Influence of vehicle size, haulage capacity and ride control on vibration exposure and predicted health risks for LHD vehicle operators

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ABSTRACT

Documented whole-body vibration (WBV) exposure levels at the operator/seat interface are limited for underground mining load-haul-dump (LHD) vehicles. Therefore, WBV exposure during the operation of eight small and nine large LHD vehicles, under loaded and empty haulage, was measured in accordance with ISO 2631-1 guidelines. Vibration exposure was also measured for a subsample of LHD vehicles equipped with a feature designed to reduce vibration exposure (ride-control). Operator health risks were predicted according to ISO 2631-1 health guidance caution zone (HGCZ) limits for daily vibration exposure. Vibration exposure was not significantly different for vehicle size or ride control but was significantly lower when driving with a loaded haulage bucket. All operators of small LHDs and one large LHD operator were exposed to vibration levels above the HGCZ.

Keywords: Whole-body vibration, ISO 2631-1, LHD vehicle, mining, ride-control

1. INTRODUCTION

Load-haul-dump (LHD) vehicles are trackless free-steered vehicles in which the operator sits perpendicular to the direction of travel (Figure 1). LHD vehicles are used in underground mining environments to transport large quantities of ore/rock to haulage trucks, crushing stations, or ore dump locations. Operators of LHD vehicles are exposed to whole body vibration (WBV) and impact shocks[1,2], increasing their risk of developing a health problem associated with daily exposure to WBV.

The human body harmlessly attenuates most vibration; however, frequencies between 1-20 Hz cause the pelvis and spine to resonate[3,4]. Over time, vibration exposure can lead to structural damage and health problems including: lower-back pain, spinal degeneration, gastro-intestinal tract problems, sleep problems, headaches, neck problems, autonomic nervous system dysfunction, hearing loss, and nausea[4,5,6,7].

Figure 1. Example LHD vehicle used in underground mining The vehicle shown is approximately 2.7 m wide, 2 5 m high, 10.5 m long with a 5.4 m^3 bucket

Occupational vibration exposure has been documented for agricultural vehicles[5, 8, 9 10], construction vehicles[9, 11,12], forestry vehicles[13,14, 15, 16], transportation vehicles including cars[9,17], trucks[9,18] helicopters [9,19], busses[9,20] , subways[21], and trains[22]. Despite health concerns related to WBV exposure, a limited number of studies have evaluated the health risk associated with WBV during the operation of underground LHD vehicles[1,2].

In a 1989 study by Village and colleagues[2], WBV experienced by LHD vehicle operators was measured for 11 LHD vehicles ranging in size from 2.7-6.2 m^3 bucket haulage capacity.

Measurements were performed under different driving tasks (driving loaded, dumping, driving full, driving empty) and for different driving speeds. Attempts were made to control for operator experience (all experienced), tire pressure (all inflated to manufacturers' specifications), seat suspension (all used the same seat), and road conditions (all vehicles driven over the same terrain). The authors reported higher WBV exposures when driving than when either loading or dumping the bucket. They also reported higher WBV exposure values for small LHD vehicles (2.7 m^3 bucket haulage capacity) and when all the LHD vehicles were driven at higher speeds. In 2006, Eger and colleagues[1] reported operators of 2.7 m^3 bucket haulage capacity LHD vehicles were exposed to vibration levels above the 1997 ISO 2631-1 guidelines and operators of 5.4 m^3 bucket haulage capacity LHD vehicles were exposed to vibration levels within HGCZ boundaries.

Although the findings by Village[2] and Eger[1] both indicated that operation of LHD vehicles is associated with vibration levels that placed operators at increased health risks, further research is warranted to confirm their findings. Village and colleagues completed their work over 15 years ago; since that time, some changes have been made to the LHD vehicle design (e.g., suspension seats, ride-control, and improved operator cab design), and mine sites claim to have recognized the importance of road maintenance in reducing vibration. Village and colleagues also carried out their study under the 1985 ISO-2631/1 guidelines and thus did not apply the 1997 ISO revisions to weighting factors used in the calculation of frequency-weighted acceleration values[23,24]. The study by Eger and colleagues[1] had a limited sample size (two 2.7 m^3 haulage capacity LHD vehicles and one 5.4 m^3 haulage capacity LHD vehicle) and the LHD vehicle measurements were conducted at one mine site. Paddan and Griffin[9] clearly showed that vibration levels vary when a single vehicle is repeatedly driven over the same terrain, and the variability is even greater when comparisons are made across vehicles of the same type. Therefore, repeated measurements are suggested for each vehicle from a sample of multiple vehicles of the same type before making conclusions about vibration exposure.

The present study builds on the work of Village and associates[2] and Eger et al.[1]. WBV was measured during the operation of eight small and nine large haulage capacity LHDs, while performing three tasks (loaded travel, unloaded travel, and mucking) over similar underground mining terrain at eight mine sites in Ontario. WBV exposure was also measured when ride-control, a feature designed to dampen vibration, was engaged and not engaged. The primary objective of the present study was to characterize WBV exposure associated with the operation of small and large LHD vehicles under both loaded and unloaded travel conditions. A second purpose was to determine if there were possible health risks to LHD operators based on a comparison of measured vibration exposure levels with HGCZ limits. The third objective was to determine the utility of the ride-control feature that was designed to reduce vibration levels experienced by LHD vehicle operators.

2. METHODS

2.1 Selection of LHD vehicles, mine test sites, and LHD operators

The make and model of LHD vehicles tested and the test locations were determined in consultation with a technical advisory committee on underground equipment associated with the Mines and Aggregates Safety and Health Association of Ontario, Canada. Eight mine sites participated in testing in which nine large LHDs (> 3 m^3 bucket haulage capacity) and eight small LHDs (<3 m^3 bucket haulage capacity) were evaluated (Table II). The age of the vehiclts is not provided; however, the participating companies indicated all vehicles were in good operating condition. A different equipment operator, who was selected from a sample of convenience, drove each of the seventeen vehicles. Laurentian University's Research Ethics Board approved the study and participating LHD operators signed a consent prior to beginning the study.

2.2 Data collection procedures

Prior to WBV measurement, each vehicle operator completed a short questionnaire regarding operating experience and previous musculoskeletal injury history. A location in each mine, with typical terrain (road conditions were representative of an underground hard-rock mine) over which each LHD vehicle was driven, was selected for WBV testing. Each participating operator was asked to drive forward for 30 seconds over the selected route and then reverse backward to the starting location, resulting in a one-minute WBV collection period. The Operator's were asked to drive at a typical speed (operating speed used for forward and backward driving) over the testing circuit, repeating this route ten times with a loaded bucket and ten times with an empty bucket.

WBV at the operator/seat interface was also measured during a muck run, for a sub-sample of the tested LHD vehicles. A muck run involves loading the bucket and driving with the loaded bucket over rough terrain. The rough terrain is typically present in the area of a mine that has recently been blasted and is being cleared of rock; thus, vibration exposure is generally greater under these conditions. Four large LHD vehicles and four small LHD vehicles were measured while performing muck runs. Four of the large LHD vehicles, equipped with ride-control were evaluated further. Ride-control is an engineering intervention that works on the LHD vehicle's bucket lift cylinder. Ride-control is designed to act as a shock absorber, reduce fore-aft and pitching motion and dampen bucket forces. Four additional one-minute measurements with a loaded bucket and four one-minute measurements with an empty bucket were recorded with ride-control engaged and disengaged. All measurements were conducted with the LHD vehicles driving over typical terrain. An overview of all the measurements performed on each LHD vehicle is summarized in Table I.

Table 1

Overview of the testing performed on each LHD vehicle. Vibration measurements were performed on all LHD vehicles driving forward and backward with the bucket loaded (LB) and unloaded (UB), four small and four large LHD vehicles mucking, and four large LHD vehicles equipped with ride-control. Predicted health risks, based on ISO 2631-1 health guidance caution zone (HGCZ) boundaries were possible for four large and all four small LHD vehicle operators.

LHD Size	LHD Model	Description of Trials									ISO 2631-1 HCGZ Comparisons
		# of trials (30s duration)				Total # of minutes of data recorded (represents a minimum of two mucking cycles)[1]	# of trials (30 s duration)				
		Driving				Mucking	Ride-control				
		Forward		Backward		Forward & Backward Driving	Forward		Backward		
		LB	UB	LB	UB	Mixed (LB & UB)	LB	UB	LB	UB	
Small LHDs	I-4	10	10	10	10						
	K-7	10	10	10	10						
	L-7	10	10	10	10						
	M-7	10	10	10	10						
	J-8	10	10	10	10	5					Yes
	N(1)-8	10	10	10	10	25					Yes
	N(2)-8	10	10	10	10	7					Yes
	P-8	10	10	10	10	5					Yes
Large LHDs	A-1	10	10	10	10		4	4	4	4	
	B-1	10	10	10	10		4	4	4	4	
	C-2	10	10	10	10	6					Yes
	D-3	10	10	10	10	18					Yes
	E-4	10	10	10	10						
	C-5	10	10	10	10		4	4	4	4	
	D-5	10	10	10	10						
	F-5	10	10	10	10	2					Yes
	G-6	10	10	10	10	2	4	4	4	4	Yes

[1] the length of the mucking trials varied due to environment factors related to mucking that vary by work location in each mine

2.3 Measurement of whole-body vibration

WBV exposure measurements were conducted in accordance with ISO 2631[23]. A Series 2, 10g tri-axial accelerometer manufactured by NexGen Ergonomics (Montreal, QC), in conjunction with a P3X8-2C DataLOG II, datalogger manufactured by Biometrics (Gwent, UK), was used to measure WBV exposure. The accelerometer measured vibration in three translational axes (fore-and-aft = x-axis; lateral = y-axis, and vertical = z-axis), required a supply voltage of +4.50 volts DC from the datalogger, and had less than 5% crosstalk. Vibration data was recorded at 500 Hz, and the datalogger allowed 1 3-bit analog to digital conversion, resulting in a resolution of 0.0025 g at the ± 10 g full scale range. The accelerometer was secured in a rubber seat pad and affixed to the supporting seat surface between the ischial tuberosities of the seated operator. Collected data was saved on a SD memory card and transferred to an IBM Thinkpad laptop computer for later analysis.

2.4 Analysis of whole-body vibration exposure

Vibration analysis was conducted in accordance with ISO-263 1-1 guidelines and carried out with Vibration Analysis Tool-Set (VATS 2.4.0) software distributed by NexGen Ergonomics (Montreal, QC). The measures used in this study were: frequency-weighted root-mean-square (r.m.s.) accelerations, peak accelerations, crest factors, vibration dose values, the 8-hour equivalent frequency-weighted r.m.s. acceleration, and the 8-hour equivalent vibration dose value. A general description of data processing is provided below. Readers can refer to ISO2631-1 for detailed information on mathematical calculations.

Frequency-weighted root-mean-square (r.m.s.) accelerations (a_{wx}; a_{wy}; a_{wz}) were calculated using the appropriate weighting factors as described in IS0 2631-1 (x-axis = W_d; y-axis = W_d; z-axis = W_k). Scaling factors associated with the determination of health for seated exposure are also applied (x-axis, k = 1.4; y-axis, k = 1.4; z-axis, k = 1.0). The peak accelerations (maximum instantaneous acceleration during the measurement duration) for each axis are reported along with the frequency-weighted r.m.s. vector sum value (a_v). The crest factor (CF) and vibration dose values (VDV) were calculated for each orthogonal axis, as frequency-weighted r.m.s. acceleration measurements are insensitive to occasional shocks that are present in the signal. If a vibration measurement contains one or more transient spikes, it will lead to a high peak acceleration, which will result in a high crest factor ratio. If CF values are above nine, the ISO-2631-1 standard indicates the VDV should also be considered when determining health risks.

When determining health effects, the ISO 2631-1 standard provides two options for comparison with limits established in the HGCZ. The basic evaluation method uses the axis with the highest frequency-weighted r.m.s. acceleration values. However, if any crest factor value is greater than nine,the lS0 2631-1 standard recommends that the axis with the highest VDV be used in the determination of health risks. When an 8-hour exposure duration is considered, the upper and lower boundaries of the HGCZ for frequency-weighted r.m.s. accelerations are 0.9 m/s^2 and 0.45 m/s^2 respectively. The equivalent HGCZ boundaries for the 8-hour VDV are 17 $m/s^{1.75}$ and 8.5 $m/s^{1.75}$. Therefore, both the eight-hour equivalent frequency-weighted r.m.s. acceleration value (A8), and the 8-hour equivalent VDV (VDV_{total}) were calculated for each operator by considering the vibration experienced while performing daily vehicle operating tasks. In consultation with a member of the technical advisory committee from the Mines and Aggregates Safety and Health Association of Ontario, Canada, it was estimated that LHD drivers spend 7 hours per work day performing common working tasks on their underground mobile equipment. The task of driving with a loaded bucket was estimated to occur for 2.75 hours in the course of am 8-hour work day, while the tasks of diving with an unloaded bucket, mucking (loading the bucket), and off the LHD vehicle (breaks and travelling to and from the production area) were estimated to occur for 2.25 hours, 2 hours and I hour respectively. These task durations were used to calculate the A(8) and VDV_{total} values.

2.5 Statistical analysis

A general linear model univariate analysis of variance was carried out to determine statistical differences between the defendant variable, a_v, and independent variables, LHD size (large and small) and LHD hauling condition (loaded and unloaded). A general linear model multivariate analysis of variance was carried out to determine statistical differences between the dependant variables, a_{wx}, a_{wy}, and a_{wz}, and the independent variables, ride-control (on and off and LHD hauling condition (loaded and unloaded). In both analyses a Bonferroni correction was applied when comparing means and alpha was set at a level of 0.05.

3 RESULTS

Vehicle characteristics, operator characteristics, and operator injury profiles are summarized in Table II. The mean age, mass, and height of the 17 participating operators was 38 ± 9 yrs, 84 ± 12 kg, and 1.7 ± 0.12 m respectively. Three operators did not provide a musculoskeletal injury history; of the remaining 14 LHD operators, nine reported at least one body region in which they had experienced a musculoskeletal injury (MSI) (i.e., ache, discomfort, pain, or injury) in the previous six months. The low back region received the greatest number of MSI reports (n = 5), with an average severity rating of 2.8 on the 4-point scale (4 = severe discomfort). Four LHD operators indicated they had an MSI in the neck region and provided an average severity rating of 2.8 on the 4-point scale. MSI reports (Table II) were also indicated for the knee region (n-4),-foot region (n = 3), upper back region (n = 1), shoulder region (n = 1), and hand region (n = 1).

3.1 Frequency-weighted r.m.s. acceleration

Frequency-weighted r.m.s. acceleration values, crest factor values, vibration dose values, and dominant frequency values measured at the operator/seat interface for loaded driving and unloaded driving conditions are presented in Table IIIA and Table IIIB. The axis associated with the highest frequency-weighted r.m.s. acceleration levels was predominantly the z-axis. Only one small LHD vehicle (L) in the unloaded driving condition and two large LHD vehicles (D-3; G) in the loaded driving condition had a dominant x-axis exposure. The highest frequency-weighted r.m.s. acceleration was 2.49 m/s^2 measured in the z-axis (a_{wz}) for a large LHD vehicle (E) during loaded driving. The highest value measured for a small LHD vehicle (J) also occurred in the z-axis (a_{wz}) but was associated with unloaded driving: 2.46 m/s^2. The lowest zaxis frequency-weighted r.m.s. acceleration value recorded occurred during loaded driving and was 0.65 m/s^2 for a small LHD vehicle (M) and 0.40 m/s^2 for a large LHD vehicle (C-5). There was no statistically significant difference in frequency-weighted vector sum r.m.s. acceleration when LHD vehicle size was considered; however, driving with an unloaded bucket resulted in a significantly greater frequency-weighted vector sum r.m.s. acceleration value ($P<0.001$) than driving with a full bucket.

The mean dominant frequencies for small LHD vehicles in the x, y, and z axes were 1.47 Hz, 1.30 Hz, and 4.21 Hz respectively for unloaded travel and shifted to 1.40 Hz, 1.25 Hz and 3.80 Hz under loaded driving conditions for the x, y, and z axes respectively (Table IIIA). The mean dominant frequencies for the large LHD vehicles were lower than the values for the small LHD vehicles (Table IIIB).

Vibration at the operator/seat interface for four large LHD vehicles and four small LHD vehicles was also measured during a mucking task (Table IV). The highest z-axis frequency-weighted r.m.s. acceleration for large LHD vehicles was 2.34 m/s^2 (LHD F), and the highest value amongst the small LHD vehicles was 1.93 m/s^2 (LHD J). The dominant frequency for large LHD vehicles in the x-axis and y-axis fell between 1.00 Hz and 1.25 Hz, while the dominant frequency in the z-axis ranged between 3.15 Hz and 4.00 Hz. The dominant frequency associated with the mucking task was typically higher for the small LHD vehicles (Table IV). The dominant frequency for small LHD vehicles in the x-axis and y-axis fell between 1.00 Hz and 2.00 Hz, and the dominant frequency in the z-axis ranged between 4.00 Hz and 5.00 Hz.

Table II

Summary of LHD vehicles, operator characteristics, and operator injury profiles

		Vehicle Characteristics				Participant Characteristics				Musculoskeletal Disorder Report (experienced in the previous 6 months)				
LHD Model	Test Mine	Size (width, height, length) (m)	Haulage Capacity (m^3)	Approximate Vehicle Mass-Empty (kg)	Ride-control Feature	Age (yrs)	Height (m)	Mass (kg)	Driving Experience (yrs)	Neck	Upper Back	Low Back	Shoulders	other
										severity (1=mild; 2=moderate; 3=severe; 4=very severe)				
I	4	2.9, 1.6, 8.5	2.7	17,510	no	53	1.8	84	23	Yes (3)	yes (3)	yes (3)	yes (3)	hands (3) knees (3) feet (3)
K	7	2.9, 1.7, 8.5	2.7	17,510	no	44	1.8	73	25	yes (3)	no	no	no	no
L	7	1.4, 1.4, 5.5	1.1	6,759	no	28	1.6	69	4	yes (3)	no	yes (3)	no	feet (3)
M	7	1.5, 2, 7.3	1.7	14,320	no	34	1.8	75	13	No	no	no	no	no
J	8	1.8, 1.6, 7.9	2.3	12,700	no	29	1.7	81	6	-----not reported-----				
N (1)	8	1.4, 1.3, 5.5	1.1	6,650	no	28	1.6	77	8	No	no	no	no	no
N(2)	8	1.4, 1.3, 5.5	1.1	6,650	no	30	1.8	93	7	-----not reported-----				
P	8	1.8, 1.7, 8.0	2.3	not available	no	30	1.6	80	8	-----not reported-----				
A	1	2.8, 2.6, 10.6	5.7	38,500	yes	33	1.6	84	4	No	no	no	no	knee (2)
B	1	2.8, 2.6, 10.6	5.7	38,500	yes	49	1.8	98	9	No	no	yes (2)	no	no
C	2	3, 2.8, 11	7.6	44,000	no	43	1.7	75	20	yes (2)	no	yes (3)	no	knee (1)
D	3	3, 2.6, 10.7	6.9	38,500	no	24	1.9	109	3	No	no	no	no	no
E	4	2.7, 2.5, 10.5	6.1	39,200	no	48	1.7	61	29	No	no	yes (3)	no	no
C	5	3, 2.8, 11	7.6	44,000	yes	43	1.6	95	4	No	no	no	no	no
D	5	3, 2.6, 10.7	6.9	38,500	no	48	1.9	84	25	No	no	no	no	feet
F	5	2.9, 2.7, 11	7.5	40,200	no	44	1.6	86	16	No	no	no	no	no
G	6	2.7, 2.5, 10.5	6.1	33,700	yes	34	1.9	98	4	No	no	no	no	knee (4)

Table III A

Summary of frequency-weighted accelerations (aw), crest factor values (CF), vibration dose values (VDV), and dominant frequency values measuted at the operator/seat interface for small LHD vehicles. Ten one-minute recordings were performed, while driving over the same terrain at the same operating speed (average values are plovided in the table). Dominamt axis values and CF values over nine are bolded.

LHD Size	LHD Model & Test Mine	Frequency-weighted r.m.s.				Crest factors			Vibration dose values			Dominant frequencies		
		a_{wx} m/s^2	a_{wy} m/s^2	a_{wz} m/s^2	a_v m/s^2	CF_x	CF_y	CF_z	VDV_x $m/s^{1.75}$	VDV_y $m/s^{1.75}$	VDV_z $m/s^{1.75}$	DFx Hz	Dfy Hz	DFz Hz
Small LHDs Unloaded	I-4	1.05	0.67	**1.71**	2.44	5.4	4.6	**9.7**	4.66	2.81	**8.44**	1.21	1.52	4.00
	K-7	1.28	0.72	**1.62**	2.62	5.0	4.6	5.1	5.60	3.04	**6.87**	1.64	2.00	3.66
	L-7	1.14	0.65	**1.35**	2.28	5.9	5.4	7.0	5.16	2.77	**6.19**	1.58	1.16	4.00
	M-7	0.27	0.32	**0.74**	0.95	7.0	8.2	4.4	1.63	2.02	**3.07**	1.45	1.15	4.00
	J-8	1.07	1.12	**2.46**	3.28	5.4	5.1	6.5	4.62	4.59	**10.65**	1.26	1.13	4.00
	N(1)-8	1.03	0.46	**1.71**	2.33	5.4	5.4	4.9	4.42	1.97	**7.16**	1.45	1.10	5.00
	N(2)-8	0.84	0.52	**2.17**	2.57	5.5	5.9	4.1	3.72	2.45	**9.08**	1.25	1.23	5.00
	P-8	1.12	0.57	**1.80**	2.51	5.5	5.6	5.1	5.13	2.50	**7.92**	1.96	1.15	4.00
	Mean	0.97	0.63	**1.70**	2.37	5.63	5.58	5.85	4.37	2.77	**7.42**	1.47	1.30	4.21
	SD	0.31	0.24	0.51	0.65	0.61	1.15	1.87	1.24	0.82	2.24	0.25	0.31	0.50
Small LHDs Loaded	I-4	0.97	0.62	**1.39**	2.12	5.2	5.0	**9.1**	4.25	2.63	**6.49**	1.30	1.61	3.15
	K-7	1.12	0.63	**1.82**	2.55	4.7	5.4	7.6	4.95	2.74	**8.24**	1.92	1.47	3.15
	L-7	**1.05**	0.55	0.71	1.80	5.7	6.3	6.1	**4.90**	2.52	3.12	1.57	1.29	4.10
	M-7	0.28	0.23	**0.65**	0.83	6.7	8.7	4.5	1.34	1.47	**2.79**	1.25	1.10	4.00
	J-8	0.84	0.50	**1.78**	2.24	4.9	5.1	6.7	3.62	2.12	**7.83**	1.08	1.13	4.00
	N(1)-8	0.97	0.53	**1.49**	2.15	4.5	4.5	4.5	3.88	2.10	**6.09**	1.23	1.15	4.00
	N(2)-8	0.76	0.45	**1.66**	2.07	4.9	5.2	4.5	3.32	1.98	**7.05**	1.10	1.08	4.00
	P-8	0.97	0.45	**1.69**	2.26	6.1	5.7	5.1	4.70	2.01	**7.53**	1.73	1.23	4.00
	Mean	0.87	0.49	**1.40**	2.00	5.36	5.74	6.01	3.87	2.20	**6.14**	1.40	1.25	3.80
	SD	0.26	0.12	0.46	0.52	0.76	1.30	1.71	1.18	0.42	2.09	0.31	0.19	0.40

Table III B

Summary of frequency-weighted accelerations (aw), crest factor values (CF), vibration dose values (VDV), and dominant frequency values measured at the operator/seat interface for large LHD vehicles. Ten one-minute recordings were performed, while driving over the same terrain at the same operating speed (average values are provided in the table). Dominant axis values and CF values over nine are bolded.

LHD Size	LHD Model & Test Mine	Frequency-weighted r.m.s.				Crest factors			Vibration dose values			Dominant frequencies		
		a_{wx} m/s^2	a_{wy} m/s^2	a_{wz} m/s^2	a_v m/s^2	CF_x	CF_y	CF_z	VDV_x $m/s^{1.75}$	VDV_y $m/s^{1.75}$	VDV_z $m/s^{1.75}$	DFx Hz	Dfy Hz	DFz Hz
Large LHDs Unloaded	A-1	0.55	0.41	**0.82**	1.26	4.2	6.5	4.0	2.22	2.08	**3.10**	1.40	1.08	4.00
	B-1	0.46	0.33	**1.33**	1.54	5.8	8.0	7.1	2.40	2.00	**8.04**	1.57	1.15	4.00
	C-2	0.57	0.58	**1.00**	1.52	4.5	5.6	5.9	2.41	2.60	**4.81**	1.46	1.11	4.00
	D-3	**0.59**	0.46	0.46	1.15	4.4	5.9	4.1	**2.41**	2.01	1.75	1.40	1.29	3.62
	E-4	0.64	0.51	**1.69**	2.04	5.8	5.6	**12.4**	2.81	2.55	**10.97**	1.33	1.65	4.00
	C-5	0.32	0.31	**0.53**	0.82	6.3	8.4	**13.2**	1.46	1.93	**3.57**	1.40	1.06	4.50
	D-5	0.37	0.32	**0.69**	0.97	5.1	8.4	4.5	1.69	1.71	**2.90**	1.53	1.14	4.00
	F-5	0.88	0.55	**1.81**	2.32	4.1	5.2	4.7	3.50	2.50	**7.56**	1.29	1.10	4.00
	G-6	**0.72**	0.61	0.68	1.49	4.8	5.9	4.6	**3.05**	2.85	2.85	1.54	1.57	3.54
	Mean	0.57	0.45	**1.00**	1.46	4.99	6.63	6.71	2.44	2.25	**5.06**	1.43	1.24	3.96
	SD	0.17	0.12	0.50	0.49	0.78	1.30	3.57	0.63	0.38	3.10	0.10	0.22	0.27
Large LHDs Loaded	A-1	0.48	0.38	**0.81**	1.18	4.4	6.3	4.2	2.08	2.11	**3.25**	1.44	1.08	3.22
	B-1	0.40	0.29	**0.79**	1.04	5.4	6.6	**10.6**	2.10	1.57	**5.17**	1.31	1.06	3.15
	C-2	0.51	0.61	**0.89**	1.42	4.8	4.9	6.0	2.21	2.65	**4.34**	1.29	1.00	3.15
	D-3	0.51	0.30	**0.55**	1.00	4.6	6.3	3.4	**2.13**	1.39	1.98	1.10	1.18	3.15
	E-4	0.77	0.45	**2.49**	2.79	6.0	5.7	**9.1**	3.58	2.11	**16.14**	1.65	1.53	3.15
	C-5	0.31	0.27	**0.40**	0.70	5.4	6.9	5.2	1.45	1.40	**1.68**	1.34	1.06	3.15
	D-5	0.29	0.24	**0.45**	0.69	5.4	6.6	4.7	1.39	1.18	**1.92**	1.57	1.15	3.15
	F-5	0.83	0.51	**1.62**	2.11	4.6	4.5	5.1	3.48	2.06	**7.07**	1.36	1.53	3.15
	G-6	0.62	0.53	**0.66**	1.31	5.1	6.6	6.1	2.65	2.73	**2.86**	1.19	1.19	3.15
	Mean	0.52	0.40	**0.96**	1.36	5.08	6.03	6.05	2.34	1.91	**4.94**	1.36	1.20	3.16
	SD	0.19	0.13	0.68	0.69	0.53	0.82	2.33	0.78	0.56	4.56	0.17	0.20	0.02

Table IV

Summary of frequency-weighted accelerations (aw), crest factor values (CF), vibration dose values (VDV) and dominant frequency values measured at the operator/seat interface during LHD vehicle operation for the mucking task. Dominant axis values are bolded, and CF values over nine are bolded.

LHD Size	LHD Model	Test Mine	Duration of Measurement (minutes)	Mucking Task											
				Frequency-weighted r.m.s. acceleration values			Crest factor values			Vibration dose values			Dominant frequency		
				a_{wx} m/s^2	a_{wy} m/s^2	a_{wz} m/s^2	CF_x	CF_y	CF_z	VDV_x $m/s^{1.75}$	VDV_y $m/s^{1.75}$	VDV_z $m/s^{1.75}$	DF_x Hz	DF_y Hz	DF_z Hz
Large LHDs	C	2	6	0.64	0.80	**1.18**	7.63	5.74	7.94	3.95	5.14	**8.34**	1.25	1.00	3.15
	D	3	18	**0.64**	0.55	0.54	8.50	**9.96**	**17.52**	**5.44**	4.94	4.94	1.25	1.00	4.00
	F	5	2	0.94	0.87	**2.34**	5.01	4.68	5.88	4.57	4.33	**12.14**	1.25	1.25	4.00
	G	6	2	0.73	0.68	**0.89**	5.18	5.98	**22.30**	3.53	3.43	**6.93**	1.25	1.25	3.15
			Mean	0.74	0.73	**1.24**	6.58	6.59	**13.41**	4.37	4.46	**8.09**	1.25	1.13	3.58
			SD	0.14	0.14	0.78	1.75	2.32	7.80	0.83	0.77	3.04	0.00	0.14	0.49
Small LHDs	J	8	5	0.98	0.55	**1.93**	7.14	5.55	6.73	5.27	2.76	**9.63**	1.13	1.13	4.00
	N(1)	8	25	1.04	0.63	**1.20**	8.70	**10.64**	7.40	10.44	6.40	**12.11**	1.00	1.00	4.00
	N(2)	8	7	0.60	0.46	**1.36**	6.91	6.43	6.16	3.68	2.67	**8.40**	1.13	1.00	5.00
	P	8	5	1.11	0.58	**1.63**	5.66	6.10	5.65	6.00	2.94	**8.23**	2.00	1.13	4.00
			Mean	0.93	0.56	**1.53**	7.10	7.18	6.49	6.35	3.69	**9.59**	1.32	1.07	4.25
			SD	0.23	0.07	0.32	1.25	2.34	0.75	2.90	1.81	1.79	0.46	0.08	0.50

3.2 Determination of health risks

Health risks were determined for a sub-sample of four large LHD vehicles and four small LHD vehicles. Based on Table IV, three of the eight LHD vehicles (D-3, G, N(l)) had at least one CF value greater than nine; therefore, according to the ISO 2631-1 standard, both the frequency-weighted r.m.s. acceleration values and the VDV should be used to determine health risks. As a result, the A(8) values (Table V) and the VDVtotal values (Table VI) were calculated and compared to the respective HGCZ limits. Two large LHD vehicle operators were exposed to A(8) vibration levels above the HGCZ limits, and two large LHD vehicle operators were exposed to A(8) vibration levels within the HGCZ (Table V; Figure 2). All four small LHD vehicle operators experienced A(8) vibration levels above the HCGZ (Table V; Figure 2). According to the VDVtotal values, three of the four large LHD vehicle operators were exposed to vibration levels above the HGCZ, and the other large LHD vehicle operator was exposed to vibration levels within the HGCZ (Table VI; Figure 3). All four of the small LHD vehicle operators were exposed to VDVtotal vibration levels above the HGCZ.

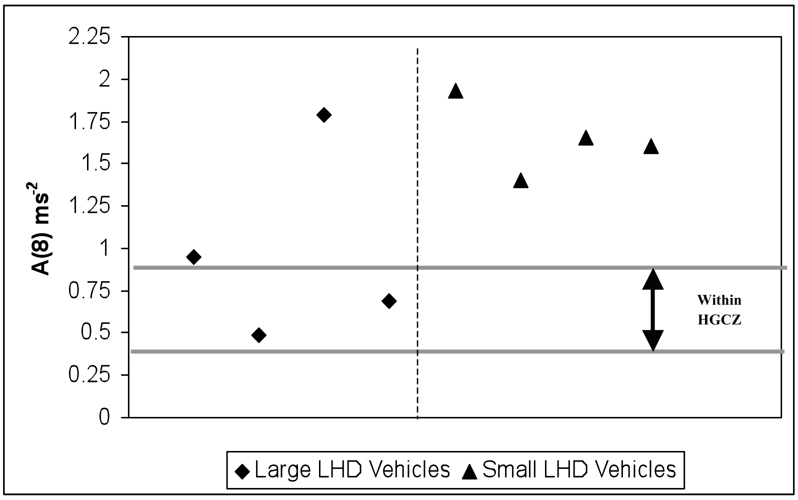

Figure 2. A(8) value associated with daily vibration exposure for four large and four small LHDs. Plotted A(8) values are shown with respect to the upper (0.9 m/s^2) and lower (0 45 m/s^2) boundary of the ISO 2631-1 health guidance caution zone (HGCZ) for an eight-hour daily exposure.

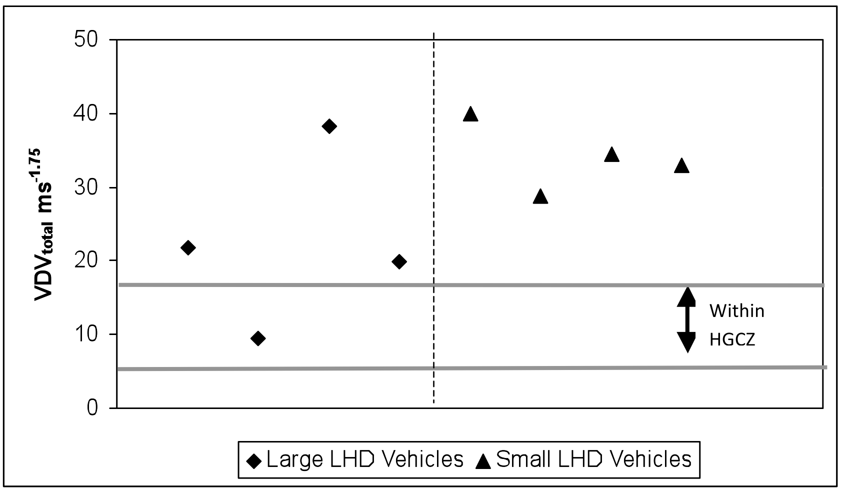

Figure 3. VDV_{total} values associated with daily vibration exposure for four large and four small LHDs. Plotted VDV_{total} values are shown withrespect to the upper(17$m/s^{1.75}$) and lower (8.5$m/s^{1.75}$) boundary of the ISO 2531-1 health guidance caution zone (HGCZ) for an eight-hour daily exposure.

Table V

Determination of health risk based on the estimated 8-hour equivalent frequency-weighted r.m.s acceleration value, A(8)

Vehicle Size	LHD Model	Mine site	Task	[1]Driver's Estimated Daily Exposure (hours)	Duration of Measurement (min)	[2]Mean Vibration Magnitude on Seat (dominant axis) (ms^{-2})	A(8) (ms^{-2})	[3]ISO 2631-1 HGCZ (based on an 8-hour exposure duration)
Large LHD Vehicles	C	2	driving loaded	2.75	1	0.89	0.95	**above HGCZ**
			driving unloaded	2.25	1	1.00		
			loading the bucket	2.00	6	1.18		
	D	3	driving loaded	2.75	1	0.55	0.55	within HGCZ
			driving unloaded	2.25	1	0.46		
			loading the bucket	2.00	18	0.64		
	F	5	driving loaded	2.75	1	1.62	1.79	**above HGCZ**
			driving unloaded	2.25	1	1.81		
			loading the bucket	2.00	2	2.34		
	G	6	driving loaded	2.75	1	0.66	0.70	within HGCZ
			driving unloaded	2.25	1	0.68		
			loading the bucket	2.00	2	0.89		
Small LHD Vehicles	J	8	driving loaded	2.75	1	1.78	1.93	**above HGCZ**
			driving unloaded	2.25	1	2.46		
			loading the bucket	2.00	5	1.93		
	N(1)	8	driving loaded	2.75	1	1.49	1.40	**above HGCZ**
			driving unloaded	2.25	1	1.71		
			loading the bucket	2.00	25	1.20		
	N(2)	8	driving loaded	2.75	1	1.66	1.65	**above HGCZ**
			driving unloaded	2.25	1	2.17		
			loading the bucket	2.00	7	1.36		
	P	8	driving loaded	2.75	1	1.69	1.60	**above HGCZ**
			driving unloaded	2.25	1	1.80		
			loading the bucket	2.00	5	1.63		

[1] a common exposure duration profile was used-based on typical LHD operations (each driver also spent one-hour off the LHD vehicle)

[2] the 1-minute driving loaded and driving unloaded values are the mean 1 -minute values from ten 1- minute samples (Table III)

[3] frequency-weighted acceleration values corresponding to the lower and upper limits of the HGCZ (for 8 hrs of exposure) are 0.45 and 0.90 ms^{-2}

Table IV

Determination of healh risk based on the estimated 8-hour vibration dose value, VDVtotal

Vehicle Size	LHD Model	Test Mine	Task	[1]Driver's Estimated Daily Exposure (hours)	Duration of Measurement (min)	[2]Mean VDV on seat (dominant axis) ($ms^{-1.75}$)	VDV_n ($m/s^{1.75}$)	VDV_{total} ($m/s^{1.75}$)	[3]ISO 2631-1 HGCZ (based on an 8-hour exposure duration)
Large LHD Vehicles	C	2	driving loaded	2.75	1	4.34	15.56	21.84	**above HGCZ**
			driving unloaded	2.25	1	4.81	16.40		
			loading the bucket	2.00	6	8.34	17.64		
	D	3	driving loaded	2.75	1	2.13	7.63	9.91	within HGCZ
			driving unloaded	2.25	1	2.41	8.21		
			loading the bucket	2.00	18	5.44	8.74		
	F	5	driving loaded	2.75	1	7.07	25.35	38.31	**above HGCZ**
			driving unloaded	2.25	1	7.56	25.76		
			loading the bucket	2.00	2	12.14	33.78		
	G	6	driving loaded	2.75	1	2.86	10.24	19.95	**above HGCZ**
			driving unloaded	2.25	1	3.05	10.40		
			loading the bucket	2.00	2	6.93	19.29		
Small LHD Vehicles	J	8	driving loaded	2.75	1	7.83	28.06	40.01	**above HGCZ**
			driving unloaded	2.25	1	10.65	36.30		
			loading the bucket	2.00	5	9.63	21.31		
	N(1)	8	driving loaded	2.75	1	6.09	21.84	28.78	**above HGCZ**
			driving unloaded	2.25	1	7.16	24.41		
			loading the bucket	2.00	25	12.11	17.93		
	N(2)	8	driving loaded	2.75	1	7.05	25.26	34.47	**above HGCZ**
			driving unloaded	2.25	1	9.08	30.96		
			loading the bucket	2.00	7	8.40	17.10		
	P	8	driving loaded	2.75	1	7.53	26.98	32.89	**above HGCZ**
			driving unloaded	2.25	1	7.92	26.98		
			loading the bucket	2.00	5	8.23	18.21		

[1] A common exposure duration profile was used-based on typical LHD operations (each driver also spent one-hour offthe LHD vehicle)

[2] the l-minute driving loaded and driving unloaded values are the mean l-minute values from ten 1- minute samples (TableIII)

[3] VDVs corresponding to the lower and upper limits of the HGCZ (for 8hrs of daily exposure) are 8.5 and 17 $m/s^{1.75}$ respectively.

3.3 Ride-control

Four LHD vehicles equipped with ride-control were evaluated while driving with a loaded bucket and an unloaded bucket. Frequency-weighted r.m.s. acceleration levels with ride-control engaged and not engaged are presented in Table VII. Although there appeared to be a reduction in vibration exposure at the operator/seat interface with ride-control engaged, the decrease was not statistically significant.

Table VII

Comparison of ftequency-weighted r.m.s. acceletation values (a_{wx}, a_{wy}, a_{wz}) with the ride-control feature engaged ard disengaged for driving with a loaded bucket and driving with an unloaded bucket.

LHD Model	Test Mine	Ride-control Unloaded driving			Ride-control Unloaded driving			Ride-control Loaded driving			Ride-control Loaded driving		
		a_{wx} m/s^2	a_{wy} m/s^2	a_{wz} m/s^2	a_{wx} m/s^2	a_{wy} m/s^2	a_{wz} m/s^2	a_{wx} m/s^2	a_{wy} m/s^2	a_{wz} m/s^2	a_{wx} m/s^2	a_{wy} m/s^2	a_{wz} m/s^2
A	1	0.54	0.45	0.99	0.55	0.41	0.82	0.47	0.36	0.90	0.48	0.38	0.81
B	1	0.47	0.35	1.49	0.46	0.33	1.33	0.38	0.30	0.75	0.40	0.29	0.79
C	5	0.35	0.34	0.68	0.32	0.31	0.53	0.31	0.27	0.39	0.31	0.27	0.40
G	6	0.74	0.63	0.67	0.72	0.61	0.68	0.61	0.51	0.65	0.62	0.53	0.66
	Mean	0.52	0.44	0.96	0.51	0.41	0.84	0.44	0.36	0.67	0.45	0.37	0.66
	SD	0.17	0.13	0.38	0.17	0.13	0.34	0.13	0.11	0.21	0.13	0.12	0.19

4.0 DISCUSSION

This study found that driving an LHD vehicle with an unloaded bucket resulted in significantly higher levels of vibration exposure than driving with a loaded bucket. Vibration levels experienced by the LHD operators also indicated health risks were likely to develop[23]. Vehicles equipped with ride-control had a tendency to produce less vibration although the difference was not statistically significant; however, the sample size was very small (n = 4) and further testing is warranted.

Results from this study (Table III; Table IV) are consistent with vibration levels reported by other researchers who have monitored vibration levels during the operation of heavy equipment. Paddan and Griffin[9] reported mean dominant axis frequency-weighted r.m.s. acceleration values for tractors, excavators, armored vehicles, and dumpers to be 0.73 m/s^2, 0.91 m/s^2, 0.85 m/s^2, and 1.82 m/s^2 respectively. Mean dominant axis frequency-weighted r.m.s. acceleration values reported for 2-ton dump trucks, 2-ton garbage trucks, and 4-ton garbage trucks reported by Maeda and Morioka[25] were 0.9 m/s^2, 0.92 m/s^2 and 1.1 m/s^2 respectively. Moreover, results from the present study are in line with vibration levels reported for LHD vehicles previously studied[1,2]. Both prior studies reported higher frequency-weighted r.m.s. acceleration levels for smaller LHD vehicles (2.7 m^3 bucket) than larger LHD vehicles (5.4 – 6.1 m^3 bucket). The mean frequency-weighted r.m.s. acceleration in the z-axis for combined tasks (driving loaded, dumping, driving empty and mucking) reported by Village et al., was 1.56 m/s^2[2] while Eger et al., reported 1.67 m/s^2[1] (for small LHD vehicles); the values for large LHD vehicles reported by Village and colleagues and Eger and colleagues were 0.98 m/s^2[2] and 0.52 m/s^2[1], respectively. In the current study, the mean 8-hour equivalent frequency-weighted r.m.s. acceleration value was 1.65 m/s^2 for small LHD vehicles and 1.0 m/s^2 for large LHD vehicles (Table V). Findings from the cu rent study, when considered with the work of Village et al. [2] and Eger et al.[1] indicate that vibration levels experienced during the operation of LHD vehicles continue to be above established health guidelines[23]. The current study also provides updated vibration exposure measurements. Exposure values reported by Village et al., were published in 1989 and were performed according to guidance provided in the 1982 version of ISO 2631. The reported vibration exposure values from Eger et aL, were published in 2006 and processed according to me 1997 version of ISO 2631-1; however, the sample size was limited. Therefore, the vibration exposure values reported in this paper for large and small LHD vehicle operation represent an updated data set that could be used to comment on potential health effects to workers operating LHD vehicles.

Although it is not possible to conclude that high levels of WBV exposure were the only cause of the reported neck and back discomfort (Table II), evidence from the current study suggests vibration levels above the health guidance caution zone could be indicative of a higher probability of injury to the back. When the A(8) values were considered, two of the four evaluated large LHD vehicle operators and all four of the evaluated small LHD vehicle operators experienced vibration levels above the HGCZ (Table V). When the 8-hour equivalent VDV values were considered, three of the four evaluated large LHD vehicle operators and all four of the evaluated small LHD vehicle operators were above the HGCZ (Table VI). Moreover, the operator who drove the LHD vehicle with the highest z-axis frequency-weighted r.m.s. acceleration value (E) indicated he had experienced back discomfort (Table II). Furthermore, the operator who drove the small LHD vehicle (M) and the operator who drove the large LHD vehicle (C-5), lowest z-axis frequency-weighted r.m.s. acceleration levels, reported no musculoskeletal injuries. High rates of back injury amongst LHD vehicle operators were also reported by Village and colleagues[2]. Therefore, analysis of all operators' injury profiles and their vibration profiles will be important in future studies in order to determine whether these variables are related.

Other researchers have reported a positive association between WBV and low back complaints. Bovenzi and Betta[8] reported a significant relationship between WBV and low back pain (LBP) when vibration exposure was expressed as either acceleration magnitude in m/s^2 or duration of driving in years (after adjusting for age). In the range between 0.5 m/s^2 and 1.0 m/s^2, the estimated odds ratio for LBP was 1.6; however, if the vibration exposure level was greater than 1.0 m/s^2, the odds ratio jumped to 2.1. When years of driving were considered, workers with fewer than 15 years of driving exposure had an odds ratio for LBP of 1.8, which jumped to 2.3 with greater than 25 years of driving exposure[8]. These results implied that lifetime exposure (cumulative vibration exposure) was more important than magnitude (peak vibration levels) when examining LBP risks. Dupuis and Zerlett[26] evaluated morphological changes in the lumbar spine in a cross-sectional study of 352 operators of earth-moving machinery who had been exposed to WBV for at least three years, 251 machine operators who had been exposed to vibration for at least ten years, and a control group of 215 non-exposed persons. They found morphological changes in the lumbar spine were present, occurred earlier, and occurred more frequently in operators with at least ten years of exposure to WBV[26]. More recently, in a longitudinal study, Schwarze and colleagues[27] examined the relationship between long-term occupational exposure to WBV and degenerative changes in the lumbar spine. Lumbar x-rays from 388 vibration-exposed workers from different driving jobs were evaluated initially and compared with another set of x-rays taken after a four-year period. The authors found that the prevalence of lumbar syndrome was 1.55 times higher in the participants with high levels of vibration exposure when compared to the reference group with low vibration exposure.

In order to reduce injury risk associated with daily vibration exposure, the mining industry will need to consider intervention strategies aimed at reducing harmful levels of vibrations[28]. Recently, several LHD equipment manufacturers have installed a ride-control feature on the LHD vehicles that is d,esigned to reduce fore-aft pitching of the bucket. Four LHD vehicles equipped with ride-control were evaluated in this study. There was a trend toward a decrease in vibration at the operator/seat interface with ride-control engaged, but significance was not reached given the small sample size. Therefore, additional testing should be carried out in order to determine if the installation of a ride-control feature will lead to reduced vibration exposure.

The mining industry will need to consider a number of different intervention strategies to have an impact on injury reduction. Recent work by Boileau and colleagues[29] showed that new "ergonomic" seats installed in LHD vehicles amplify the vibration at the operator/seat interface.

Poor road maintenance continues to be a problem[28] that results in higher levels of WBV exposure[15,30]. Future studies should also consider the contribution to injury risk associated with the adoption of twisted trunk and neck postures in combination with WBV exposure[8,10,31,32]. Additional testing of a larger sample of LHD vehicles equipped with ride-control is required before a definitive statement about the benefits of ride-control cam be made. Furthermore, the evaluation and implementation of control strategies addressing road maintenance, operating speed, vehicle maintenance, and operator seat design will be required to reduce LHD operator' vibration exposure levels below values associated with elevated injury risk.

5. CONCLUSION

Driving a LHD vehicle with an empty bucket exposed LHD operators to significantly higher vibration levels than driving with a full bucket. Operators of small LHD vehicles were exposed to vibration levels above ISO 2631-1 HGCZ limits (for am 8-hour work shift). Some large LHD vehicle operators experienced vibration levels that placed them within the HGCZ while others experienced vibration levels that placed them above the HGCZ.

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