The evaluation of whole-body vibration in a South African opencast mine

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Synopsis

Vibration levels on a variety of equipment in a South African opencast mine were measured in this study. The well-established ISO 2631-1 (1997) standard methodology was used for the computation of weighted root mean square (WRMS) and vibration dose value (VDV). This method was used to evaluate the whole-body vibration (WBV) on a wide range of equipment in the opencast mine using the two main parameters, namely the daily exposure A(8) which is based on the WRMS concept and the VDV which measures shocks. The results obtained show that while the majority of the equipment rendered exposure levels that are below the exposure limit value (ELV), exposure levels on about half of the equipment do exceed the exposure action levels. The study also highlights the importance of shock in the observed responses.

Keywords

whole-body vibration, opencast mine, LHDs, excavators, other equipment.

Introduction

Heavy equipment and vehicles used in mining activities may expose operators to significant levels of shock and vibration over extended periods. These vibration exposures could be detrimental and lead to discomfort, interference with activities, and impaired health[1]. These multifaceted and varied effects on the human body are usually dealt with by considering human vibration as either a whole-body vibration (WBV) problem, which occurs when the body is supported on a surface that is vibrating, or a hand-arm vibration (HAV) problem, which occurs when the hand is in contact with a vibrating surface such as hand-held equipment[2]. This work deals with WBV.

Numerous epidemiological studies have been conducted all over the world, documenting the detrimental effects of high levels of vibration exposure on human beings. Occupational health and safety issues have been investigated in several countries including British Columbia[3], Croatia[4], Finland[5] and Spain[6] amongst others. In South Africa Van Niekerk et al.[2,7] reported on vibration levels on some typical equipment in South African mines[8].

Different international standards have been developed that regulate the way in which human vibration should be measured and reported, as well as provide indications of the health risk involved. In this regard ISO 2631 (1997)[9] is well known. More recently European Parliament legislation[10] stipulated minimum standards for the health and safety of workers exposed to WBV. Unlike Europe, South Africa does not have legislation that governs maximum acceptable vibration levels. However, it might be expected that the European Union (EU) initiative may gradually start to influence the situation in South Africa[11].

The EU legislation specifies daily vibration exposure levels (exposure action value (EAV) and exposure limit value (ELV)) in terms of weighted root mean square (WRMS) acceleration and vibration dose value (VDV) over an 8 hour period as shown in Table I. In addition, it requires employers to reduce worker vibration exposure levels wherever it is practically possible. Where an operator is likely to be exposed to vibration, an assessment of the likely daily vibration exposure is to be made. If the exposure level is above the EAV, a range of actions must be taken to reduce exposure and decrease risks. If the ELV is exceeded, immediate action must be taken to reduce vibration exposure below the ELV and procedures implemented to prevent it being exceeded again.

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The evaluation of whole-body vibration in a South African opencast mine

To assist employers in the evaluation and assessment of risks arising from WBV, the EU published a guide[12]. This guide suggests that employers should perform an assessment of the risk, including estimation of worker daily vibration exposure level, to determine whether the EAV or ELV are likely to be exceeded during normal work on vibrating equipment. It is therefore of considerable importance that a comprehensive database of WBV levels and daily exposure data be generated to encompass a wide range of equipment and operations.

This work aims to provide such a database for South African opencast mines. The study considers 34 different pieces of equipment in a very large South African mine. The equipment is roughly categorized as load haul dumpers (LHDs), excavators, and other equipment.

Methodology

Measured parameters and transducers

In accordance with ISO 2631-1 (1997)[9], acceleration levels were measured on the operator's seat of the equipment under consideration along three basicentric (i.e. fixed to surfaces that come in contact with the body) axes (seat x - longitudinal, seat y - transverse, seat z - vertical, see Figure 1) by means of a Dytran Model 5313A triaxial seat accelerometer.

The seat accelerometer was attached to the seat cushion using duct tape to prevent it from slipping away during operation (see Figure 2). The instrumentation was calibrated in the laboratory before leaving for the measurement site, and again upon return. Transducer and overall calibration details are provided in Table II. A digital camera and laptop computer were also taken to the site for photograph and transfer of data respectively.

Data acquisitioning and recording

Signals from the triaxial accelerometer were passed to a Sound Vibration Analyzer 958 (SVAN958) Human Vibration Meter (HVM), where the data was digitally recorded (see Figure 2) using a 16GB external flash disk attached to the SVAN958 to enable it to store data of long duration.

The SVAN958 HVM samples at a fixed frequency of 48 kHz. Anti-aliasing filters are embedded in the system. The HVM was used to record raw acceleration time histories as well as unweighted root mean square (RMS) values of the acceleration signals. The data was downloaded to a personal computer (PC) for post-processing and further analysis in software such as MATLAB or OCTAVE. Since the interest is here primarily in frequencies of between 0 and 100 Hz, the data were resampled to 2 kHz.

A minimum of about 10 minutes was required for both the fitting and removal of the transducers and the data acquisition system. Hence, to reduce disruption of the mining activities, fitting and removal were performed during normal work breaks. This led to overall data recording periods that were generally between 30 minutes and 1 hour per station, and which is comfortably more than the minimum measurement time of 10 minutes[13].

Data analysis

The data time histories were recorded in volts in WAV file format on the SVAN958 and subsequently downloaded to a
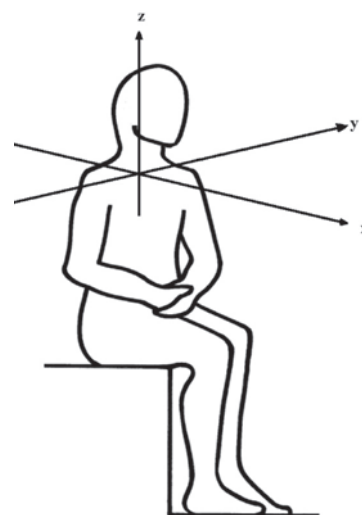

Figure 1—Basicentric axes for a seated person (adapted from ISO 2631-1[9])

Figure 2—Dytran triaxial seat accelerometer (left) and SVAN958 HVM data acquisition system (right)

Table II

Dytran triaxial seat accelerometer calibration

Axis	Calibration	
	Transducer	Overall channel
x	100.0 mV/g	138.7 m/s^2/V
y	98.9 mV/g	140.3 m/s^2/V
z	97.7 mV/g	142.0 m/s^2/V

The evaluation of whole-body vibration in a South African opencast mine

PC. Dedicated software was used to enable reading the very large WAV files. The calibration factors reported in Table II for seat x, seat y, and seat z were then applied to obtain the equivalent acceleration-time history in m/s² from the WAV format data.

The acceleration time histories recorded on the operator's seat of the target equipment were post-processed to compute the following:

➤ Frequency and measurement axis-weighted acceleration time histories, processed in accordance with the requirements of ISO 2631-1 (1997)

➤ Estimated operator daily vibration exposure, presented in 8-hour energy-equivalent continuous, frequency-WRMS acceleration A(8) and VDV forms

➤ Crest factor (CF) for each piece of target equipment

➤ Time to reach the EAV and ELV, when specified both in A(8) and VDV forms.

As a check on the integrity of the results the externally post-processed RMS and VDVs were computed and compared with the SVAN958 internally calculated values. The VDVs for an 8-hour exposure period defined in EU Directive 2002/44/EC (see Table I) were also computed. Plots of the weighted acceleration histories were also constructed from the data obtained.

The required parameters were then computed and extrapolated to cover the entire duration of exposure using dedicated software developed in the MATLAB environment. The acceleration was frequency-weighted based on ISO 2631-1 (1997), again using dedicated software. Subsequently the WRMS acceleration and VDV were computed.

Repeated exposure to vibration that exceeds the ELV based on A(8) could lead to low back pains. ISO 2631-1 (1997) recommends that if a CF higher than 9 is attained this indicates the presence of shocks and the A(8) approach is not sufficient. The VDV must then be computed. The VDV is a fourth-power value that takes into account the cumulative effect of vibration for the duration under consideration and therefore captures shocks better.

Weighted root mean square (WRMS) is the square root of the average of the squares of the weighted values. The WRMS acceleration is expressed in m/s² for translational vibration and calculated as follows:

$$a_w = \left[\frac{1}{T} \int_0^T a_w^2(t) dt \right]^{\frac{1}{2}}$$ [1]

where $a_w(t)$ is the weighted acceleration time history and T is the duration of the measurement.

The daily exposure (A(8)) is the daily exposure (8-hour energy-equivalent continuous, frequency-WRMS acceleration).

The crest factor (CF) is the ratio of the maximum weighted acceleration value to the WRMS.

Vibration dose value (VDV) is the fourth root of the integral of the fourth power of acceleration after it has been frequency weighted. The frequency-weighted acceleration is measured in m/s² and the time over which the VDV is measured is in seconds, yielding VDVs in m/s^1.75. The VDV is computed as follows:

$$VDV = \left[\int_0^T \left[a_w(t) \right]^4 dt \right]^{\frac{1}{4}}$$ [2]

where $a_w(t)$ is the weighted instantaneous acceleration magnitude and T is the duration of the measurement. The fourth power in the expression for VDV emphasizes the presence of shocks in the data.

Results

Summary of equipment WBV levels based on ISO 2631-1 (1997) using WRMS parameter

The recorded data consisted of WBV levels measured with respect to time along the three basicentric axes (x, y, and z) on the operator's seat. This data was weighted as shown in Figures 3 and 4 for a Hitachi Excavator Zaxis 670 LCR. The highest vibration magnitude computed from the weighted acceleration history of the excavator was obtained as 0.41 m/s² and in the z-direction, which is below the EAV. From Figure 3 one can observe the presence of shocks. The CF would therefore need to be computed, and if higher than 9 then the VDV would have to be computed for evaluation of risk to health. The Hitachi Excavator Zaxis 670 LCR has CF higher than 9 in all three directions (x-, y-, and z-axes) as shown in Table IV. This indicates the presence of shocks in
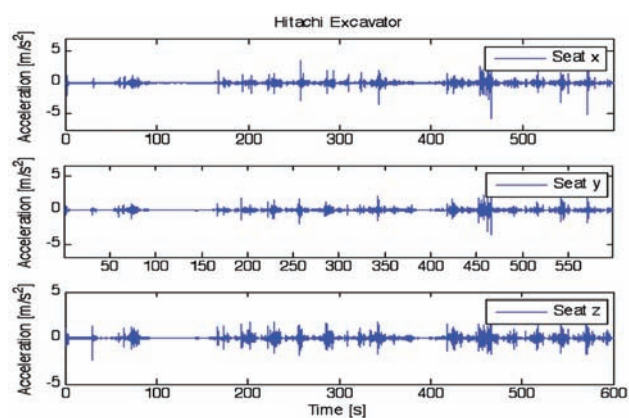
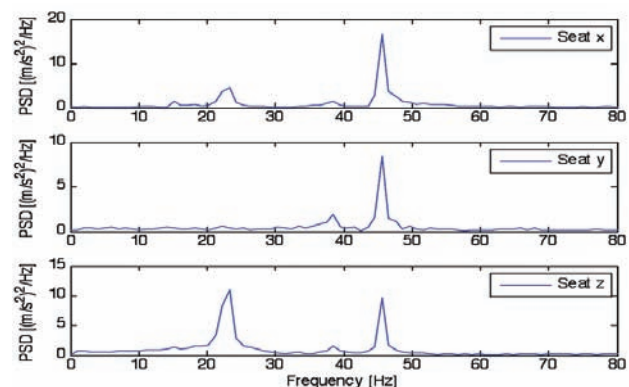Figure 3—Weighted acceleration spectrum for Hitachi Excavator Zaxis 670 LCR

Figure 4—PSD for Hitachi Excavator Zaxis 670 LCR

The evaluation of whole-body vibration in a South African opencast mine

the data collected for the equipment. The equipment excavates top soil or coal and loads into LHDs operating over a rough surface. This leads to the multiple recurring high-magnitude transient shocks as shown in Figure 3.

In Figure 4 the peaks are at 22 and 45 Hz indicate the dominant frequencies. From the literature the frequency range of 4–20 Hz is known to be the most uncomfortable for humans[1]. Hence, in this particular case the peak response frequencies are close to the range of maximum sensitivity, which indicates that small changes in the configuration could easily lead to significantly increased exposure. The WRMS,

CF, and time to EAV (A(8)) and ELV (A(8)) were calculated and tabulated separately for each equipment combination identified, and the results shown in Tables III, IV, and V.

Summary of equipment WBV levels based on ISO 2631-1 (1997) using VDV parameter

A summary overview is shown in Tables VI, VII and VIII for VDV analyses for LHDs, excavators, and other equipment respectively.

Table III

LHDs: RMS, CF, and A(8) acceleration summary of WBV seat data

Equipment	WRMS acceleration (m/s²) a_w				Crest factor (CF)			Time to EAV (h) (A(8))	Time to ELV (h) (A(8))
	x	y	z	Main	x	y	z		
Volvo A35 LHD	0.61	0.49	0.54	x	6.30	11.14	11.52	5.00	16.00
Mercedes Actros V8 LHD	0.44	0.55	0.65	z	8.18	8.64	8.19	5.00	16.00
Caterpillar 785B	0.50	0.54	0.70	z	11.08	9.59	9.15	4.00	14.00
Tata Novus Truck 3434	0.33	0.43	0.59	z	13.21	12.40	11.41	5.00	16.00
Bell rear dumper B25D	0.41	0.43	0.38	y	11.10	9.48	11.40	12.00	>24.00
Bell rear dumper B40D	0.47	0.81	0.41	y	12.86	6.42	7.72	2.00	6.00
Bell rear dumper B50D	0.32	0.44	0.35	y	7.53	9.32	10.44	12.00	>24.00
Iveco truck/trailer (double)	0.54	0.53	0.60	z	14.88	10.88	8.64	5.00	16.00
MAN TGA 33.400 trailer	0.28	0.43	0.35	z	15.32	12.19	36.90	12.00	>24.00
Dragline	0.10	0.18	0.12	y	7.80	9.38	5.95	>24.00	>24.00

Table IV

Excavators: RMS, CF, and A(8) acceleration summary of WBV seat data

Equipment	WRMS acceleration (m/s²) a_w				Crest factor (CF)			Time to EAV (h) (A(8))	Time to ELV (h) (A(8))
	x	y	z	Main	x	y	z		
Hitachi excavator Xavis 670 LCR	0.36	0.34	0.41	z	54.28	55.22	54.78	12.00	>24.00
Volvo excavator EC700Blc	0.39	0.36	0.34	x	36.46	34.20	43.50	12.00	>24.00
CAT excavator 320D	0.35	0.21	0.24	x	12.28	14.22	10.38	12.00	>24.00
Hitachi excavator Xavis 370 LCR	0.36	0.29	0.37	z	19.83	15.08	14.37	12.00	>24.00
Hitachi excavatorXavis 500 LCR	0.33	0.38	0.39	z	27.53	19.14	13.85	12.00	>24.00
Komatsu excavator PC1250SP	0.45	0.47	0.51	z	19.36	15.84	12.53	8.00	24.00
Hitachi excavator Xavis 670 LCR	0.21	0.18	0.21	z	15.78	16.71	10.29	>24.00	>24.00

Table V

Other equipment: RMS, CF, and A(8) acceleration summary of WBV seat data

Equipment	WRMS acceleration (m/s²) a_w				Crest factor (CF)			Time to EAV (h) (A(8))	Time to ELV (h) (A(8))
	x	y	z	Main	x	y	z		
CAT FEL 992G	0.19	0.29	0.21	y	15.42	11.79	8.15	20.00	>24.00
Kawasaki Safika FEL 852 IV	0.38	0.36	0.48	z	12.29	13.81	9.86	8.00	24.00
Kawasaki FEL	0.34	0.33	0.42	z	16.03	13.05	18.28	12.00	>24.00
CAT track dozer D9T	0.63	0.98	0.50	y	9.33	9.27	6.69	2.00	6.00
CAT caterpillar D10R	0.76	0.77	0.76	y	17.40	11.81	8.39	4.50	15.00
Bell TLB 315SG	0.35	0.42	0.52	z	7.89	6.62	7.91	8.00	24.00
Shantui	0.73	1.07	0.49	y	8.06	7.72	10.66	2.00	6.00
Pit Viper	0.38	0.36	0.21	x	8.33	23.28	19.79	12.00	>24.00
DMM2 drilling machine	0.23	0.23	0.28	z	18.45	20.48	17.75	20.00	>24.00
CAT grader 16G	0.42	0.53	0.68	z	7.13	5.87	9.84	5.00	16.00
Sany grader	0.19	0.26	0.26	z	8.36	6.00	6.13	24.00	>24.00
Komatsu grader 9D825A	0.33	0.39	0.33	y	12.51	23.78	15.09	12.00	>24.00
Bell water bowser B20C	0.54	0.85	0.55	y	9.66	15.57	9.83	2.50	8.00
Powerstar 2628 refueller	0.78	0.68	0.89	z	17.68	17.69	17.42	2.50	8.00
CAT 740 diesel bowser	0.61	1.12	0.65	y	8.87	8.52	17.50	2.00	5.00
Toyota Fortuner	0.56	0.73	0.55	y	8.04	10.47	10.18	3.00	7.00
Landpac compactor	0.87	0.82	0.91	z	7.41	6.79	5.32	2.00	6.00

The evaluation of whole-body vibration in a South African opencast mine

Table VI

LHDs: VDV summary of WBV seat data

Equipment	Estimated 8-hour VDV (m/s^1.75)				Time to EAV (h) (VDV)	Time to ELV (h) (VDV)
	x	y	z	Major axis		
Volvo A35 LHD	11.21	9.02	9.84	x	3.5	>24.00
Mercedes Actros V8 LHD	8.05	9.97	11.80	z	2.83	>24.00
Caterpillar 785B	9.20	9.77	12.77	z	2.06	>24.00
Tata Novus Truck 3434	6.09	7.78	10.81	z	4.02	>24.00
Bell rear dumper B25D	7.43	7.78	6.87	y	14.98	>24.00
Bell rear dumper B40D	8.61	14.80	7.46	y	1.14	>24.00
Bell rear dumper B50D	5.76	8.05	6.36	y	13.04	>24.00
Iveco truck/trailer(double)	9.92	9.74	10.91	z	3.87	>24.00
MAN TGA 33.400 trailer	5.06	7.87	6.39	y	14.30	>24.00
Dragline	1.88	3.35	2.23	y	>24.00	>24.00

Table VII

Excavators: VDV summary of WBV seat data

Equipment	Estimated 8-hour VDV (m/s^1.75)				Time to EAV (h) (VDV)	Time to ELV (h) (VDV)
	x	y	z	Major axis		
Hitachi excavator Xavis 670 LCR	6.59	6.18	7.52	z	17.19	>24.00
Volvo excavator EC700Blc	7.13	6.57	6.26	x	21.19	>24.00
CAT excavator 320D	6.36	3.85	4.39	x	>24.00	>24.00
Hitachi excavator Xavis 370 LCR	6.65	5.25	6.81	z	>24.00	>24.00
Hitachi excavator Xavis 500 LCR	6.07	6.92	7.15	z	21.02	>24.00
Komatsu excavator PC1250SP	8.14	8.55	9.25	z	7.49	>24.00
Hitachi excavator Xavis 670 LCR	3.88	3.24	3.84	x	>24.00	>24.00

Table VIII

Other equipment: VDV summary of WBV seat data

Equipment	Estimated 8-hour VDV (m/s^1.75)				Time to EAV (h) (VDV)	Time to ELV (h) (VDV)
	x	y	z	Major axis		
CAT FEL 992G	3.42	5.25	3.89	y	>24.00	>24.00
KawasakiSafika FEL 852 IV	7.00	6.63	8.82	z	9.05	>24.00
Kawasaki FEL	6.15	6.04	7.65	z	16.01	>24.00
CAT track dozer D9T	11.41	17.83	9.11	y	0.54	>24.00
CAT caterpillar D10R	13.86	14.07	13.94	y	1.40	>24.00
Bell TLB 315SG	6.33	7.73	9.55	z	6.60	>24.00
Shantui	13.36	19.46	8.89	y	0.38	>24.00
Pit Viper	6.94	6.57	3.85	x	>24.00	>24.00
DMM2 drilling machine	4.14	4.11	5.18	z	>24.00	>24.00
CAT grader 16G	7.70	9.60	12.45	z	2.28	>24.00
Sany grader	3.47	4.68	4.72	z	>24.00	>24.00
Komatsu grader 9D825A	6.06	7.16	6.10	y	20.90	>24.00
Bell water bowser B20C	9.81	15.57	10.05	y	0.93	>24.00
Powerstar 2628 refueler	22.24	21.04	25.68	z	0.22	7.93
CAT 740 diesel bowser	11.06	20.43	11.91	y	0.31	>24.00
Toyota Fortuner	10.28	13.27	10.08	y	1.77	>24.00
Landpac compactor	15.95	14.98	16.62	z	0.72	>24.00

Discussion of results

WBV results based on ISO 2631-1 (1997) using WRMS approach

Figures 5, 6, and 7 schematically summarize the WRMS acceleration levels that were observed. Two groups can be identified, namely those where the vibration levels are less than the EAV of 0.5m/s^2 and which constitute about half of the equipment considered, and the other half where the vibration levels exceed the EAV of 0.5 m/s^2 but are still less than the ELV of 1.15 m/s^2. In some equipment the highest value is in the z-direction whereas in others it is along either the y- or z- axis. None of the equipment displayed WRMS values exceeding the limit value of 1.15 m/s^2, as shown in Tables III, IV, and V.
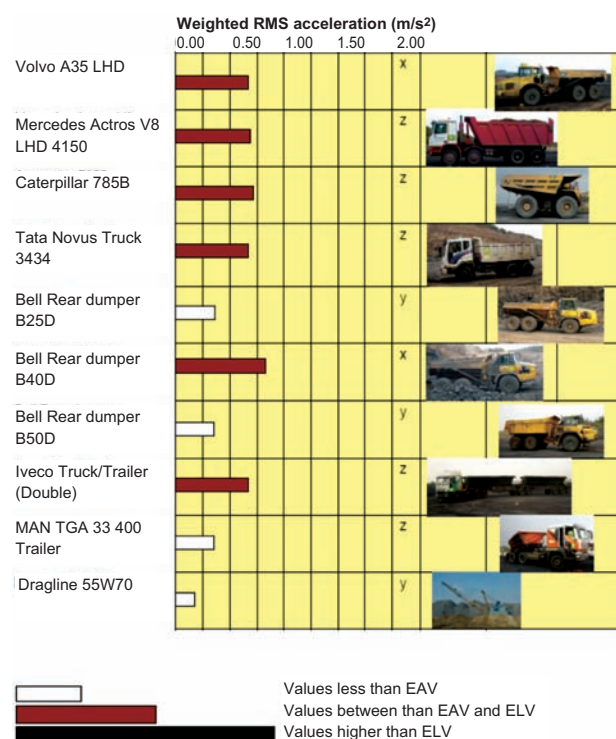

Values less than EAV
Values between than EAV and ELV
Values higher than ELV

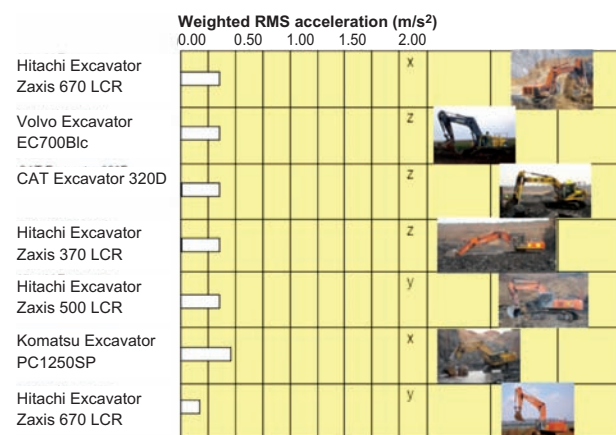**Figure 5—WRMS acceleration magnitudes for LHDs**

Figure 6—WRMS acceleration magnitudes for excavators

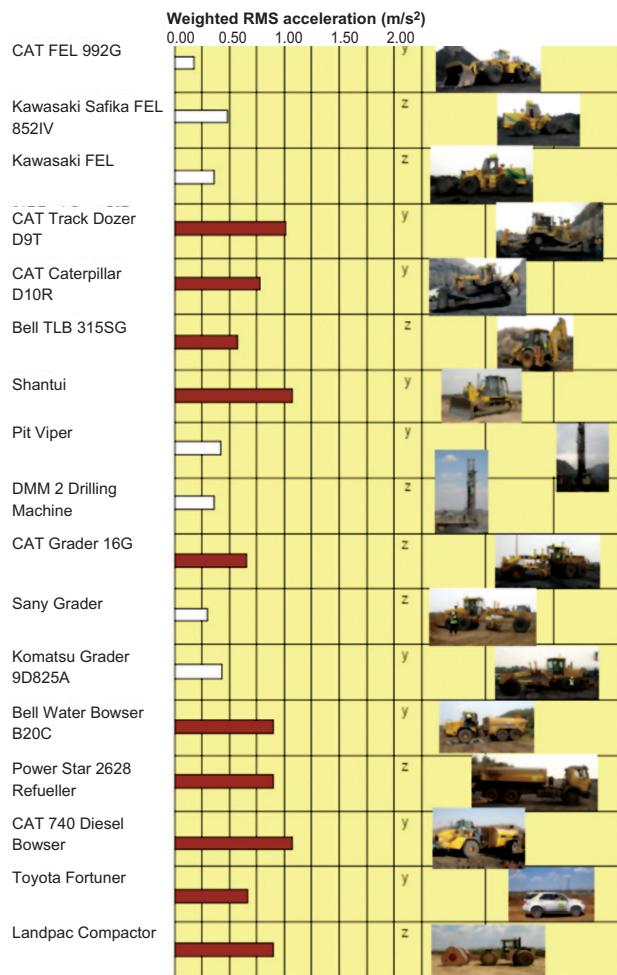# The evaluation of whole-body vibration in a South African opencast mine

Figure 7—WRMS acceleration magnitudes for other equipment

For each piece of equipment shown in Tables III, IV and V, the decision on the presence of shocks is taken based on the direction with the highest CF. 12% of the equipment have CF less than 9 in all three directions. The remaining 88% have CF above 9 in at least one direction. Of the four pieces of equipment with CF less than 9, the Landpac compactor in Table V has the lowest CF of 7.41 in the x-axis (worst direction). This is quite close to CF of 9 as any slight increase in vibration could result to CF above 9. This therefore again confirms the presence of shocks in the data collected. The equipment in Tables III, load, haul and dump top soil or coal operating over rough road resulting to transient shocks. Similarly, the equipment in Table IV and V operate over similar conditions leading to multiple recurring transient shocks.

As was observed before, the maximum accelerations can either be in the x-, y- or z-directions. This implies that one cannot assume that vertical acceleration will always be worst.

WBV results based on ISO 2631-1 (1997) using VDV approach

Figures 8, 9 and 10 give a summary of the equipment where the WBV levels are either below the VDV action value of 9.1 m/s1.75 or between the VDV action and limit values of

9.1 $m/s_{1.75}$ and 21 $m/s_{1.75}$ respectively, or above the VDV limit values of 21 $m/s_{1.75}$ as shown in Tables VI, VII, and VIII. Half of the equipment had VDVs below the VDV action value. Forty seven per cent of the equipment had VDVs between the VDV action and limit value. The remaining three per cent of the equipment had VDVs above the VDV limit values. A significant proportion of the equipment has exposure values above the action value and as such action needs to be taken to reduce these exposures.

The number of equipment items with vibration values below the EAV and between the EAV and ELV is almost the same for both the A(8) and VDV, as shown in Figures 5 to 10. In Figure 10 the black bar indicates a case where the ELV has been exceeded and action should be taken to reduce the vibration level or reduce the operator exposure to the equipment. This again emphasizes the importance of shock in
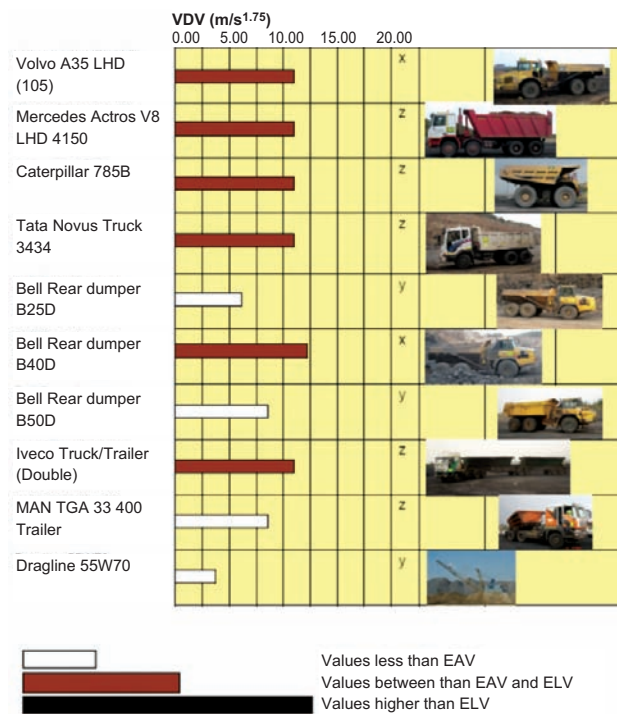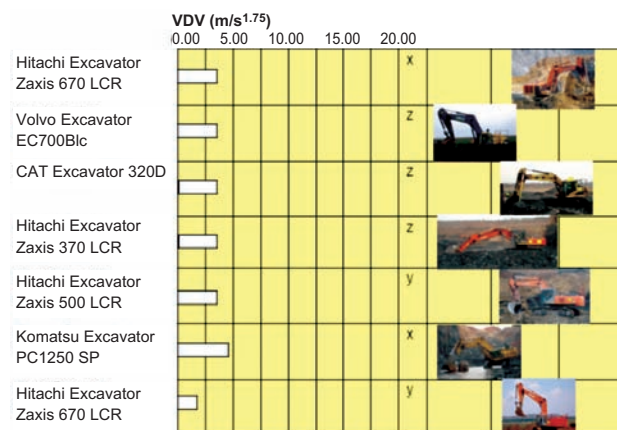

Figure 8—VDV magnitudes for LHDs

Figure 9—VDV magnitudes for excavators

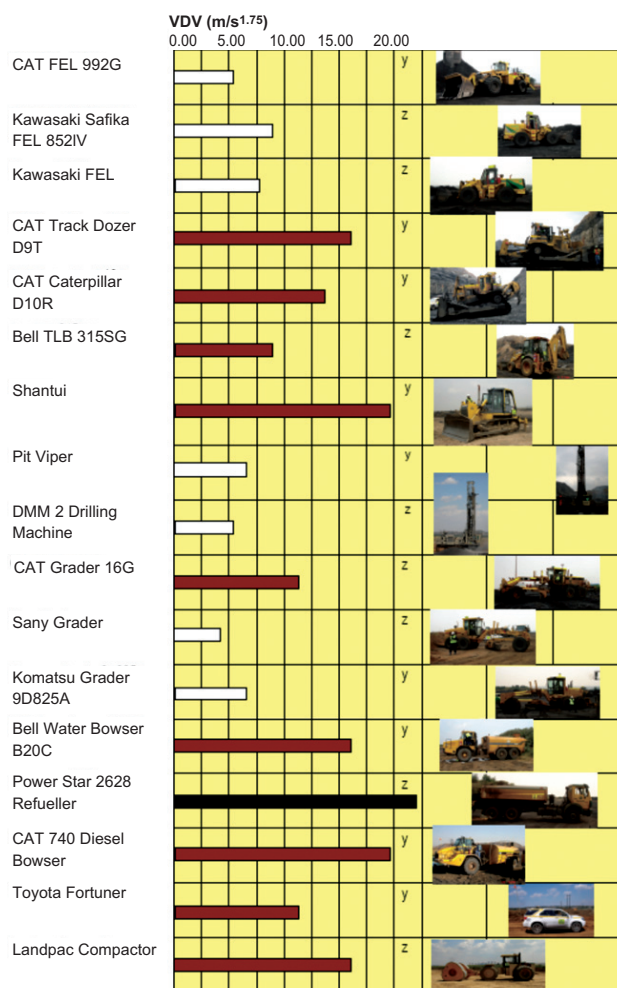# The evaluation of whole-body vibration in a South African opencast mine

Figure 10—VDV magnitudes for other equipment

vibration exposures that exceed exposure action values. This is very significant and suggests the necessity for proper vibrational risk assessment and management in mining applications. Shocks can be important, as can be seen when using the VDV parameter; one of the pieces of equipment exceeds the ELV. Actions to reduce vibration levels are recommended. These include regular grading of roads and training of operators on how to use the equipment.

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the evaluation of vibration exposure for some mining equipment. Even though the exposure limit value has not been exceeded for most of the equipment, it can be seen that the exposure values lie between the EAV and ELV. Hence, action has to be taken to mitigate the exposure to vibration. Berezan *et al.*[14] found that aggressive driving patterns, rough and poorly maintained roads and pit floors, along with the occasional bump and poorly placed load from a shovel, can create intense and sometimes serious vibration levels on a heavy hauler. Ameliorative action for the mitigation of vibration levels includes the regular grading of roads to ensure they are level and training of operators on how to use the equipment effectively.

Conclusions

This study provides a WBV database for a large range of equipment typically found on South African opencast mines. The ISO 2631-1 (1997) standard methodology was used to evaluate typical WBV levels on these equipment, using the A(8) and VDV parameters. The results obtained from this standard indicate that some 95% of the equipment is associated with vibration levels below the exposure limit values. Typically some 50% of the equipment causes