



Assessment of whole-body vibration exposure of mining truck drivers

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Synopsis

Whole-body vibration (WBV) exposure measurements taken from 105 truck drivers employed in 19 mines and other workplaces were evaluated with the criteria prescribed in EU 2002/44/EC directive, BS 6841 (1987), ISO 2631-1 (1997), and ISO 2631-5 (2004) standards. The highest vibration acceleration was measured on the vertical Z-axis. The highest WBV exposure occurred in the RETURN, HAUL, and SPOT phases while the lowest exposure took place in the LOAD and WAIT phases. Crest factors on all axes were generally greater than nine, yet strong correlation coefficients were achieved in VDV-eVDV analyses. Driver seats generally dampened the vibration along the Z-axis but exacerbated it along X and Y axes. The dominant frequency for the X and Y-axes rose up to 40 Hz while it ranged between 1 Hz and 2.5 Hz along the Z-axis. While the probability of an adverse health effect was higher with BS 6841 (1987) and ISO 2631-1 (1997) standards, it was low according to EU 2002/44/EC and ISO 2631-5 (2004). The 91 t, 100 t, and 170 t capacity trucks produced lower vibration magnitudes. Drivers were exposed to approximately equivalent levels of WBV acceleration and dose in contractor-type trucks and mining trucks. Rear-dump trucks exposed their drivers to a slightly higher level of vibration than bottom-dump trucks. Underground trucks exposed their drivers to a significantly higher level of vibration than mining trucks. Both driver age and driver experience were inversely proportional to vibration acceleration and dose. Conversely, there was a positive relationship between the truck service years and the WBV acceleration and dose to which drivers were exposed to. Loads of blocky material exposed drivers to higher vibration acceleration and dose levels than non-blocky material.

Keywords

whole-body vibration, mining truck, A(8), BS 6841, EU 2002/EC/44, ISO 2631-1, ISO 2631-5, VDV(8).

Introduction

Operators of trucks, buses, locomotives, helicopters, heavy machinery, and farm equipment as well as workers using vibrating machines are exposed to occupational whole-body vibration (WBV). Continuous exposure to mechanical vibration can cause irreversible physical damage, depending on the intensity and frequency of the vibration. The International Labour Organization (ILO, 1977) described vibration as a professional hazard, emphasising that ‘measures should be taken to protect workers from vibration’ and that the responsible authorities should establish criteria to determine the hazard.

There is consensus among researchers about the vibration exposure of machinery operators and the long-term adverse health effects of WBV (Miyashita *et al.*, 1992; Mandal and Srivastava, 2010; Aye and Heyns, 2011). Risk factors include muscle fatigue, decreased stability, vestibular dysfunction, and impairment to the female reproductive system (Seidel and Heide, 1986; Bongers *et al.*, 1988; Griffin, 1998). Frequencies between 1 Hz and 20 Hz can cause damage to the body in the form of back pain, spinal degeneration, stomach problems, headache, and sleep problems (Thalheimer, 1996; Okunribido, Magnusson, and Pope, 2006; Eger *et al.* 2008).

Factors affecting WBV exposure such as operating conditions, tonnages, service lives of machinery, and properties of the material handled were evaluated individually or collectively. Mandal *et al.* (2006) stated that 18% of the workers in the Indian mining industry were subjected to occupational vibration. Noorloos *et al.* (2008) reported that the vibration magnitude caused by a vehicle depends on many factors such as conditions of the site, maintenance status, operator’s driving style and speed, type of propelling mechanism, type of seat, characteristics of material handled, and operator experience. In

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contrast, Darby, Heaton, and Mole (2010) stated that the exact cause of back pain is unclear, but back pain is more common in those working over long distances or on bad ground conditions. They also commented that shocks and sudden jolts during driving would increase pain. Working for prolonged durations in an incorrectly adjusted seat position, sitting for a long time without changing the posture, and exposure to shocks and sudden jolts during operation are among the causes of back pain, the most reported effect of WBV exposure. Waters *et al.* (2008) emphasized the possibility of a causal relationship between working as a heavy equipment operator and lower back pain. However, according to Burgess-Limerick (2012) it is difficult to clearly demonstrate the link between WBV and back pain, as there are many possible causes of back pain.

In a survey conducted by Palmer *et al.* (2000) it was found that the BS 6841 (1987) limit of $15 \text{ m}\cdot\text{s}^{-1.75}$ for the vibration dose value (VDV) during daily operations was exceeded for truck drivers, farmers, agricultural workers, and forklift drivers in Great Britain. Cann, Salmoni, and Eger (2004) studied the effects of driver experience, truck service years, road conditions, truck type, truck mileage, and seat type on WBV exposure. They concluded that the drivers were not subjected to negative health effects caused by daily exposure in accordance with the ISO 2631-1 (1997) standard. In an evaluation of dumper operators' WBV exposure in India, Mandal and Srivastava (2010) found that the RMS acceleration values along the dominant Z-axis ranged from 0.644 m/s^2 to 1.820 m/s^2 . When evaluated together with an average daily exposure of 5 hours, it was found out that all dumpers caused high health risks according to the ISO 2631-1 (1997) standard.

Previous studies indicate that vehicles of different models affect WBV exposure. Village, Morrison, and Leong (1989) studied mining trucks and reported that vehicle size plays an important role in WBV exposure. Maeda and Morioka (1998) found that heavy road conditions caused an increase in WBV exposure of garbage truck drivers. In contrast, Noorloos *et al.* (2008) conducted surveys of 467 participants using various types of vehicles, including automobiles, minibuses, trucks, wheel loaders, dumpers, excavators, bulldozers, steamrollers, mobile cranes, and asphalt machines. There was no significant relationship between WBV exposure and low back pain, which was attributed to the small number of samples. Lundström and Holmlund (1998) reported that the WBV acceleration recorded in the Z direction was much more detrimental than vibration in the X and Y directions, supporting other studies and the ISO 2631-1 (1997) standard.

Nishiyama, Taoda, and Kitahara (1998) conducted a study on a small number of samples in order to evaluate drivers' back pain and determined that old model trucks caused higher WBV exposure. Kumar (2001) recorded the vibration measurements to which dumper operators in open-pit mines were subjected along three orthogonal axes. Vibration-induced effects were detected in operators' third lumbar and seventh neck vertebrae. The data obtained from new and old trucks of different makes and carrying capacities revealed that the exposure threshold of ISO 2631-1 (1997) has been exceeded. In another study, Kumar (2004) commented that the driver's gender and truck capacity have no significant impact on vibration; however, the body mass of the driver, the vehicle segment, and the measurement region showed significant differences in vibration. He concluded that heavy mining trucks pose a significant health hazard to

operators in extreme mining conditions and generate WBV accelerations that often exceed ISO standards. Smets, Eger, and Grenier (2010) evaluated the vibration exposure of heavy truck drivers against the ISO 2631-1 (1997) and ISO 2631-5 (2004) standards. According to the ISO 2631-1 (1997) criteria, drivers were exposed to vibration levels above the daily exposure limit, but there was a low probability of adverse health effects in accordance with ISO 2631-5 (2004). The authors emphasized the discrepancy between the two standards.

Mayton, Jobs, and Miller (2008) and Mayton *et al.* (2018) found that old trucks gave higher vibration values, with the vibration acceleration in the Z-axis being dominant. An evaluation of the WBV and GPS position data revealed that most of the shocks occurred during loading and unloading, and from the potholes in the road. In another study by Mayton, Jobs, and Gallagher (2014) it was found that roughly half of the dominant vibration was either in the Z-axis or Y-axis. Frimpong, Galecki, and Chang (2011) stated that significant improvements in production and economy have been achieved with the use of trucks of larger than 360 t capacity and electric excavators of >90 t per cycle. However, in terms of operator health, significant negative side effects of continuous work and long working hours were also revealed.

In this study, WBV exposure measurements taken from the driver's seat in 105 trucks of different types, brands, and models, which were deployed in several open pits and one underground mining operation in Turkey, were analysed. The assessment of truck drivers' WBV exposure was based on four criteria; BS 6841 (1987), ISO 2631-1 (1997), European Directive 2002/44/EC (2002), and ISO 2631-5 (2004). The potential health risk categories described in each criterion are given in Table 1.

Materials and method

Data acquisition

The seat accelerometer, which was mounted in a polyurethane housing, was placed and secured on the seat pan to accommodate the driver's ischial tuberosities. A floor-type accelerometer was used to determine the seat effective amplitude transmissibility (SEAT) factor. It was placed on the floor in an appropriate position, very close to where the seat foot joins the floor. In order to prevent any shock-induced damage caused by the operator to the highly sensitive accelerometer, a steel container was built and attached to the floor with strong magnets.

A SV106 model six-channel vibration analyser (serial no. 34613) manufactured by Svantek Ltd (2013) was used to record and process data from the accelerometer's $1/3$ -octave (with the centre frequencies from 2.50 kHz down to 0.40 Hz) digital passband filters in real time. The sampling rate was 6000 Hz with 16-bit resolution. Measurement results were stored on a micro-SD flash card and downloaded to a PC using a USB interface, and processed on the environmental monitoring module of the SvanPC++ software (Svantek, 2015).

A SV38V triaxial seat-type disk accelerometer (serial no. 32980) was used to determine drivers' WBV exposure at the seat pan. This required a supply voltage of 5.2 V DC and had a sensitivity of $50 \text{ mV}/(\text{m/s}^2)$ at 15.915 Hz. Another SV151 triaxial accelerometer (serial no 31359) was used to determine the vibration level on the cabin floor. It required a supply voltage of 3.3 V DC and had a sensitivity of $5.81 \text{ mV}/(\text{m/s}^2)$ at 15.915 Hz. The instrumentation set-up is shown in Figure 1.

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Figure 1 – The WBV exposure recording instrumentation set-up

Vibration measurement

A haul truck cycle is composed of five consecutive phases: approaching the loader or dumping point at reduced speed (SPOT), being loaded when it is immobile (LOAD), travelling with a full load (HAUL), offloading when it is immobile (DUMP), and travelling with no load (RETURN). Apart from the DUMP and SPOT phases, the truck may come to a complete halt with the engine idling in a specific phase. In this situation, that part in the acceleration-time log is regarded as a separate phase (WAIT). Lastly, the overall WBV exposure of the driver in a typical truck cycle was recorded in (RECORD). It should be noted that although effort was made to monitor at least a complete truck cycle, a few records did not include all phases. For example, a driver moved to park the truck instead of travelling to the loading point after dumping, as he thought the shift had finished.

The WBV exposure was recorded from six channels, three of which were from the seat ($Seat_x$, $Seat_y$, $Seat_z$) and three from the cabin floor ($Floor_x$, $Floor_y$, $Floor_z$) in accordance with TS EN 1032+A1 (TSE, 2011), which refers to ISO 2631-1 (1997). The frequency-weighted acceleration (a_w), vibration dose (VDV), maximum transient vibration value (MTVV), peak vibration acceleration (PEAK), and peak-to-peak vibration acceleration (P-P) were recorded on both the seat pan and the cabin floor. The recording times varied from 00:04:46 hours to 00:52:37 hours.

A researcher travelled with the driver to observe the hauling operation during the recording process. A precision stopwatch was started simultaneously with the vibration analyser, to mark the start and finish times of the phases of a cycle. For all cases, the first 10 seconds were removed from the RECORD as it was observed that the driver's involuntary movements while he was trying to sit down on or get up from the seat could result in very high vibration accelerations.

Parameters related to WBV in all phases were calculated in accordance with the ISO 2631-1 (1997) and ISO 2631-5 (2004) standards.

BS 6841 (1987) uses the w_b frequency weighting filter for the vertical accelerations on the seat cushion, while ISO 2631-1 (1997) utilizes the w_k frequency weighting filter. As there are minor differences between the two frequency weighting filters, in this study, data recorded with the w_k filter was used while assessing the probability of adverse health risk in accordance with both standards.

Contrary to ISO 2631-1 (1997), the vibration dose for the seated person is calculated using different multiplying factors (unity for all axes) according to the BS 6841 (1987) standard. For this reason, the daily vibration dose values were calculated according to both standards and the driver exposures were evaluated by considering the health risk criteria of the relevant standards given in Table I.

Study domain

Out of 105 trucks 33 were of 30 t nominal load capacity, 48 of 77 t, two of 91 t, three of 100 t, and 19 of 170 t. The 30 t units were typical contractor trucks while the remaining 72 were mining trucks. All contractor trucks and 69 out of the 72 mining trucks were dumpers, while the three trucks of 100 t capacity were bottom-dump machines.

All mines, trucks, and drivers were coded. The test sites included coal, gold, and iron mines; aggregate, marble, gypsum, clay, and limestone quarries, road construction sites, and ore preparation and scrap iron plants. The types of trucks and operations from which WBV exposure measurements were taken are illustrated in Figure 2. Distribution of trucks among workplaces is given in Table II.

Results and discussion

RECORD phase

Evaluation by vibration acceleration

The equivalent vibration acceleration normalized to an 8-hour shift, $A(8)$ on the driver's seat of the trucks for the worst-case axis (WCA) ranged from 0.319 m/s^2 to 1.172 m/s^2 , with mean and standard deviation of $0.707 \pm 0.174 m/s^2$. On the other hand, $A(8)_{xyz}$ for the vector sum (VS), as recommended in BS 6841 (1987), ranged from 0.427 m/s^2 to 1.444 m/s^2 with mean and standard deviation $0.949 \pm 0.198 m/s^2$.

The WCA with the highest vibration was the Y-axis in 9 trucks, and the Z-axis in 96 trucks. This result is corroborated by previous studies (Özkaya, Goldsheyder, and Willems, 1997; Newell, Mansfield, and Notini, 2006). The vibration acceleration measured by Cann *et al.* (2005) was 0.79–0.83 m/s^2 on the X-axis, 0.81–0.97 m/s^2 on the Y-axis, and 1.08–1.36 m/s^2 on the Z-axis. In a study on 18 trucks, Mandal and Srivastava

Table I

Potential health risk zones for WBV (Eger and Godwin, 2014)

Health risk	ISO 2631-1(1997)		EU 2002/44/EC (2002)		BS 6841 (1987)	ISO 2631-5 (2004)	
	$A(8)_v$ (m/s^2)	VDV_c ($m/s^{-1.75}$)	$A(8)$ (m/s^2)	VDV ($m/s^{-1.75}$)	VDV ($m/s^{-1.75}$)	Sed (MPa)	R
Low	<0.45	<8.5	<0.5	<9.1	<0.50	<0.80	
Moderate	0.45–0.90	8.5–17.0	0.5–1.15	9.1–21.0	–	0.5–0.80	0.80–w1.20
High	>0.90	>17.0	>1.15	>21.0	>15.0	>0.80	>1.20

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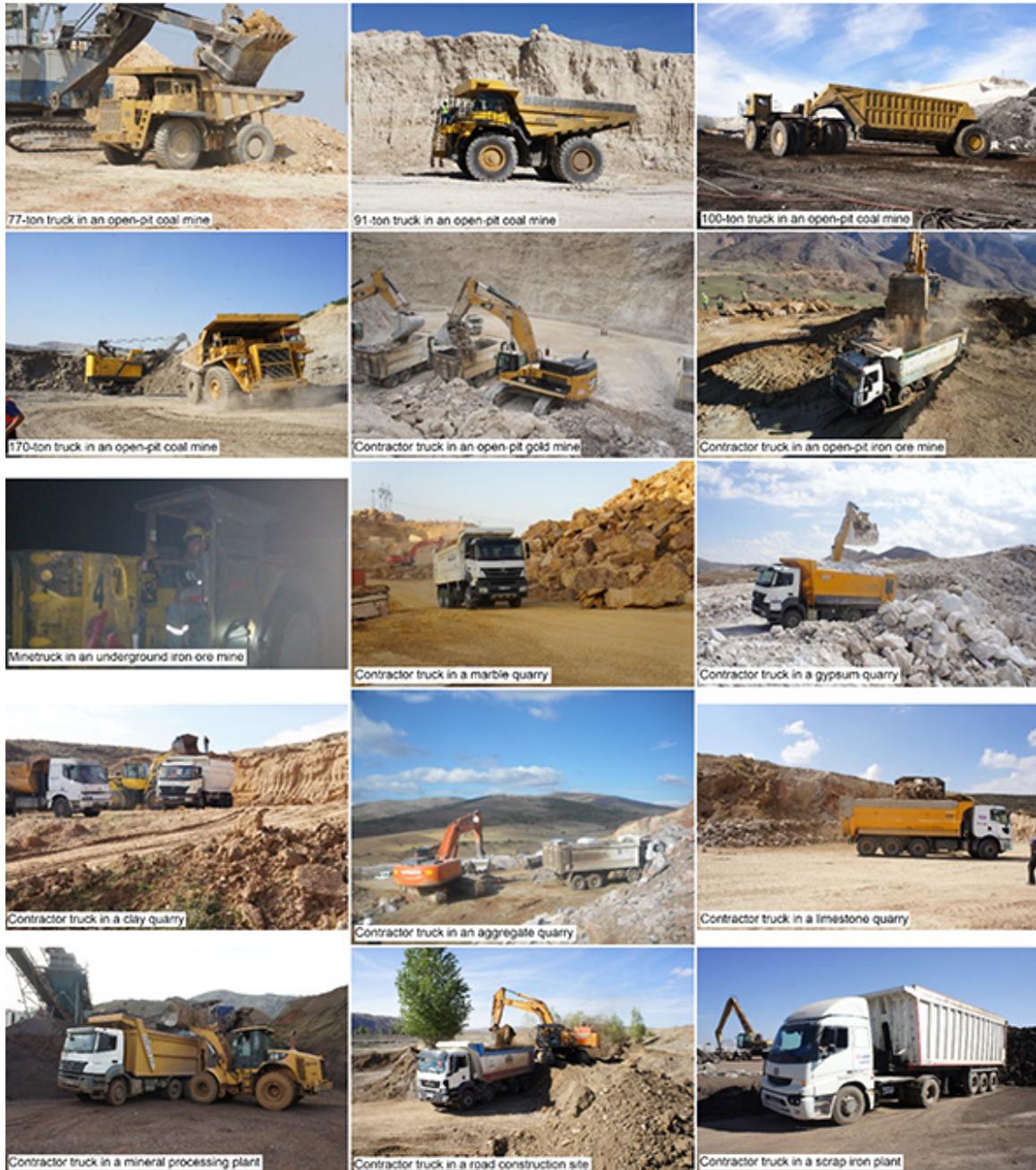


Figure 2—Types of truck and operation

(2010) recorded the highest vibration on the Z-axis. Measured values ranged from 0.64 m/s^2 to 1.82 m/s^2 and the average was 1.10 m/s^2 . Eger *et al.* (2011) recorded vibration values in the dominant Z-axis between 0.89 m/s^2 and 1.18 m/s^2 . Chaudhary, Bhattacharjee, and Patra (2015) measured the highest vibration value in the Z-axis as 1.61 m/s^2 . In the study by Burström *et al.* (2016), which included 95 machines of different models and capacities, the daily average vibration exposure was between 1.9 and 6.7 hours, and the average $A(8)$ value ranged from 0.2 m/s^2 to 1.0 m/s^2 .

Table III shows that according to the EU 2002/44/EC (2002) directive, the vast majority of the trucks are within the health guidance caution zone (HGCZ) when the WCA and VS criteria are taken into consideration. Considering the WCA criterion according to ISO 2631-1 (1997), which is more conservative, the

majority of the trucks again remain within the HGCZ, while the greater part of the trucks are above the daily ELV limit as per the VS criterion as the averaged $A(8)$ and $A(8)_{xyz}$ are just below and above the $0.90 \text{ m}\cdot\text{s}^{-2}$ limit respectively.

Considering the WCA criterion, the time required to reach the daily exposure action value ($EAV_{TT(RMS)}$) of truck drivers ranged from 01:27:22 hours to 19:37:45 hours with mean and standard deviation of $04:53:00 \pm 2:50:52$ hours. The time required to reach the daily exposure limit value ($ELV_{TT(RMS)}$), however, ranged between 07:42:09 and 103:50:20 hours with mean and standard deviation $25:50:00 \pm 15:03:52$ hours. In this case, 95 out of 105 trucks exposed their drivers to enough vibration to reach the daily exposure action value (EAV) before the end of the 8-hour shift, while only one truck reached the daily exposure limit (EL) before the end of the shift.

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The crest factor shows the sudden load and shocks to which the drivers are exposed. In cases where this is greater than nine, exposure assessment should be done by considering the vibration acceleration and vibration dose values together in accordance with ISO 2631-1 (1997). In the RECORD phase, the crest factor was greater than nine for 51 trucks in the X-axis, 36 trucks in

Table II

The number of trucks in the workplaces

Capacity class								
Mine type ^a	Workplace	30 t	77 t	91 t	100 t	170 t	Σ	Σ Σ
①	Mine 1		2	2	3	4	11	72
	Mine 3		15			6	21	
	Mine 4		22			9	31	
	Mine 5		9				9	
②	Mine 1	7					7	7
③	Mine 1	2					2	2
④	Mine 1	2					2	2
⑤	Mine 2	1					1	2
	Mine 3	1					1	
⑥	Mine 1	3					3	4
	Mine 2	1					1	
⑦	Mine 1	3					3	3
	Mine 1	3					3	
⑧	Mine 1	2					2	3
	Mine 2	1					1	
⑨	Mine 1	3					3	3
⑩	Plant 1	1					1	1
⑪	Plant 1	3					3	4
	Plant 4	1					1	
⑫	Plant 1	2					2	2
Σ		33	48	2	3	19	105	105

- a
- ① Open-pit coal mine
 - ② Open-pit gold mine
 - ③ Open-pit iron ore mine
 - ④ Underground iron ore mine
 - ⑤ Marble quarry
 - ⑥ Gypsum quarry
 - ⑦ Clay quarry
 - ⑧ Aggregate quarry
 - ⑨ Limestone quarry
 - ⑩ Mineral processing plant
 - ⑪ Road construction site
 - ⑫ Scrap iron plant

Table IV

Crest factors for vibration acceleration

Crest factor	CF _x	CF _y	CF _z
Minimum	6.359	5.263	5.982
Maximum	24.975	29.223	46.167
Mean	9.779	8.792	12.155
Standard deviation	3.364	2.806	6.019
≥9	51	36	70
<9	54	69	35

the Y-axis, and 70 trucks in the Z-axis (Table IV). Yet, in another study on nine trucks by Mandal *et al.* (2006) the crest factor was between 4.4 and 8.2.

The frequency spectrum of WBV acceleration was evaluated with ¹/₃ – octave band distribution. The dominant frequency ranged between 10 and 40 Hz on the X-axis, 20–40 Hz on the Y-axis, and 1–2.5 Hz on the Z-axis. Village, Morrison, and Leong (1989) found that the dominant frequencies were between 1.6 and 2 Hz in the X- and Y-axes and 3.15 Hz in the Z direction. Sherwin *et al.* (2004) recorded the highest vibration value on the Z-axis with 3.2 Hz as the dominant frequency. Mansfield, Newell, and Notoni (2009) found that less than 1% of the vibration energy in the Z-axis was below 1 Hz. According to Smets, Eger, and Grenier (2010) the dominant frequencies were in the range of 1 Hz to 1.25 Hz.

The SEAT value, which shows the vibration isolation efficiency of the driver's seat, ranged from 0.494 to 1.702 for the X-axis, from 0.732 to 1.600 for the Y-axis, and from 0.589 to 1.286 for the Z-axis. The vibration was attenuated in 21 trucks in the X-axis, 12 in the Y-axis, and 75 trucks in the Z-axis. Driver seats attenuated vibration in the Z-axis while amplifying it in the other axes.

Evaluation by vibration dose

The equivalent vibration dose normalized to an 8-hour shift, VDV(8), on the driver's seat of trucks ranged from 7.684 m/s^{-1.75}

Table III

Comparison of health risk severity of truck drivers

A(8)				Human response			
ISO 2631-1 (1997)		EU 2002/44/EC (2002)		ISO 2631-5 (2004)			
WCA ^a	VS ^a	WCA ^b	VS ^b	S _{ed} ^c		R ^d	
5 Low	1 Low	10 Low	1 Low	70 Low	100 Low		
87 Moderate	45 Moderate	94 Moderate	89 Moderate	23 Moderate	4 Moderate		
13 High	59 High	1 High	15 High	12 High	1 High		
VDV(8)							
ISO 2631-1 (1997)		BS 6841 (1987)		EU 2002/44/EC (2002)			
WCA ^e	VS ^e	WCA ^f	VS ^f	WCA ^g		VS ^g	
2 Low	1 Low	62 Low	55 Low	2 Low	1 Low		
74 Moderate	66 Moderate	— Moderate	— Moderate	92 Moderate	90 Moderate		
29 High	38 High	43 High	50 High	11 High	14 High		

- a The frequency-weighted acceleration values corresponding to the EAV and ELV limits for 8-hour exposure are 0.45 m/s² and 0.90 m/s²
- b The frequency-weighted acceleration values corresponding to the EAV and ELV limits for 8-hour exposure are 0.50 m/s² and 1.15 m/s²
- c While the negative health effect of S_{ed} value below 0.5 MPa is low, the Sed value above 0.8 MPa has a high negative health effect
- d While the negative health effect of R value below 0.8 is low, an R value above 1.2 has a high negative health effect
- e Vibration dose values corresponding to EAV and ELV limits for 8-hour exposure are 8.5 m/s^{-1.75} and 17.0 m/s^{-1.75}
- f Vibration dose value corresponding to hazard limit for 8-hour exposure is 15.0 m/s^{-1.75}
- g Vibration dose values corresponding to EAV and ELV limits for 8-hour exposure are 9.1 m/s^{-1.75} and 21.0 m/s^{-1.75}

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to $32.914 \text{ m}\cdot\text{s}^{-1.75}$ with a mean and standard deviation of $15.479 \pm 4.414 \text{ m}\cdot\text{s}^{-1.75}$. $\text{VDV}(8)_{\text{xyz}}$ ranged from $8.366 \text{ m}\cdot\text{s}^{-1.75}$ to $33.754 \text{ m}\cdot\text{s}^{-1.75}$ with a mean and standard deviation of $16.820 \pm 4.130 \text{ m}\cdot\text{s}^{-1.75}$. According to the measurements taken by Mandal *et al.* (2006) on nine trucks, VDV values ranged from $7.71 \text{ m}\cdot\text{s}^{-1.75}$ to $13.0 \text{ m}\cdot\text{s}^{-1.75}$. Vanerkar *et al.* (2008) reported that the average vibration dose in 60 dumpers in an open pit iron operation was $10.81 \pm 3.44 \text{ m}\cdot\text{s}^{-1.75}$, and the average for a bauxite mine was $9.27 \pm 3.98 \text{ m}\cdot\text{s}^{-1.75}$. In a study on 18 trucks, VDV(8) ranged from $6.05 \text{ m}\cdot\text{s}^{-1.75}$ to $25.13 \text{ m}\cdot\text{s}^{-1.75}$ (Mandal and Srivastava, 2010). Burström *et al.* (2016) reported VDV(8) values between $7 \text{ m}\cdot\text{s}^{-1.75}$ and $17 \text{ m}\cdot\text{s}^{-1.75}$.

A comparison of the VDV(8) and $\text{VDV}(8)_{\text{xyz}}$ values of all trucks with the HGCZ limits according to BS 6841 (1987), ISO 2631-1 (1997) and EU 2002/44/EC (2002) is presented in Table III. When the exposures are examined with reference to ISO 2631-1 (1997) and EU 2002/44/EC (2002), the majority of trucks fall within the HGCZ when the WCA and VS criteria are taken into consideration.

Similarly, considering the WCA criterion according to BS 6841 (1987) standard the majority of trucks fall below the hazard limit of $15 \text{ m}\cdot\text{s}^{-1.75}$. According to the VS criteria, more than half of the trucks remained in the area below the hazard limit. The smooth transition of truck units between criteria could be attributed to the fact that average VDV(8) values fluctuate around the $15 \text{ m}\cdot\text{s}^{-1.75}$ limit.

The estimated vibration dose value (eVDV, $\text{m}\cdot\text{s}^{-1.75}$) is the cumulative measure of vibration received by a person and is calculated using the frequency-weighted RMS value. As the eVDV is not suitable for shocks, repeated shocks, and intermittent vibration and will give correct results when the crest factor is less than six, it is recommended that the vibration dose value be determined directly from the entire acceleration-time log for vibration recordings where the crest factor is greater than about six (BS 6841, 1987). Of the 105 trucks sampled in the study, the crest factor was greater than six in 105, 101, and 104 trucks in the X-, Y-, and Z axes, respectively. The eVDV – VDV relationship for the trucks is presented in Figure 3. The coefficients of

determination of linear regression analyses ranged from 80.57% to 86.90%, indicating a strong correlation although almost all crest factors were greater than six.

In terms of the WCA criterion, the time required to reach the daily exposure action value (EAVTT_(VDV)) of truck drivers ranged from 00:02:48 to 15:44:15 hours with a mean and standard deviation of $01:52:01 \pm 02:22:29$ hours. The time required to reach the daily exposure limit value (ELVTT_(VDV)) of truck drivers, however, ranged between 01:19:32 and 446:19:14 hours with mean and standard deviation $52:56:38 \pm 67:20:54$ hours. 103 out of 105 trucks exposed their drivers to enough vibration to reach the EAV before the end of the shift, while 11 trucks reach the ELV before the end of the shift.

Evaluation by vibration containing multiple shocks

According to ISO 2631-5 (2004), a S_{ed} value less than 0.5 MPa for lifetime exposure indicates a low probability of an adverse health impact caused by vibration, and a value greater than 0.8 MPa a higher probability. Likewise, a daily risk factor (R) below 0.8 for a certain number of working days per year indicates a low probability of an adverse health effect, while values greater than 1.2 pose a high probability of adverse health effects.

S_{ed} values, which were calculated using acceleration values measured at the seat pad (asx, asy, asz) ranged between 0.141 MPa and 1.749 MPa with mean and standard deviation of 0.466 ± 0.240 MPa. The R(IOP) factor ranged between 0.109 and 1.351 with mean and standard deviation 0.401 ± 0.201 , and the R(TOP) factor between 0.177 to 2.187, with mean and standard deviation 0.583 ± 0.300 .

When the WBV exposure is evaluated with S_{ed} , 70 drivers are exposed to a pressure of less than 0.5 MPa and the probability of adverse health effects due to vibration is low, 23 are exposed to between 0.5 MPa and 0.8 MPa with moderate probability of adverse health effects, and 12 are exposed to greater than 0.8 MPa with high probability of adverse health effects (Table III). Evaluation with the R(IOP) factor reveals that 100 drivers have an R factor less than 0.8 MPa and the probability of an adverse health effect due to vibration is low, four have an R factor

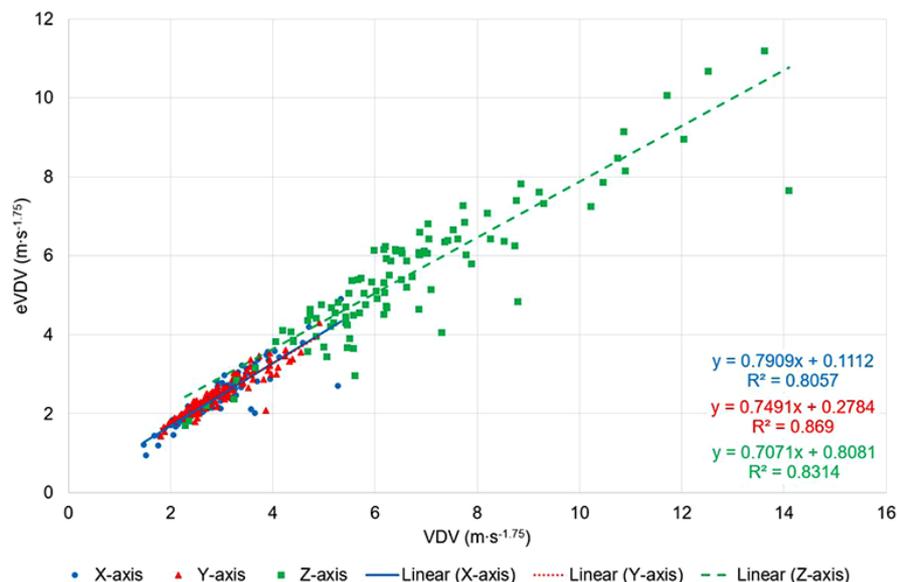


Figure 3—eVDV – VDV relationship for the RECORD phase

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between 0.8 and 1.2 with moderate probability of an adverse health effect, and only one has an R factor greater than 1.2 with a high probability of an adverse health effect.

According to the ISO 2631-5 (2004) standard, the majority of drivers fall in the low health risk category. More specifically, according to the S_{ed} criterion, the majority of drivers are unlikely to suffer adverse health effects. According to the R factor, the probability of an adverse health effect for almost all drivers is low. With the ISO 2631-5 (2004) standard, the adverse health risk due to WBV exposure is prominently low compared to the BS 6841 (1987) and ISO 2631-1 (1997) standards and the SEU 2002/44/EC (2002) directive.

Evaluation of truck cycle phases

Evaluation of truck cycle phases by vibration acceleration

Parameters related to the WBV acceleration to which truck drivers were exposed are evaluated separately for the phases of the truck cycle. Assuming that the working shift is composed of a specific phase, averaged $A(8)$, $A(8)_{xyz}$, $EAV_{TT(RMS)}$, and $ELV_{TT(RMS)}$ values, along with the number of units sampled, are presented in Table V for all phases. For the WCA, the highest WBV exposure occurs during the RETURN phase followed by the HAUL and SPOT phases, while the lowest WBV exposure was recorded in the WAIT phase. The same pattern is observed in the VS criterion.

The health risk severity of the WCA and VS criteria according to the EU 2002/44/EC (2002) directive and ISO 2631-1 (1997) standard in truck cycle phases is presented in Table VI. As far as the WCA criterion is concerned, all drivers were exposed to a vibration level below the HGCZ, indicating a low probability of adverse health risk in the WAIT phase. LOAD is another passive phase, the vibration transmitted to the driver increases only when the loader dumps the bucket into the truck body, while the remaining parts of the phase are quiet in terms of vibration. A similar pattern is observed for the DUMP phase. However, since the VS criterion produces a greater WBV acceleration, more trucks pass into the HGCZ of moderate health risk. In terms of the WCA criterion, the SPOT, HAUL, and RETURN phases are located within the HGCZ. However, according to the more conservative VS criterion, more than half of the trucks are above the HGCZ where an adverse health risk is likely.

Table VII shows the WCA with the highest vibration recorded for all phases. In the RETURN and HAUL phases, where the

drivers are subjected to high levels of vibration, and to a lesser degree in the DUMP phase, this is the Z-axis. On the relatively undulating ground characterized by higher rolling resistances than main haul roads, where the truck is manoeuvring to approach the loader or the dump point, the WCA in the SPOT phase was Y, indicating excessive lateral movement. In other words, the WBV delivered to the driver along the vertical Z-axis by the slow-moving trucks in the SPOT phase was less than that along the horizontal Y-axis, where a shaking movement was predominant due to rough ground conditions. A similar pattern is observed in the LOAD phase. The vibrations caused by the material being dumped into the body of the stationary truck jolt it mostly along the sideways (lateral) Y-axis. On the other hand, during the WAIT phase, while the truck was stationary and the engine was running at low speed, the WCA was the Z-axis. In general terms, the WCA was the Z-axis in the phases where the truck was at a higher speed, and the Y-axis in the phases at lower speeds.

Averaged crest factors in all axes in the SPOT, HAUL, DUMP, and RETURN phases are less than the critical threshold of nine. These phases consist of stable sections in terms of vibration, where the driver is less exposed to shocks. In the WAIT phase, where 50 trucks were recorded, the crest factors of 24, 15, and 24 trucks were greater than nine on the X-, Y-, and worst-case Z-axis, respectively. In this phase, where the vehicle is stationary, and therefore the vibration exposure is very low, the crest factor could easily exceed nine, as even small jolts could cause high amplitudes in terms of WBV acceleration. In the LOAD phase, where some 99 trucks were recorded, the crest factor in the driver's seat was greater than nine for 62 trucks on the X-axis, 32 in the Y-axis (the WCA), and 70 trucks on the Z-axis. Shocks on the X and Z axes are greater than the Y-axis, where the highest vibration acceleration values are recorded. This indicates that the driver's seat is subjected to a steadily high acceleration along the Y-axis, and that the shocks on the X and Y axes caused by dumping the bucket are returned to the stationary state more quickly.

Analysis of the SEAT factor in the truck cycle phases revealed that vibration on the cabin floor is attenuated in some of trucks but exacerbated in others in all three axes. Driver seats exacerbated vibration in the X and Y axes in all cycle phases. More clearly, the driver's seat had almost no vibration dampening capability in the Y-axis. Although it exhibited a

Table V

Descriptives of vibration acceleration in cycle phases in accordance with ISO 2631-1

Phase	n	Mean	A(8) (m/s ²) standard deviation	Min.	Max.	Mean	A(8) _{xyz} (m/s ²) standard deviation	Min.	Max.
Spot	89	0.628	0.184	0.267	1.159	0.904	0.241	0.306	1.521
Load	99	0.243	0.182	0.064	1.421	0.335	0.224	0.099	1.766
Haul	104	0.762	0.171	0.430	1.404	0.988	0.180	0.593	1.609
Dump	99	0.423	0.153	0.171	1.226	0.588	0.198	0.273	1.469
Return	102	0.862	0.251	0.398	1.552	1.147	0.271	0.546	1.914
Wait	50	0.116	0.079	0.008	0.344	0.154	0.103	0.012	0.392
		Mean	EAV _{TT(RMS)} (hh:mm:ss) standard deviation	Min.	Max.	Mean	ELV _{TT(RMS)} (hh:mm:ss) standard deviation	Min.	Max.
Spot		06:48:41	05:01:42	01:29:20	>24	>24	>24	07:52:34	>24
Load		>24	>24	00:59:26	>24	>24	>24	05:14:23	>24
Haul		03:57:31	01:43:43	01:00:53	10:49:36	20:56:28	09:08:40	05:22:02	>24
Dump		15:34:44	11:30:25	01:19:47	>24	>24	>24	07:02:04	>24
Return		03:31:43	02:20:49	00:49:49	12:39:05	18:39:59	12:24:58	04:23:33	>24
Wait		>24	>24	16:51:42	>24	>24	>24	>24	>24

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Table VI

Decomposition of health risk severity of drivers in truck cycle phases

Phases	ISO 2631-1 (1997)				A(8)				Human response ISO 2631-5 (2004)			
	WCA ^a		VS ^a		WCA ^b		VS ^b		Sed ^c		R ^d	
Spot	17	Low	3	Low	23	Low	4	Low	80	Low	89	Low
	64	Moderate	37	Moderate	65	Moderate	71	Moderate	9	Moderate	–	Moderate
	8	High	49	High	1	High	14	High	–	High	–	High
Load	92	Low	80	Low	95	Low	88	Low	94	Low	97	Low
	5	Moderate	17	Moderate	3	Moderate	9	Moderate	4	Moderate	2	Moderate
	2	High	2	High	1	High	2	High	1	High	–	High
Haul	1	Low	–	Low	3	Low	0	Low	73	Low	99	Low
	88	Moderate	38	Moderate	98	Moderate	89	Moderate	25	Moderate	5	Moderate
	15	High	66	High	3	High	15	High	6	High	–	High
Dump	64	Low	24	Low	76	Low	36	Low	93	Low	97	Low
	34	Moderate	69	Moderate	22	Moderate	61	Moderate	4	Moderate	2	Moderate
	1	High	6	High	1	High	2	High	2	High	–	High
Return	2	Low	–	Low	7	Low	0	Low	71	Low	92	Low
	58	Moderate	19	Moderate	82	Moderate	50	Moderate	17	Moderate	9	Moderate
	42	High	83	High	13	High	52	High	14	High	1	High
Wait	50	Low	50	Low	50	Low	50	Low	49	Low	50	Low
	–	Moderate	–	Moderate	–	Moderate	0	Moderate	1	Moderate	–	Moderate
	–	High	–	High	0	High	0	High	–	High	–	High
Phases	ISO 2631-1 (1997)				VDV(8) BS 6841 (1987)				EU 2002/44/EC (2002)			
	WCA ^e		VS ^e		WCA ^f		VS ^f		WCA ^g		VS ^g	
Spot	10	Low	5	Low	79	Low	69	Low	18	Low	7	Low
	66	Moderate	60	Moderate	–	Moderate	–	Moderate	68	Moderate	79	Moderate
	13	High	24	High	10	High	20	High	3	High	3	High
Load	74	Low	68	Low	96	Low	96	Low	77	Low	72	Low
	23	Moderate	29	Moderate	–	Moderate	–	Moderate	21	Moderate	25	Moderate
	2	High	2	High	3	High	3	High	1	High	2	High
Haul	1	Low	0	Low	57	Low	54	Low	1	Low	0	Low
	78	Moderate	71	Moderate	–	Moderate	–	Moderate	96	Moderate	95	Moderate
	25	High	33	High	47	High	50	High	7	High	9	High
Dump	31	Low	24	Low	92	Low	92	Low	28	Low	29	Low
	65	Moderate	71	Moderate	–	Moderate	–	Moderate	58	Moderate	67	Moderate
	3	High	4	High	7	High	7	High	3	High	3	High
Return	1	Low	0	Low	42	Low	34	Low	2	Low	1	Low
	59	Moderate	45	Moderate	–	Moderate	–	Moderate	75	Moderate	70	Moderate
	42	High	57	High	60	High	68	High	25	High	31	High
Wait	46	Low	45	Low	49	Low	45	Low	48	Low	47	Low
	4	Moderate	5	Moderate	–	Moderate	–	Moderate	2	Moderate	3	Moderate
	–	High	–	High	1	High	5	High	–	High	–	High

Table VII

WCA distribution for A(8) in truck cycle phases

Phase	Number of trucks		
	X	Y	Z
Spot	19	48	22
Load	15	55	29
Haul	1	8	95
Dump	24	21	54
Return	–	6	96
Wait	9	15	26

similar behaviour on the X-axis, the vibration dampening ability here was somewhat better. Yet, the seat dampened the vibration in the Z-axis except for SPOT phase, where the dampening and aggravation numbers were close.

Evaluation of truck cycle phases by vibration dose

Assuming that the working shift is composed of a specific phase, vibration dose values measured in the driver's seat were converted to VDV(8) along the WCA and to VDV(8)_{xyz} for the VS for all phases. The highest level of vibration dose that drivers are exposed to in the seat was in the RETURN phase, followed by the HAUL, SPOT, and DUMP phases. The lowest vibration dose occurs during LOAD and WAIT (Table VIII). Similarly, if the shift only consisted of a certain phase the drivers would, for example, reach the daily exposure action value (EAV_{TT(VDV)}) after 1 hour 39 minutes and 1 hour 49 minutes of work at the RETURN and HAUL phases, respectively. On the contrary, a driver would never reach the daily exposure action value in 24 hours of work if the shift consisted of WAIT or LOAD phases.

The vibration dose values are examined in Table VI for HGCZ limits in accordance with BS 6841 (1987), ISO 2631-1 (1997),

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Table VIII

Descriptives of vibration dose in cycle phases in accordance with ISO 2631-1

Phase	VDV(8) (m·s ^{-1.75})				VDV(8)xyz (m·s ^{-1.75})			
	Mean	Standard deviation	Min.	Max.	Mean	Standard deviation	Min.	Max.
Spot	12.949	3.766	6.865	23.781	14.596	3.963	7.248	25.774
Load	6.721	4.194	1.616	29.466	7.438	4.344	1.883	30.123
Haul	15.241	4.423	7.816	35.785	16.287	4.199	10.141	36.566
Dump	10.450	3.728	3.988	26.547	11.359	3.678	5.087	27.065
Return	17.252	5.742	7.897	35.391	18.645	5.504	8.651	36.397
Wait	3.389	3.005	0.490	15.596	3.605	3.105	0.544	15.840

Phase	EAV _{TT(VDV)} (sa)				ELV _{TT(VDV)} (sa)			
	Mean	Standard deviation	Min.	Max.	Mean	Standard deviation	Min.	Max.
Spot	04:22:38	05:09:17	00:10:17	>24	>24	>24	04:51:52	>24
Load	>24	>24	00:04:22	>24	>24	>24	02:03:50	>24
Haul	01:49:14	01:53:19	00:02:00	14:42:05	>24	>24	00:56:56	>24
Dump	14:15:02	>24	00:06:38	>24	>24	>24	03:07:57	>24
Return	01:39:11	02:16:30	00:02:06	14:06:14	>24	>24	00:59:30	>24
Wait	>24	>24	00:55:38	>24	>24	>24	26:11:34	>24

and the EU 2002/44/EC directive (2002). In terms of the WCA criterion, most of the trucks fall within the HGCZ in the RETURN, HAUL, SPOT, and DUMP phases. LOAD and WAIT phases are below the HGCZ. When evaluated according to the VS criterion, there are no significant transitions between the HGCZ and the region above the HGCZ according to the ISO 2631-1 (1997) standard and EU 2002/44/EC directive (2002) as the phase averages fall in the HGCZ. Most drivers were exposed to vibration levels below the BS 6841 (1987) hazard limit of 15 m·s^{-1.75} in phases other than RETURN for both WCA and VS criteria. If the 8-hour shift consisted only of the RETURN phase, most drivers would have been exposed to a vibration dose over the hazard limit before the shift ended, according to both WCA and VS criteria.

Similar to vibration acceleration, the WCA along which drivers were exposed to the highest level of vibration dose is the Z-axis for RETURN, HAUL, DUMP, and WAIT phases (Table IX). Again, the WCA is the Y-axis for the SPOT and LOAD phases in which trucks are stationary or moving very slowly on the undulating ground.

The estimated VDV (eVDV, m·s^{-1.75}) that truck drivers are exposed to was calculated in accordance with the BS 6841 (1987) standard and the eVDV–VDV relationship for all stages is given in Figure 4. Linear regression analyses for all three axes produced coefficients of determination (R²) that varied between 71% and 96%. A strong correlation between the VDV and eVDV relationship is indicated for phases including those with a crest

Table IX

WCA distribution for VDV(8) in truck cycle phases

Phase	Number of trucks		
	X	Y	Z
Spot	20	41	28
Load	21	51	27
Haul	–	8	96
Dump	27	17	55
Return	1	7	94
Wait	9	17	24

factor greater than six. It should be noted that for the vast majority of trucks, the crest factor is less than six on the X and Z axes only for the SPOT phase. Again, it is less than six on the SPOT, DUMP, and RETURN phases on the Y-axis. In all other cases, it is greater than six.

Evaluation of truck cycle phases by vibration containing multiple shocks

Averaged equivalent static compression dose value (S_{ed}), risk factor for the individual operator R(IOP), and typical operator R(TOP) values of the drivers are presented in Table X for all phases. In general terms, drivers are in the low adverse health risk zone in all phases. If the phases are examined individually, the highest S_{ed} and R factors belong to RETURN and HAUL. The negative health risk assessment of all truck drivers according

Table X

S_{ed} and R factor values of drivers based on cycle phases

Phase	S _{ed} (MPa)				R(IOP)				R(TOP)			
	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.
Spot	0.300	0.140	0.086	0.761	0.259	0.133	0.082	0.765	0.375	0.175	0.107	0.952
Load	0.201	0.155	0.041	1.024	0.176	0.142	0.028	0.853	0.251	0.194	0.052	1.280
Haul	0.426	0.216	0.142	1.294	0.369	0.192	0.118	1.000	0.533	0.270	0.178	1.619
Dump	0.297	0.159	0.098	1.122	0.260	0.144	0.084	0.981	0.372	0.198	0.123	1.403
Return	0.482	0.289	0.134	2.088	0.413	0.235	0.103	1.613	0.602	0.362	0.168	2.612
Wait	0.100	0.128	0.012	0.793	0.088	0.110	0.008	0.580	0.126	0.161	0.015	0.992

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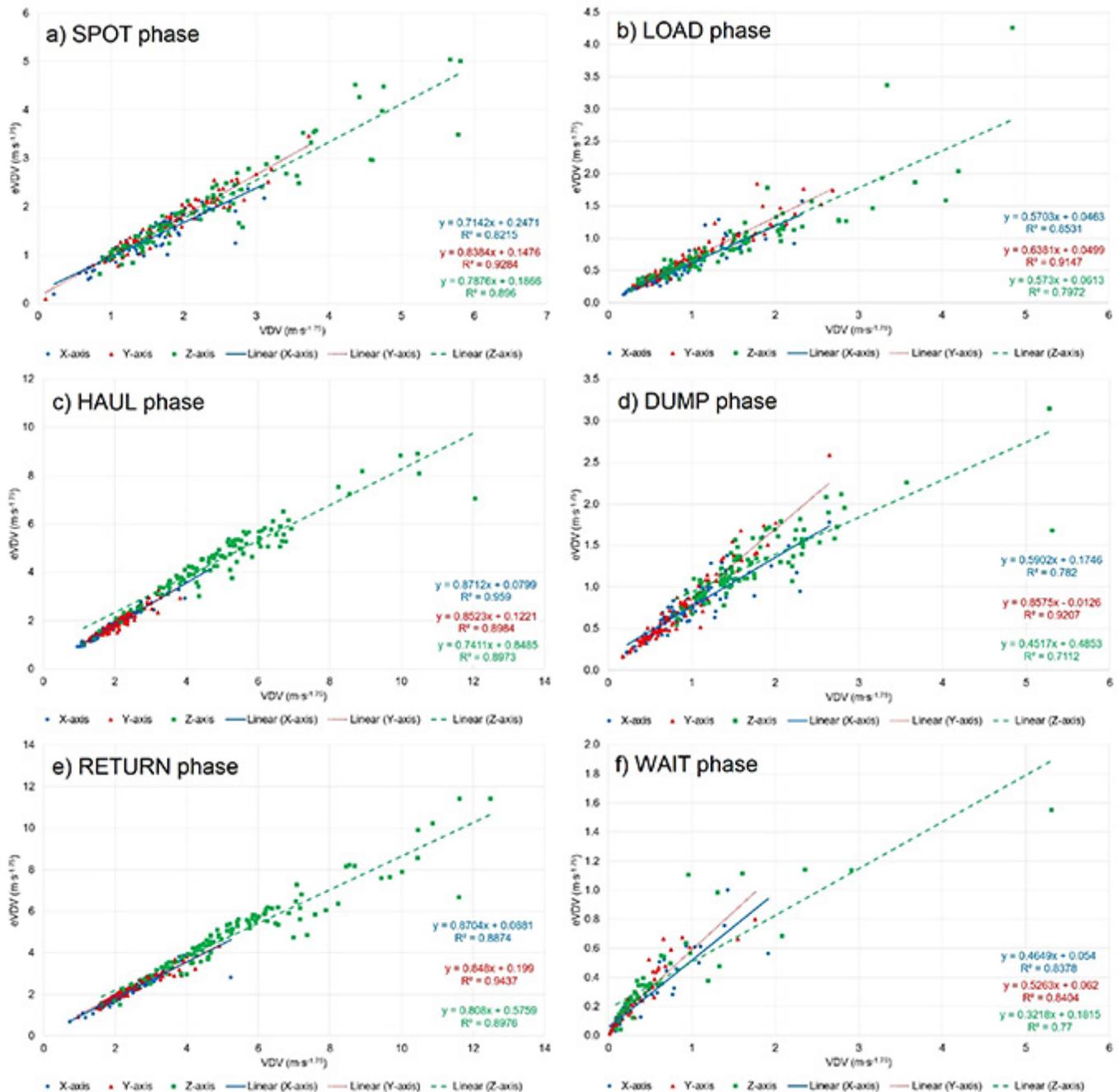


Figure 4—eVDV-VDV relationship for truck cycle phases

to the S_{ed} and R factor criteria can be seen in Table VI. In the RETURN phase, 14 drivers are exposed to compression greater than 0.8 MPa, and the potential for adverse health effects due to vibration is high. Twenty-five drivers in the HAUL phase and 17 in the RETURN phase are subjected to a pressure in the range of 0.5 MPa to 0.8 MPa, and the probability of adverse health effects due to vibration is moderate. In other phases, almost all drivers are exposed to a compression level of less than 0.5 MPa and the probability of adverse health effects due to vibration is low. When the drivers are evaluated according to the risk factor (R) criterion, the health risk for almost all drivers is low except for one driver in the RETURN phase.

Statistical analyses

Whole-body vibration data collected in this study was analysed

using the SPSS statistics package (George and Mallery, 2010). The effect of differences in truck cycle phases, truck capacity, truck type (contractor truck/mining truck and regular/underground), unloading mechanism, driver age and experience, truck service life, and material hauled were evaluated by hypothesis testing. Normality of data was tested prior to analysis by the Shapiro-Wilk test and skewness-kurtosis values. The confidence interval (CI) was chosen as 95%.

The one-way analysis of variance was used to determine whether there are any statistically significant differences between the means of A(8) and VDV(8) levels of truck cycle phases. The difference between the means of phases constituting the truck cycle was examined by the Tamhane test in multiple comparison tables. As far as the vibration acceleration is concerned, there was significant difference between the means of all cycle phases

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at 95% CI. For the vibration dose, there was no significant difference between the HAUL, RETURN, and SPOT phases, but there was a statistically significant difference between all other phases at the 0.05 level.

In order to analyse the effect of hauling capacity on vibration level, trucks were grouped based on hauling capacity; 30 t (33 trucks), 77 t (48 trucks), 100 t (two 91 t and three 100 t), and 170 t (19 trucks). The difference between group means was examined by the Tamhane test in multiple comparison tables. Both for the vibration acceleration and vibration dose, there was a statistically significant difference between 30 t and 170 t trucks and between 77 t and 170 t trucks at the 0.05 level.

The independent sample test was used to determine whether WBV acceleration and dose levels changed significantly with truck type. There were 33 contractor trucks and 72 mining trucks. There was no significant difference between the group means. Thus, 30 t contractor trucks and ≥ 77 t mining trucks expose drivers to equivalent levels of vibration acceleration and dose.

The independent sample test was used to determine whether WBV acceleration and dose levels changed significantly with unloading method. There were three bottom-dump trucks and 102 rear-dump trucks (Figure 5). There was no significant difference between group means, revealing that bottom-dump and rear-dump trucks exposed drivers to equivalent levels of vibration acceleration and dose.

To investigate the effect of driver age on vibration exposure, drivers were grouped based on age; 20–30 years (11 drivers), 31–40 years (46 drivers), 41–50 years (41 drivers), and ≥ 51 years (7 drivers). The difference between group means was examined by the Tukey test in multiple comparison tables. Both for the vibration acceleration and vibration dose, there was not a statistically significant difference between age groups at the 0.05 level.

Any likely effect of driver experience on vibration exposure was examined. Drivers were grouped based on experience; 1–5 years (27 drivers), 6–10 years (37 drivers), 11–15 years (20 drivers), 16–20 years (13 drivers), 21–25 years (3 drivers) and ≥ 26 years (5 drivers). The difference between group means was examined by the Tukey test in multiple comparison tables. For the vibration dose, there was not a statistically significant difference between age groups at the 0.05 level. For the vibration acceleration, there was a statistically significant difference between 1–5 years experience group and 16–20 years experience group at the 0.05 level.

To study the impact of truck service life on vibration exposure, trucks were grouped: 1–10 years (31 trucks), 11–20 years (22 trucks), 21–30 years (6 trucks) and 31–40 years (46

trucks). The difference between group means was examined by the Tamhane test for vibration acceleration and the Tukey test for vibration dose in multiple comparison tables. Both for the vibration acceleration and vibration dose, there was a statistically significant difference between the 11–20 years of service life group and 31–40 years of service life group at the 0.05 level.

The independent sample test was used to determine whether WBV acceleration and dose levels changed significantly with working environment. There were 103 units allocated to surface operations and two in underground operations. A significant difference between group means showed that surface and underground working environments exposed drivers to different levels of vibration acceleration and dose.

The independent sample test was used to determine whether WBV acceleration and dose levels changed significantly with material hauled. While marble, gypsum, and limestone quarries were characterized by blocky material, the clay quarry, road construction site, mineral processing plant, and scrap iron plant provided representative examples of non-blocky material. Figure 6 depicts typical scenes of handling blocky material in the upper row and non-blocky material in the lower row. Forty-seven trucks hauled blocky material and 58 hauled non-blocky material. There was no significant difference between the group means, indicating that different materials hauled exposed drivers to equivalent levels of vibration acceleration and dose.

The independent sample test was used to determine whether WBV acceleration and dose levels differed significantly with cycle phase. Trucks were grouped based on cycle phases; laden (HAUL, 104 units) and unladen (RETURN, 102 units). A significant difference between group means illustrated that change in cycle phase exposed drivers to different levels of vibration acceleration and dose.

The independent sample test was used to determine whether WBV acceleration and dose levels changed significantly with vehicle speed. HAUL, with 104 units, was accepted as a speedy phase and SPOT, with 89 units, as slow. For the vibration dose, there was no significant difference between HAUL and SPOT, but for the vibration acceleration there was a statistically significant difference at the 0.05 level. Thus, different vehicle speeds exposed drivers to different levels of vibration acceleration.

In a similar effort, trucks were grouped based on cycle phases; speedy (RETURN, 102 units) and slow (SPOT, 89 units). The independent sample test was used to determine whether WBV acceleration and dose levels changed significantly with vehicle speed. For vibration acceleration and vibration dose, there was a significant difference between RETURN and SPOT at the 0.05 level.



Figure 5—Rear-dump and bottom-dump trucks

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Figure 6—Blocky (top row) and non-blocky materials

Conclusions

Whole-body vibration exposure measurements were taken from 105 trucks of different make, model, and capacity used in open-pit and underground mines. The measurements were evaluated through the work cycle phases of the machines by using a vibration analysis package. Thus, the entire and phase-based vibration exposure of all operators could be determined separately. Operator exposures were evaluated on the worst-case axis and vector sum approaches by taking into account the vibration acceleration and the vibration dose parameters in accordance with the EU 2002/44/EC (2002) directive, ISO 2631-1 (1997), and BS 6841 (1987) standards and by the daily equivalent pressure dose and the risk factor parameters in accordance with the ISO 2631-5 (2004) standard.

When the operator exposures are evaluated with the worst-case axis and vector sum approaches, taking into account the vibration acceleration ($A(8)$) and the vibration dose ($VDV(8)$), vibration exposures are within the HGCZ, which indicates a moderate level of adverse health risk. When the evaluation is made in accordance with ISO 2631-1 (1997), trucks fall in the HGCZ, pointing to a moderate level of adverse health risk. Based on the BS 6841 (1987) standard, which recommends evaluation over the vector sum criterion with more conservative limits, vibration exposures are within the region below the prescribed hazard limit. According to the ISO 2631-5 (2004) standard, when the daily equivalent pressure dose (S_{ed}) parameter is examined with the WCA criterion, trucks are placed in the moderate health risk category. When the evaluation is made according to the vector sum criterion, trucks are located in the low health risk zone. When the R factor is examined according to WCA and VS criteria, vibration exposures are within the low health risk zone.

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