Assessment of continuous and impulsive whole body vibration exposures in heavy equipment mining vehicles

Peter W. Johnson [a], Jack Dennerlein [b], Luz Marin Ramirez [b], Claudia Arias [c], Andrés Camilo Rodríguez Escallón [c], Ivon Estefany Rey Becerra [c], Lavi Aulck [a], Hugo Piedrahita [d], Lope H. Barrero [c]

[a] University of Washington, Seattle, WA, USA; [b] Northeastern University, Boston, MA, USA; [c] Pontificia Universidad Javeriana, Bogota, COLOMBIA; [d] Cerrejón, Inc., COLOMBIA

The purpose of the study was to collect, compare and contrast continuous [A(8)] and impulsive [VDV(8) and S_{ed}(8)] WBV exposures in 190, 240 and 320 ton mining trucks in order to determine whether the WBV exposures were above ISO and European Union action limits whether there were any differences in injury risk prediction across the WBV exposure parameters. All exposure parameters showed that the z-axis appeared to be the predominant axis of exposure with no exposure differences across trucks, whereas the x- and y-axis exposures differed and increased with truck size. In all trucks, the predominant axis A(8) and VDV(8) WBV exposures were below ISO and European Union (EU) action limits; however, all vector sum exposures were above action limits. In contrast, the S_{ed}(8) WBV exposures were below ISO action limits. In conclusion, it appears that there is differential prediction of health risks between S_{ed}(8) and the A(8) and VDV(8) WBV exposure parameters.

Practitioner Summary: In the three types of mining truck evaluated, the vehicle operation times to reach the daily action limits for the vector sum A(8) and VDV(8) WBV exposures were less than 7 and 5 hours per day, respectively; in contrast, there was no daily limit for vehicle operation based on S_{ed}(8) WBV exposure parameter. It appears the S_{ed}(8) WBV exposure parameter may underestimate health risks.

Keywords: Average Weighted Vibration; Static Compressive Dose, Vibration Dose Value;

1. Introduction

Mining heavy equipment vehicle (HEV) operators are exposed to whole body vibration (WBV) through various forms of work-related activities. The WBV exposures are in the form of continuous low-level vibrations and sometimes contain higher-energy impulsive shocks. Exposure to WBV is thought to be a risk factor for the onset and development of low back pain (Burström et al., 2015). Epidemiological studies have consistently shown that there is an association between exposure to WBV and low back pain (NRC/IOM, 2001; Pope *et al.*, 1998) with four possible types of exposures which my contribute to injury: 1) the cumulative exposure to low-level vibrations over longer periods of time, 2) the cumulative exposure to multiple shocks over shorter periods of time, 3) acute exposures to high level shocks over a single or few episodes, or 4) the combination of 1) and 2). WBV exposures have previously been characterized in mine HEV operators using International Standard Organization (ISO) time-weighted-average (TWA) exposures (ISO 2631-1, 1997), but data on raw, impulsive WBV exposures (ISO 2631-5, 2004) is limited. The purpose of the study was to collect, compare and contrast continuous and impulsive WBV exposures across three common types of mining trucks in order to determine whether the WBV exposures are above ISO and European Union (European Council, 2002) action limits, and to determine whether there are differences in injury risk prediction across the WBV exposure parameters. Ultimately, in future work, using a 5-year health claim database of 3036 workers, we want to determine what WBV parameters, if any, may be best suited for identifying vehicle operating conditions which may put a worker at risk for subsequent injury.

2. Method

Full-shift (12 hour) WBV exposures were measured from 190 ton, 240 ton and 320 ton trucks using 8, 14 and 18 HEV operators respectively. All study procedures were approved by the Pontificia Universidad Javeriana Human Subjects Division. Per ISO standards (ISO 2631-1, 1997; ISO 2631-5, 2004), a tri-axial seat-pad accelerometer (Model 356B40; PCB Piezotronics; Depew, NY) was mounted on the HEV operator's seat and either an identical tri-axial or single axis (z-axis) accelerometer (Model 352C33; PCB Piezotronics; Depew,NY) was magnetically mounted to the truck floor beneath the driver's seat. Acceleration data were collected at 1280 Hz using either a four or eight channel data recorder (Model DA-20 or DA-40; Rion Co. LTD; Tokyo, Japan). Vehicle speed and location were simultaneously recorded at 1 Hz using a GPS logger (Model DG-100; GlobalSat; Chino, CA).

Continuous and impulsive WBV exposures were calculated over each HEV operator's 12-hour shift. First, for each operator, WBV exposures were calculated across each hour of operation and the median of the hourly exposures for each parameter was used to characterize that subject's and vehicle's WBV exposures. Then, to enable comparison to daily limits, the WBV exposures were normalized to represent a daily exposure of 8 hours. A LabVIEW program (v2012; National Instruments; Austin, TX) was used to calculate the ISO 2631-1 TWA continuous [A(8)] and TWA impulsive [VDV(8)] exposures and the ISO 2631-5 raw impulsive [Sed(8)] WBV exposures. Given the relatively small sample sizes per vehicle, non-parametric Kruskal-Wallis tests were used to determine whether there were differences in the WBV exposures across the three truck types and the potential vibration-related health risks predicted by the three types of WBV exposure parameters. All data were presented using median values (minimum and maximum) and differences were considered statistically significant when p-values were below 0.05.

3. Results

The WBV exposure results are summarized by vibration parameter, truck and axis in Table 1 below. As can

Table 1. Median (min – max) WBV exposures by axis and grouped by truck type (190 Ton, n = 8; 240 Ton, n = 14; 320 Ton n = 18). ISO daily exposure action limit values for acceptable WBV exposures are listed in brackets under each WBV exposure parameter in the left side of the table and vector sum exposures (Σxyz) are presented in the last row. P-values indicate significant differences across trucks.

		Truck			
Parameter	**Axis**	**190 Ton**	**240 Ton**	**320 Ton**	**p-value**
A(8) [0.50 m/s^2]	**1.4x**	0.29 (0.21 - 0.35)	0.31 (0.26 - 0.36)	0.35 (0.25 - 0.39)	0.01
	1.4y	0.24 (0.2 - 0.29)	0.25 (0.22 - 0.34)	0.31 (0.23 - 0.37)	<0.0001
	z	0.37 (0.28 - 0.42)	0.39 (0.26 - 0.48)	0.39 (0.31 - 0.54)	0.14
	Σxyz	0.54 (0.4 - 0.57)	0.57 (0.45 - 0.66)	0.61 (0.49 - 0.72)	0.0009
VDV(8) [9.1 m/s$^{1.75}$]	**1.4x**	6.7 (5.6 - 8.1)	7.7 (6.8 - 8.1)	7.9 (5.7 - 9.4)	0.05
	1.4y	5.5 (4.9 - 9.4)	5.9 (5.4 - 13.2)	6.8 (6.3 - 11.6)	0.008
	z	9.1 (7.6 - 10.4)	9.0 (6.6 - 10.2)	8.3 (7.1 - 8.9)	0.34
	Σxyz	10.3 (8.4 - 12)	10.4 (8.8 - 14.1)	10.4 (8.8 - 12.6)	0.96
S_{ed}(8) [0.50 MPa]	**1.4x**	0.11 (0.09 - 0.13)	0.14 (0.12 - 0.16)	0.15 (0.1 - 0.19)	0.006
	1.4y	0.16 (0.15 - 0.49)	0.22 (0.18 - 1.02)	0.23 (0.21 - 0.78)	0.03
	z	0.28 (0.25 - 0.34)	0.28 (0.19 - 0.44)	0.28 (0.23 - 0.4)	0.98
	Σxyz	0.29 (0.25 - 0.50)	0.31 (0.25 - 1.02)	0.31 (0.27 - 0.78)	0.83
Speed	-	12.2 (9.1 - 18.3)	13.3 (0.3 - 18.2)	16.0 (10.4 - 20.5)	0.09
% Time Moving	-	0.61 (0.49 - 0.80)	0.63 (0.38 - 0.83)	0.77 (0.43 - 1.00)	0.96

be seen in the bottom of Table 1, there was a trend indicating small speed differences across the trucks (p = 0.09), with the speed increasing with truck size; and the GPS data indicated that there were no differences in the percent time the trucks were moving. The TWA continuous A(8) exposures showed that the z-axis appeared to be the predominant axis of exposure with no exposure differences across trucks, whereas the x- and y-axis exposures differed across trucks (p = 0.01 and <0.0001, respectively) and increased with truck size. In addition, none of the single axis A(8) WBV exposures were above ISO and European Union (EU) action limits (0.50 m/s^2). However, there were differences in vector sum (Σxyz) exposures across trucks (p = 0.0009) with all vector sum exposures above ISO and EU action limits and increasing with truck size.

The TWA impulsive VDV(8) and raw impulsive Sed(8) exposures predominantly mirrored the A(8) exposures. The x-axis and y-axis impulsive exposures increased with truck size and the exposures were significantly different across the trucks. Once again the z-axis was the predominant axis of exposure, there were no z-axis exposure differences across trucks and all of the single axis exposures were below ISO and EU action limits. However, unlike the A(8) vector sum exposures, there were no differences in the VDV(8) and Sed(8) vector sum exposures across trucks;, the vector sum VDV(8) exposures were above ISO and EU action limits (9.1 $m/s^{1.75)}$ whereas the Sed(8) vector sum exposures were below ISO action limits (0.50 MPa -. the EU directive does not have an action limit for Sed(8).

Table 2 shows the biomechanically-based WBV exposures (left side) and the time in hours the HEVs could be operated before the drivers would reach the daily ISO and EU action limits (right side). With all exposure parameters, the shear WBV exposures (Σxy) increased with truck size and were significantly different across the trucks whereas the compressive z-axis exposures did not differ across the trucks. In addition, only the A(8) vector sum (Σxyz) exposures were different across the trucks whereas the VDV(8) and Sed(8) vector sum exposures were nearly constant across trucks. With respect to exposure levels, both the A(8) and VDV(8) vector sum exposures were above ISO and EU action limits (0.50 m/s^2 and 9.1 $m/s^{1.75}$, respectively) whereas the Sed(8) vector sum exposures were below ISO action limits (0.50 MPa). The respective times the HEVs could be operated before reaching action limits is shown in the right half of Table 2. There was no time limitation for the daily HEV operation time based on the Sed(8) exposures, the A(8) vector sum exposures limited HEV operation to 7 hours or less a day, and the VDV(8) vector sum exposures were the most restrictive, limiting HEV operation to less than 5 hours a day.

Table 2. The median (min – max) biomechanically-based WBV exposures [left side] and the time in hours the HEVs could be operated before reaching ISO and EU action limits [right side]. The ISO daily exposure action limit levels for acceptable WBV exposures are listed in brackets in the left side of the table under each WBV exposure parameter. P-values for the exposures and time to action limits across trucks were identical and these p-values are listed on the right side of the table (190 Ton, n = 8; 240 Ton, n = 14; 320 Ton, n = 18).

		Exposures			Time to Action Limit (hrs/day)			
Parameter	**Measure**	**190 Ton**	**240 Ton**	**320 Ton**	**190 Ton**	**240 Ton**	**320 Ton**	**p-value**
A(8) [0.50 m/s^2]	Shear (Σxy)	0.38 (0.29 - 0.44)	0.40 (0.36 - 0.46)	0.47 (0.36 - 0.5)	13.6 (10.4 - 23.7)	12.2 (9.6 - 15.5)	9.0 (7.9 - 15.7)	0.0002
	Compressive (z)	0.37 (0.28 - 0.42)	0.39 (0.26 - 0.48)	0.39 (0.31 - 0.54)	15.0 (11.1 - 26.4)	13.4 (8.6 - 29.4)	13.2 (6.7 - 20.4)	0.14
	Vector Sum (Σxyz)	0.54 (0.40 - 0.57)	0.57 (0.45 - 0.66)	0.61 (0.49 - 0.72)	6.9 (6.1 - 12.5)	6.2 (4.5 - 9.8)	5.5 (3.8 - 8.4)	0.0009
VDV(8) [9.1 $m/s^{1.75}$]	Shear (Σxy)	8.0 (6.3 - 9.9)	8.4 (7.5 - 13.4)	9.1 (7.2 - 12.1)	13.9 (5.8 - 34.6)	11.0 (1.7 - 17)	7.8 (2.6 - 20.4)	0.04
	Compressive (z)	9.1 (7.6 - 10.4)	9.0 (6.6 - 10.2)	8.3 (7.1 - 8.9)	7.9 (4.6 - 16.1)	8.3 (5 - 29.7)	11.5 (8.9 - 21.7)	0.34
	Vector Sum (Σxyz)	10.3 (8.4 - 12)	10.4 (8.8 - 14.1)	10.4 (8.8 - 12.6)	4.8 (2.6 - 11)	4.7 (1.4 - 9.1)	4.7 (2.1 - 9.1)	0.96
$S_{ed}(8)$ [0.50 MPa]	Shear (Σxy)	0.17 (0.16 - 0.49)	0.23 (0.18 - 1.02)	0.24 (0.22 - 0.78)	5968.3 (8.5 - 6755.5)	951.2 (0.1 - 3308)	649.6 (0.5 - 1184.7)	0.03
	Compressive (z)	0.28 (0.25 - 0.34)	0.28 (0.19 - 0.44)	0.28 (0.23 - 0.4)	256.7 (87.4 - 526.4)	250.1 (18.2 - 2302.8)	275.9 (29.8 - 788.4)	0.98
	Vector Sum (Σxyz)	0.29 (0.25 - 0.5)	0.31 (0.25 - 1.02)	0.31 (0.27 - 0.78)	212.4 (8.1 - 482.7)	156.1 (0.1 - 555.6)	149.5 (0.5 - 359.8)	0.83

Finally, Figure 3 demonstrates that there was an interaction across trucks in the z-axis seat and floor measured A(8) WBV exposures. The ratio of the z-axis seat and floor measured A(8) WBV exposures provide an indicator as to how well the seat attenuates the floor-measured WBV exposures. As can be seen in Figure 3, seat attenuation performance significantly decreases ($p < 0.0001$) from the smaller to the larger trucks.

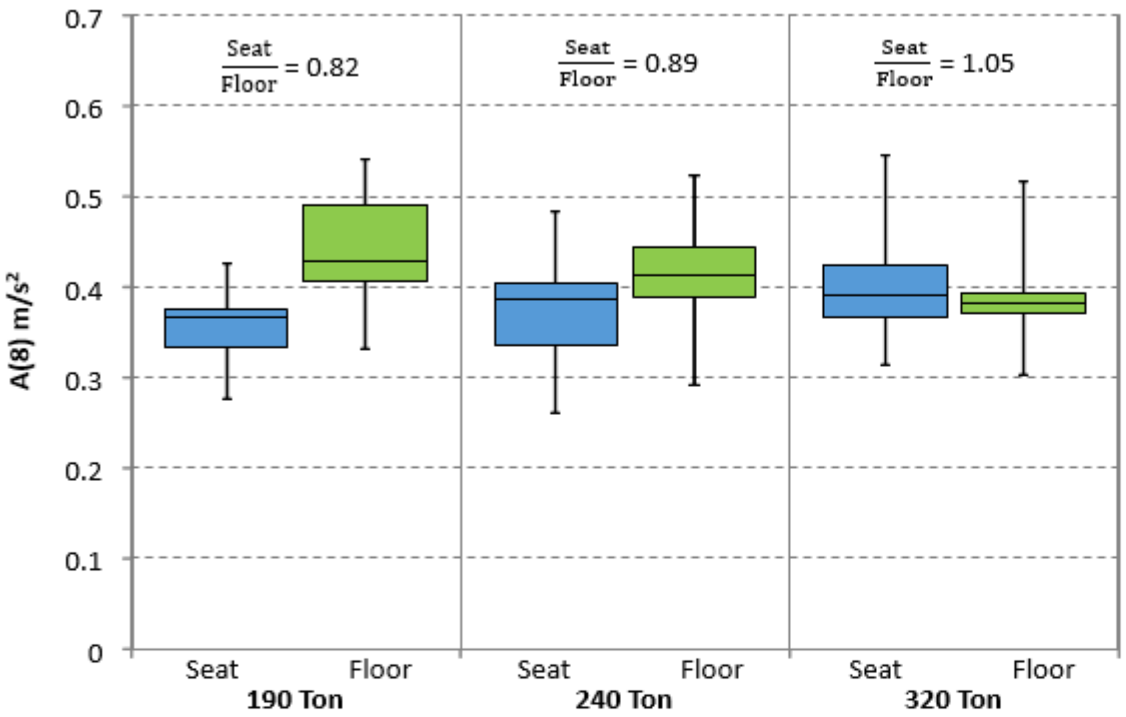

Figure 1. The median (min – max) z-axis floor and seat measured A(8) WBV exposures and seat attenuation performance [seat A(8) / floor A(8)] grouped by truck type (190 Ton, n = 8; 240 Ton, n = 14; 320 Ton, n = 18).

4. Discussion

Based on the vehicle operating time to reach daily action limits, the WBV exposures revealed that there were some parameter-based differences in the assessment of WBV-related health risks associated with the operation of the large mining trucks. The ISO 2631-1 TWA continuous A(8) exposures indicated that the z-axis was the predominant axis of exposure and that no significant differences were seen across trucks in this axis.. However, there were significant differences in x- and y-axis WBV exposure across trucks and in both these axes the WBV exposures increased with truck size. All single axis A(8) exposures were below ISO and EU action limits and just the vector sum A(8) exposures were above action limits. In addition, there was an interaction across trucks in the z-axis seat- and floor- measured A(8) WBV exposures revealing a significant difference in how the seats attenuated the floor-transmitted vibration. The seat attenuation performance progressively decreased as the truck size increased. Without further study, it is uncertain whether the seat performance differences across vehicles are a function of the type of seat and/or whether the performance differences may be related to the differences in height of the vehicles or the speed differences observed across the vehicles. A more detailed analysis of the data may better elucidate the source or sources for the differences in seat performance.

The axis-by-axis performance TWA impulsive VDV(8) and raw impulsive $S_{ed}(8)$ exposures mostly mirrored the A(8) exposures. The z-axis was the predominant axis of exposure, there were no z-axis exposure differences across trucks, the x- and y-axis impulsive exposures increased with truck size and all of the single axis exposures were below ISO and EU action limits. However, unlike the A(8) vector sum exposures which increased with truck size, there were no differences in the VDV(8) and S_{ed}(8) vector sum exposures across the trucks.

Finally, the biomechanically-based assessment of the exposures revealed some important similarities and differences across the three WBV exposure parameters. With all the exposure parameters, shear exposures significantly increased with truck size, whereas the compressive z-axis exposures did not. In addition, only the A(8) vector sum exposures were increased with truck size, whereas the VDV(8) and S_{ed}(8) vector sum exposures remained relatively constant. In addition, based on the daily time to reach action limits, there were differences in health risk prediction across the WBV exposure parameters. The S_{ed}(8) WBV exposure parameter was the most liberal and imposed no limit for daily HEV operation, the A(8) vector sum would limit HEV operation to 7 hour or less per day, and the VDV(8) vector sum was the most restrictive limiting HEV operation to 5 hours or less per day.

In conclusion, based on this initial analysis, in the three classes of trucks we evaluated, there is a potential for a differential prediction of health risks between the continuous and impulsive WBV exposure parameters. In general, based on the across axis and across vehicle trends, the VDV(8) and S_{ed}(8) WBV exposure parameter performance was similar; however, the parameters dramatically differed in vehicle operating times to reach daily action limits with the S_{ed}(8) being much more liberal. The shear and vector sum health risk predicted by A(8) and VDV(8) WBV exposure parameters were similar; however, the z-axis VDV(8) parameter was more sensitive and indicated the TWA impulsive exposures posed a greater health risk than the TWA continuous A(8) exposures. In the future, using a multi-year health claim database of 3036 workers, the ultimate goal of our work is to determine whether there are differences in health risk prediction across any of the WBV exposure parameters and whether any parameters may be better suited to identify vehicle operating conditions which may put a worker at risk for subsequent injury.

Acknowledgements

This study is funded by the Alpha Foundation. This project would not have been possible without the cooperation of the mine and the collaboration from all the heavy equipment operators.

References

Burström, L., Nilsson, T., & Wahlström, J. 2014. Whole-body vibration and the risk of low back pain and sciatica: a systematic review and meta-analysis . .Intl Arch Occ Env Hlth. 88(4):403-18

European-Council, 2002. Directive 2002/44/EC of the European parliament and of the Council of 25 June 2002 on the minimum health and safety requirements regarding the exposure of workers to the risks rising from physical agents (vibration) (sixteenth individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC). Official Journal of the European Communities 2002;L177:13-19.

ISO 2631-1 Mechanical vibration and shock, 1997. Evaluation of human exposure to whole-body vibration - Part 1: general requirements. Geneva, Switzerland: International Organization for Standardization.

ISO 2631-5 Mechanical vibration and shock, 2004. Evaluation of human exposure to whole-body vibration - Part 5: method for evaluation of vibration containing multiple shocks. Geneva, Switzerland: International Organization for Standardization.

NRC/IOM, 2001. Musculoskeletal Disorders and the workplaces: Low Back and Upper Extremities. Washington, D.C: National Academy Press.

Pope MH, Magnusson M, Wilder DG, 1998. Kappa Delta Award. Low back pain and whole body vibration. Clin Orthop Relat Res. 354:241-248.

Troup JD, 1988. Clinical effects of shock and vibration on the spine. Clin Biomech. 3(4):232-235.