to driver/operator exposures to WBV. Future activities will include additional analysis of meaningful segments of existing data (e.g., comparison of no- and full-load truck cycles) and additional data collections of WBV exposure data on the newer and older trucks at this quarry at six-month intervals for monitoring seat and truck vibration performance in terms of driver/operator exposure to WBV.

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8 REFERENCES

[1] Griffin, M.J., 1990, *Handbook of Human Vibration*. London: Elsevier Ltd.

[2] International Organization for Standardization, ISO 10326-1:1992 – Mechanical vibration and shock – laboratory method for valuating vehicle seat vibration – Part 1: Basic requirements, Geneva, Switzerland.

[3] International Organization for Standardization, ISO 2631/1:1997 – Mechanical vibration and shock – evaluation of human exposure to whole-body vibration, Part 1: General requirements, Geneva, Switzerland.

[4] Kittusamy N.K., Buchholz B., 2004, Whole-Body Vibration and Postural Stress among Operators of Construction Equipment: A Literature Review, *Journal of Safety Research* 35, 255-261.

[5] Kittusamy N.K., 2003, Self-Reported Musculoskeletal Symptoms Among Operators of Heavy Construction Equipment, Proceedings of the XVth Triennial Congress of the International Ergonomics Association, Seoul, South Korea, Aug. 24-29, www.iea.org.

[6] Kittusamy N., 2002, Ergonomic Risk Factors: A Study of Heavy Earthmoving Machinery Operators. *Professional Safety—Journal of the American Society of Safety Engineers*, October, 38-45.

[7] Bovenzi M. and Zadini A., 1992, Self-Reported Low Back Symptoms in Urban Bus Drivers Exposed to Whole-Body Vibration, *Spine 17*(9):1048–1059.

[8] Johanning E., 1991, Back Disorders and Health Problems among Subway Train Operators Exposed to Whole-Body Vibration. *Scandinavian Journal of Work Environment and Health 17*(6):414–419.

[9] Bongers P.M., Boshuizen H.C., Hulshof C.T.J., Koemeester A.P., 1988, Back Disorders in Crane Operators Exposed to Whole-Body Vibration, *International Archives of Occupational and Environmental Health 60*(2):129–137.

[10] Bongers P.M., Hulshof C.T.J., Dijkstra L., Boshuizen H.C., Groenhout H.J., and Valken E., 1990, Back Pain and Exposure to Whole-Body Vibration in Helicopter Pilots, *Ergonomics 33*(8):1007–1026.

[11] Seidel H. and Heide, R., 1986, "Long-Term Effects of Whole-Body Vibration: A Critical Survey of the Literature, *International Archives of Occupational and Environmental Health* 58, 1-26.

[12] Griffin, M.J., Howarth, H.V.C., Pitts, P.M., Fischer, S., Kaulbars, U., Donati, P.M. and Bereton, P.F., 2006, *Guide To Good Practice on Whole-Body Vibration. Non-binding guide to good practice with a view to implementation of Directive 2002/44/EC on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibrations).* Luxembourg, European Commission, 65pp. (EU Good Practice Guide WBV, 6.7g). Available at: http://www.humanvibration.com/EU/VIBGUIDE/WBV%20Good%20practice%20Guide%20v6.7g%20English%20070606.pdf

[13] Eger, T., Salmoni, A., Cann, A., and Jack R., 2006, "Whole-Body Vibration Exposure Experienced by Mining Equipment Operators. *Occupational Ergonomics* 6:3-4 121-127.