Influence of Speed in Whole Body Vibration Exposure in Heavy Equipment Mining Vehicles

Marín, LS[1].; Rodríguez, A.[2]; Rey, E.[2]; Piedrahita, H.[3]; Barrero LH.[2]; Dennerlein, J.[1]; Johnson, P[4].

[1] Department of Physical Therapy, Movement and Rehabilitation Sciences, Bouvé College of Health Science, Northeastern University, Boston, MA, 02115, USA
[2] Department of Industrial Engineering, Pontificia Universidad Javeriana, Bogotá, Colombia
[3] Industrial Hygiene & Health Management, Cerrejón, Bogotá, Colombia.
[4] Department of Environmental and Occupational Health Sciences, University of Washington, Seattle, WA, 98195-7234, USA

This study aimed to characterize and contrast the ISO 2631-1 daily average-continuous A(8) and cumulative-impulsive VDV(8) whole body vibration (WBV) exposures during the operation of mining heavy equipment vehicles (HEVs). In a cross-sectional study, WBV measurements were collected from six different types of HEVs. For each HEV, the daily A(8) and VDV(8) WBV exposures were determined for each axis (x, y and z) along with the vector sum (∑xyx).. The predominant axis of vibration exposure was related to and dependent on the type of HEV, which all have different average speeds. Most of the predominant axis WBV exposures were above the ISO daily vibration action limits and the vector sum-based WBV exposures were considerably higher. Our results indicated that mining HEV operators are exposed to high levels of both continuous and impulsive WBV exposures, being the impulsive WBV exposures more restrictive with respect the HEVs daily maximum operation hours.

INTRODUCTION

Occupational exposure to WBV in professional vehicle operators is associated with an increased risk of work-related low back pain (Bovenzi et al., 2006). Four possible types of exposures which may contribute to injury have been suggested: 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)(Pope et al., 2002). In addition, vehicle characteristics, operational demands, job organization, and individual variables may influence operator's exposure to WBV.

Heavy equipment vehicles (HEVs) are used extensively in large scale mining operations, exposing drivers regularly to WBV through various forms of work-related activities (Eger, Salmoni, Cann, & Jack, 2006; Eger et al., 2008; Wolfang & Burgess-Limerick, 2014). Mining HEV fleets include large capacity haul trucks, graders, hydraulic and electric shovels, scrapers, front loaders, bull dozers and wheel dozers which expose operators to potentially harmful levels of WBV (Eger et al., 2006).

Operators in the mining industry consistently work 12-hour shifts with limited breaks and approximately 90% of their shift time is spent driving (Wolfgang, Di Corleto, & Burgess-Limerick, 2014). Production demands also constrain the operation to few or no interruptions, 24 hours a day, 7 days a week and almost 365 days a year.

WBV exposures can be measured and analyzed according to the ISO standard 2631-1:1997, which uses the axis with the highest frequency-weighted vibration exposure to predict the potential for adverse health outcomes. The traditional ISO 2631-1:1997 standard suggests two methods for evaluating WBV: 1) the weighted root mean square (r.m.s.) acceleration (Aw in m/s^2), and 2) the vibration dose value (VDV in $m/s^{1.75}$) when the presence of mechanical shocks can be identified. For WBV exposure at or under the ISO daily vibration action limit (0.5 m/s^2 for A(8); 9.1 $m/s^{1.75}$ for VDV(8)), vehicles can be operated for 8 hours or more a day; for WBV exposures above the daily exposure limit, vehicle operation times are severely restricted and immediate changes are recommended to reduce vehicle operators' exposures to WBV and the potential for potentially adverse health outcomes. For WBV exposures in-between the daily action and exposure limits, vehicle operation is limited to less than 8 hours a day and the potential for adverse health outcomes is thought to increase as the WBV exposures increase. The goal of this study was to characterize the average-continuous and cumulative-impulsive WBV exposures across six different types of mining HEVs, with the goal of determining whether the HEV operators' WBV exposures were above ISO daily vibration action limits, and to whether there were differences between the average-continuous and cumulative-impulsive WBV exposure parameters.

METHODS

WBV exposures were measured from six HEVs as shown in Table 1. Up to 21 hours of continuous WBV exposure data were collected from each HEV which consisted of two or three shifts of vehicle operation. Thus, a typical measurement session included two or three operators using the same vehicle. WBV exposure data were collected simultaneously in two vehicles, one using an eight-channel data recorder (Model DA-40; Rion Co., LTD.; Tokyo, Japan) and the other using a 4-channel data recorder (Model DA-20; Rion Co., LTD.; Tokyo, Japan) according to ISO 2631-1 standards (2631-1: 1997). Raw, un-weighted tri-axial WBV measurements were collected at 1,280 Hz per channel using a seat pad ICP accelerometer (Model 356B41; PCB Piezotronics; Depew, NY).

Continuous and impulsive WBV exposures were determined over each HEV operator's shift. To enable comparison to daily vibration 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 average-continuous A(8) and cumulative-impulsive VDV(8) WBV exposures. Since some of the data was not normally distributed, all data are presented using median values for central tendency and the minimum and maximum values for the range of the measurements.

RESULTS

A total of 411 hours of whole-day WBV exposure data were collected from the six vehicles. The sample captured the exposure of 60 HEV operators which had on average 14 years of experience as an HEV operator (Table 1).

WBV exposures grouped by their predominant axis appeared to be dependent on the average speed of the HEV (Table 2). For the slowest HEVs, which had an average speed below 3.0 km/h, the for-aft x-axis exposures predominated. For the intermediate speed HEVs, which had an average between 6 and 12 km/h, the side-to-side y-axis exposures predominated. Finally, in the HEVs with average speed above 12 km/h, vertical up-and-down z-axis was the predominant axis of exposure. The average-continuous A(8) and the cumulative-impulsive VDV(8) exposure metrics showed similar trends in the relationship between the predominant axis of exposure and HEV speed.

Most of the predominant axis WBV exposures were above the ISO daily vibration action limits (A(8) = 0.5 m/s2 and VDV(8) = 9.1 m/s1.75) and all the vector sum-based (∑xyx) WBV exposures were considerable higher in comparison to the predominant axis exposures. Together, these results indicate that the HEV operators had WBV exposure at or above ISO daily vibration action limits and the larger vector sum exposures indicated that a single, predominant axis of exposure was uncommon.

Based on the predominant axis of exposure and the vector sum exposures, the amount of time the HEVs could be operated until reaching ISO daily vibration action limits is often shorter than a 12 hour shift (Table 3). Comparing the A(8) and VDV(8) WBV exposure parameters, HEV operation time was considerably shorter for cumulative-impulsive VDV(8) WBV exposures in comparison to the more traditional average-continuous A(8) WBV exposures. Large HEV operation time differences also existed between the predominant axis and the vector sum WBV exposures. The cumulative-impulsive VDV(8) WBV exposures reduced acceptable HEV operation times by one-half to two-thirds relative to average-continuous A(8) exposures. In addition, vector sum WBV exposures were much more restrictive in HEV operation times and cut acceptable vehicle operation times in half.

Table 1. Measuring conditions for data acquisition and descriptive measures by vehicle.

	HEVs		HEV Operators		
	Hours measured	HEVs sampled	HEVs' operators sampled	Years as a HEV operator	BMI Kg/m^2
Bull Dozer	99	4	14	11.3	28.5
Front Loader	60	2	9	19.3	29.2
Grader	53	3	9	15.0	28.8
Scraper	66	5	10	17.6	28.3
Water Truck	79	4	10	12.2	25.9
190 Ton Truck	54	2	8	9.3	28.9

Table 2. Median (min – max) daily WBV exposures by parameter and axis arranged in ascending order of vehicle speed, Σxyz is the vector sum exposure of all three axes. The shaded cells under each parameter indicate the predominant exposure axis for each HEV. Recommended daily vibration action limits are provided above each exposure parameter.

			0.5 m/s^2 A(8)				9.1 m/s$^{1.75}$ VDV(8)			
HEV	# of Meas	Average speed (km/h)	1.4x	1.4y	z	Σxyz	1.4x	1.4y	z	Σxyz
Bull Dozer	14	2.4	0.60 (0.47 - 0.80)	0.56 (0.46 - 0.87)	0.44 (0.29 - 0.76)	0.91 (0.75 - 1.4)	13.9 (11.4 - 17.2)	12.7 (10.5 - 18.4)	9.9 (6.8 – 16.0)	16.6 (13.5 - 22.8)
Front Loader	9	2.9	0.57 (0.42 - 0.67)	0.57 (0.43 - 0.71)	0.27 (0.22 - 0.37)	0.87 (0.64 - 0.98)	13.7 (10.8 - 15.1)	12.9 (11.7 - 36)	8.0 (6.5 - 10.8)	16.4 (14.5 - 36.1)
Grader	9	6.8	0.41 (0.24 - 0.53)	0.58 (0.33 - 0.82)	0.48 (0.31 - 0.57)	0.89 (0.52 - 1.14)	10.9 (8.9 - 18.4)	14.0 (9.3 - 23.9)	10.8 (9.2 - 13.8)	16.6 (13.6 - 24.3)
Scraper	10	12.0	0.51 (0.38 - 0.94)	0.69 (0.51 - 0.96)	0.65 (0.51 - 0.83)	1.10 (0.82 - 1.47)	12.3 (9.0 - 55.7)	14.8 (11.7 - 19.8)	14.4 (11.6 - 16.3)	19.3 (14.4 - 55.8)
Water Truck	10	14.0	0.36 (0.26 - 0.48)	0.38 (0.23 - 0.54)	0.48 (0.23 - 0.48)	0.72 (0.46 - 0.95)	9.6 (8.2 - 25.6)	9.9 (6.2 - 22.5)	11.8 (8.4 - 13.2)	14.5 (10.4 - 26.2)
190 Ton Truck	8	20.2	0.38 (0.26 - 0.50)	0.30 (0.24 - 0.52)	0.48 (0.27 - 0.69)	0.70 (0.50 - 0.81)	9.1 (7.0 - 23.8)	6.6 (5.6 - 26.4)	11.0 (9.8 - 12.2)	13 (11.9 - 29.6)

		Predominant Axis		Σxyz	
	n	**A(8)**	**VDV(8)**	**A(8)**	**VDV(8)**
Bull Dozer	14	5.6 (3.1, 9.1)	1.5 (0.6, 3.3)	2.4 (1.0, 3.5)	0.7 (0.2, 1.7)
Front Loader	9	6.2 (4.4, 11.3)	1.6 (1.1, 4.0)	2.6 (2.1, 4.8)	0.8 (0, 1.3)
Grader	9	8.8 (3, 18.8)	1.3 (0.2, 7.4)	2.9 (1.5, 7.5)	0.6 (0.2, 2.1)
Scraper	10	4.2 (2.2, 7.6)	1.1 (0.4, 3.0)	1.7 (0.9 – 3.0)	0.4 (0, 1.3)
Water Truck	10	8.6 (2.9, 7.6)	2.9 (1.8, 10.9)	3.9 (2.2, 9.5)	1.3 (0.1, 4.7)
190 Ton Truck	8	8.6 (8.6, 37.4)	3.8 (2.5, 6.1)	4.1 (3, 7.9)	1.9 (0.1, 2.8)

Table 3. Median (min, max) time in hours equipment could be operated until reaching the ISO daily vibration action limit (A(8) = 0.5 m/s^2 and VDV(8) = 9.1 m/s$^{1.75}$). Data grouped by the predominant axis (grey cells from Table 2) and vector sum exposures.

DISCUSSION

A major finding in this study was the apparent relationship between the predominant axis of WBV exposure and average HEV speed. The slowest vehicles' predominant WBV exposures were in the x-axis and this was likely due to the for-aft stop-and-go operation of these HEVs. The predominant axis of exposure for the vehicles which operated at moderate speeds (between 6 – 12 km/h) was the y-axis and this was likely due to the HEVs speed being limited by the rough terrain on which the vehicle operated on. Finally, the z-axis was the predominant exposure for the vehicles that had the highest average operating speeds (greater than 12 km/h), these vehicles predominantly operated on the dirt roads rather than over rough terrain.

The average-continuous A(8) and cumulative-impulsive VDV(8) WBV exposure-parameters differed in the amount of time the operators could operate their HEVs before reaching ISO daily vibration action limits. The HEV operation times were considerably shorter for VDV(8) WBV exposures in comparison to the A(8) WBV exposures. The VDV(8) WBV exposures reduced acceptable HEV operation times by one-half to two-thirds relative to the A(8) WBV exposures. Large HEV operation time differences also existed between the predominant axis and the vector sum WBV exposures, vector sum WBV exposures were much more restrictive and cut acceptable vehicle operation times in half. Given that VDV(8) metric is sensitive to impulsive exposures (Burgess-Limerick & Lynas, 2016), the HEV WBV exposures in this study certainly contained impulsive content.

These results indicated that HEV mining operators are exposed to high levels of both continuous and impulsive WBV exposures. Comparisons between the ISO 2631-1 WBV exposure parameters indicated that there were substantial differences the acceptable daily HEV operation times and that there would be differences in the prediction potential adverse health outcomes between average-continuous A(8) and cumulative-impulsive VDV(8) WBV exposures.

ACKNOWLEDGEMENTS

This study was sponsored by the Alpha Foundation for the Improvement of Mine Safety and Health, Inc. (ALPHA FOUNDATION). The views, opinions and recommendations expressed herein are solely those of the authors and do not imply any endorsement by the ALPHA FOUNDATION, its Directors and staff. Alpha Foundation Grant # AFC113-3. This project would not have been possible without the cooperation of the mine and the collaboration from all the heavy equipment operators.

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