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Investigation of human body vibration exposures on haul trucks operating at U.S. surface mines/quarries relative to haul truck activity

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Abstract

Workers who operate mine haul trucks are exposed to whole-body vibration (WBV) on a routine basis. Researchers from the National Institute for Occupational Safety and Health (NIOSH) Pittsburgh Mining Research Division (PMRD) investigated WBV and hand-arm vibration (HAV) exposures for mine/quarry haul truck drivers in relation to the haul truck activities of dumping, loading, and traveling with and without a load. The findings show that WBV measures in weighted root-mean-square accelerations (a_w) and vibration dose value (VDV), when compared to the ISO/ANSI and European Directive 2002/44/EC standards, were mostly below the Exposure Action Value (EAV) identified by the health guidance caution zone (HGCZ). Nevertheless, instances were recorded where the Exposure Limit Value (ELV) was exceeded by more than 500 to 600 percent for VDV_x and a_{wx}, respectively. Researchers determined that these excessive levels occurred during the traveling empty activity, when the haul truck descended down grade into the pit loading area, sliding at times, on a wet and slippery road surface caused by rain and overwatering. WBV levels (not normalized to an 8-h shift) for the four haul truck activities showed mean a_{wz} levels for five of the seven drivers exceeding the ISO/ANSI EAV by 9–53 percent for the traveling empty activity. Mean a_{wx} and a_{wz} levels were generally higher for traveling empty and traveling loaded and lower for loading/dumping activities. HAV for measures taken on the steering wheel and shifter were all below the HGCZ which indicates that HAV is not an issue for these drivers/operators when handling steering and shifting control devices.

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Disclaimer

The findings and conclusions in this paper are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

Keywords

Mining; Haul trucks; Whole-body/hand-arm vibration; Loading; Roadway travel; Dumping

Relevance to industry

Human vibration exposures were investigated for mine/quarry haul trucks during full-shift loading, hauling, and dumping activities to determine the potential impact on tasks that involve safe vehicle ingress/egress. This study advances the reservoir of data and knowledge of whole-body and hand-arm vibration exposure on mine/quarry haul trucks. This data can be used to determine performance metrics for equipment or tools to reduce WBV transmission to equipment operators.

1. Introduction

Workers in the industrial world, particularly those who operate off-road vehicles and earth-moving equipment are commonly exposed to whole-body vibration (WBV). Jarring or jolting (mechanical shock) is a component of WBV. When transmitted to the human body at the natural frequency of a body part or the body as a whole, WBV may produce a condition known as *resonance.* During resonance, the body or a part of the body will vibrate at a magnitude higher than the applied excitation force. In response, muscles will contract in a voluntary or involuntary way and cause fatigue or a lowering of motor performance capacity (Chaffin and Andersson, 1984). Evidence shows that the operator normally will reduce speed; whereas, experimental data indicates the pain threshold for WBV is 0.8m/s^2 (Langer, 2012). In light of postural elements, WBV is a contributing factor in the development of musculoskeletal disorders of the spine among workers exposed to a vibration environment (Kittusamy and Buchholz, 2004; Kittusamy, 2003, 2002; Bovenzi and Zadini, 1992; Johanning, 1991; Bongers et al., 1988, 1990; Seidel and Heide, 1986). Low-back pain (LBP) is a prominent and unfavorable health effect of WBV. A review by the National Institute for Occupational Safety and Health (NIOSH) reported a significant positive association between WBV exposure and LBP in 15 of 19 WBV studies reviewed by assigning the highest ranking descriptor of ‘strong evidence’ to the WBV-LBP relationship (NIOSH, 1997). A variety of field investigations have reported on WBV exposure for mining and quarry machinery (Smets et al., 2010; Mayton et al., 2009, 2008; Eger et al., 2006; Kumar, 2004; Miller et al., 2000, 2004). Smets et al. (2010) reported on a review of Canadian accident statistics for the Ontario Mining Industry, which showed that 16% of the traumatic injuries were associated with haul truck (HT) operation. Moreover, Kumar in his study of WBV on HTs concluded that HT operator exposure to WBV posed a significant health risk and noted that the exposure limit recommended in ISO 2631 was exceeded for a majority of the exposure time (Kumar, 2004; ISO, 1997).

2. Background

Various health and safety issues affect haul truck operators and include injuries from slips, trips, or falls from equipment, with the potential for high severity. Moore et al. (2009) examined circumstances surrounding injuries attributed to “falls from equipment” in the

2006 and 2007 Mine Safety and Health Administration (MSHA) databases. “Large trucks” accounted for over 20% of all falls from equipment injuries during that period. For the entire sample of falls from equipment injuries, almost 50% occurred during ingress or egress, and approximately 25% occurred while operators were performing maintenance activities during the course of operation such as changing a filter or cleaning a window that had become dirty.

Falls from haul trucks may occur as a result of a number of factors. A fall during the ingress/egress process on haul trucks can result in a drop of 10–12 feet. For mine workers, the tasks of getting on and off vehicles and equipment can be further complicated in that mine workers may carry an object with them such as a lunch box or tools while entering the equipment. Moreover, the issue of access path design has been shown to be an important factor in a person’s ability to safely enter and exit mobile equipment (Leskinen et al., 2003). In this study several issues were examined including angle of incline for the ladder handrail placement. Bottoms (1983) examined guidelines for the design of ingress/egress systems. The recommendations Bottoms presents are based on laboratory experiments to establish generally acceptable standards. This work pointed to the need for examining the access system as a whole owing to the interactions between the size and location of steps, handholds, doors, and workplace arrangement. Thus, a variety of standards exist for ladder design on mobile equipment, each with varying recommended geometries, resulting in non-uniform access systems throughout the industry.

Given the above issues, developing solutions to the complicated problems of ingress/egress should involve examination of issues beyond access systems, such as potential decreased capabilities due to WBV and hand-arm vibration (HAV) exposures. Moreover, exposure to WBV and increased postural requirements of the job have been identified as important risk factors in the development of musculoskeletal disorders for workers exposed to a WBV environment (Kittusamy, 2002, 2003; and Kittusamy and Buchholz, 2004). Although the ingress/egress systems on existing trucks may not be easily changed, the contribution to risk from other sources may be amenable to prevention efforts.

NIOSH researchers have conducted several vibration studies related to surface mine haul trucks and front-end wheel loaders. Mayton et al. (2014, 2008) reported on WBV exposures and influencing factors for quarry haul truck drivers and loader operators and WBV exposures on older and newer haul trucks at an aggregate stone quarry operation. In the former study, Mayton et al. (2014) looked at vibration exposure when traveling with and without a load of material between loading and dumping areas of two quarries. They noted that WBV measured on the floor of the operator’s cab (chassis) and on the seat were significantly lower for the loaded compared to the unloaded condition (Mayton et al., 2014). Smets et al. (2010) also reported similar results for haul trucks traveling loaded and unloaded. In this context, researchers considered it important to examine WBV in relation to four primary haul truck activities, which include traveling with and without a load, loading and dumping (ISO/TR 25398, 2006). The objective was to see how haul truck WBV exposure related to a particular activity and whether one or more of the activities posed a higher exposure risk than the others.

3. Methods

NIOSH researchers conducted field studies and collected data of WBV and HAV exposures and GPS for a total of seven vehicles and drivers/operators operating at each of the four surface mines/quarries (Table 1). The HTs were rear-dump, which differed by make/model, age, and capacity. Measurements of vibration were carried out with a Siemens (formerly LMS) SCADAS – SCR05, 16-channel, "front-end" data recorder using PDA type HP iPAQ 214 with a Windows Mobile based Bluetooth connection. Data were written to and stored on 8 or 16 GB flash cards. Two different sampling rates were used with 24-bit resolution: 256 samples per second for WBV measures and the trigger signal and 2048 samples per second for HAV measures. The sensors used to record three orthogonal axes of vibration included four PCB tri-axial accelerometers, as follows:

- chassis WBV – 356B18 (Serial No: 13982)
- seat WBV – 356B40 (Serial No: 17210)
- steering wheel HAV – 356A32 miniature – (Serial No: 92576)
- gear selector HAV – 356A32 miniature – (Serial No: 92575)

WBV and HAV data, in each direction for the floor, seat, steering wheel, and gear selector, were collected and stored in the first 12 channels of the data recorder. Channel 13 was used to collect and store a pulse or trigger signal for distinguishing between loading and dumping boundary areas in the data, and to identify haul truck activities of loading, dumping, traveling with no load, and traveling with a full load. In addition, a NIOSH researcher, in all but a few instances, rode along in the vehicles to observe truck operation during the entire shift sampling period.

The procedure for marking intervals of the different activities included one button press of the trigger upon entering and exiting the loading area, and two button presses of the trigger upon entering and exiting the dumping area. The researcher riding in the haul truck visually selected a landmark along the ramp or section of the roadway leading to the dumping/loading areas and pressed the trigger indicator button each time the haul truck reached that location. Therefore, data between single trigger markers was designated as loading, whereas data between double-trigger markers was designated as dumping. Moreover, the intervals designated for dumping/loading contained a small portion of the data with the haul truck traveling short distances with and without a load prior to and after actual dumping or loading took place. Furthermore, traveling loaded was selected by the intervals starting with one trigger marker and terminating with a double trigger marker. Similarly, traveling with no load or empty was selected by the intervals starting with a double trigger marker and terminating with one trigger marker.

Trigger markers were plotted on time data graphs with the WBV signal trace from one channel. These graphs were reviewed together with notes taken during the sampling period to verify markers and areas where discrepancies in the data seemed to occur. The marker was then identified by the exact sampling point in the data file to delineate the start and end of each of the activities. Some data points were interpolated where necessary. In addition, not all trigger markers were available owing to some malfunction with the instrumentation during the sampling period.

Truck routes varied as to where they began and ended for the shift. The locations included the pit area, loading area, maintenance shop, or truck docking and parking areas. The instrumentation was switched on just prior to the truck departing the area where the shift began. At the end of the measurement period, the instrumentation was removed when the truck returned, in most cases, to this same area.. Weather conditions ranged from dry, warm, and sunny to partly cloudy, rainy, wet, and muddy. The roadways were generally smooth for two of the mines/quarries (Subjects 2, 3, 6, and 7) and muddy, rutted, and pothole-ridden for the other two mines/quarries (Subjects 1, 4, and 5). Researchers onsite deemed all of the trucks and their respective seats to be in good working condition.

ISO 2631 and ANSI S3.18 along with EN 1032:2003 + A1:2008 (ISO, 1997; ANSI, 2002; EN, 2008) were used to evaluate the WBV exposures for haulage truck drivers in the X-, Y-, and Z-directions, and a_w and VDV were used to evaluate driver/operator exposure. Considering an eight-hour exposure period, the European Union Good Practice Guide (EUGPG) for WBV (Griffin et al., 2006) recommends, for the worst-case axis, a_w accelerations of 0.5 m/s^2 as the exposure action value (EAV) and 1.15 m/s^2 as the exposure limit value (ELV). In using VDV to assess vibration, the EUGPG recommends 9.1 $m/s^{1.75}$ as the EAV and 21 $m/s^{1.75}$ as the dose limit or ELV for an eight-hour exposure. Moreover, the EUGPG recommends measurement periods totaling a minimum of 20 min or longer, and if shorter periods are unavoidable, measurement periods should be at least 3 min long and repeated if possible, for a total time of more than 20 min. The ISO/ANSI standards are slightly more conservative with recommended a_w of 0.45 m/s^2 as the EAV and 0.90 m/s^2 as the ELV and, for VDV, 8.2 $m/s^{1.75}$ and 16 $m/s^{1.75}$, respectively.

Vibration transmitted through the seat was determined by the ratio – transmissibility (T) – of vibration level at the vehicle frame or chassis to the vibration level at the seat. A value greater than 1.0 would indicate a higher vibration level at the seat than the vehicle frame or chassis and that the seat is amplifying rather than attenuating the vibration. Griffin points out that comparing the accelerations on the seat with those at the seat base is the most direct method of obtaining transmissibility. Impedance methods offer another means for measuring or predicting transmissibility. The seat effective amplitude transmissibility (SEAT) is given in two different ways by the following equations (Griffin, 1990):

$$Ta_w = SEAT\,\% = \sqrt{\left[\int G_{ss}(f)Wi^2(f)df\right] \Big/ \left[G_{ff}(f)Wi^2(f)df\right]} \quad (1)$$

$$T_{VDV} = SEAT\,\% = VDV(seat)/VDV(floor) \times 100 \quad (2)$$

In Equation (1), G_{ss} (f) and G_{ff} (f) are the seat and floor acceleration power spectra, and W_i (f) is the frequency weighting of the human response to vibration. In Equation (2), VDV are the seat and floor or frame vibration dose values. In this study, the authors used both a_w and VDV for the seat and frame of the truck cab to approximate and compare T values.

3.1. Analysis of whole-body vibration

Daily vibration exposures were computed from a_w for the different haul trucks and drivers using Equations (3) and (4). The activities of loading, roadway travel with full load and no load, and dumping were included in these exposure levels. Similarly, vibration dose values were obtained by using Equations (5) and (6) to compute A(8) or the 8-hr equivalent values of WBV exposures for seven haul truck drivers at four surface mines/quarries.

$$\text{For the X} - \text{and Y} - \text{axes} \quad A(8) = 1.4a_w\sqrt{T\exp/To} \quad (3)$$

$$\text{And for the Z} - \text{axis} \quad A(8) = 1.0a_w\sqrt{T\exp/To} \quad (4)$$

where *Texp* is the duration of vibration exposure daily and *T*o is the reference duration of eight hours.

VDV exposures were computed from the measured samples as follows:

$$\text{For the X} - \text{and Y} - \text{axes} \quad VDV\ \exp = 1.4VDV\sqrt[4]{T\exp/Tmeas} \quad (5)$$

$$\text{And for the Z} - \text{axis} \quad VDV\ \exp = 1.0VDV\sqrt[4]{T\exp/Tmeas} \quad (6)$$

where *Texp* is the duration of vibration exposure daily and *Tmeas* is the measurement duration.

Overall weighted total a_w or vector sum normalized to an 8-hr shift is obtained by Equation (7), whereas VDV_{Tot} exposure is provided by Equation (8).

$$TOT_{aw_{A(8)}} = \sqrt{(1.4awx)^2 + (1.4awy)^2 + (1.0awz)^2} \quad (7)$$

$$VDV_{tot} = \sqrt{(1.4VDVx)^2 + (1.4VDVy)^2 + (1.0VDVz)^2} \quad (8)$$

The a_w were then calculated using the appropriate weighting factors as described in IS0 2631-1 (X-axis = W*d*; Y-axis = W*d*; Z-axis = W*k*) (ISO, 1997; ANSI, 2002). Weighting factors associated with the determination of health for seated exposure were also applied (X-axis, k = 1.4; Y-axis, k = 1.4; Z-axis, k = 1.0). The axis associated with the highest level of acceleration is used to determine likely health risks based on ISO 2631-1 HGCZ limits for 8 h of exposure (Table 2). The a_w values corresponding to the lower and upper limits of the HGCZ (for 8 h of exposure) are 0.45 and 0.90 m/s^2, respectively (ISO, 1997; ANSI, 2002). Moreover, the standard states, "health effects are not well documented for vibration exposure levels below the HGCZ. Exposures falling within the HGCZ should be viewed with caution in regards to health risks, while health risks are likely if the exposure is above the HGCZ" (ISO, 1997; ANSI, 2002).

In addition, the ISO/ANSI standard describes *crest factor* as the ratio of the maximum instantaneous peak value of the frequency-weighted acceleration signal to its RMS value. The crest factor may be used to determine whether the basic evaluation method is suitable for describing the severity of the vibration in relation to its effects on humans. The basic evaluation method is normally sufficient for vibration with crest factors below or equal to 9. A crest factor greater than 9 indicates the data should be examined for components of jarring/jolting.

3.2. Analysis of hand-arm vibration

HAV data were collected and analyzed in accordance with ISO 5349/ANSI S2.70 standards (ISO 5349-1 and -2:2001: ANSI S2.70:2006) for the measurement and evaluation of human exposure to vibration transmitted to the hand. HAV exposure was recorded for three directions and used to compute the vector sum or a_{wTotal} value for the first half of the day (from start of shift to lunch break) and the second half of the day (from end of lunch break to end of shift).

HAV data were transformed into levels of weighted a_w for each orthogonal axis (X, Y, Z) from which the vector sum or a_{wTotal} value was computed for the different haul trucks and drivers using Equation (9). The daily vibration exposure is computed using the magnitude of the vibration – vibration total value (Equation (10)) and the daily exposure duration (Equation (11)):

$$a_{wh} = \sqrt{\sum_i (W_{hi} a_{hi})^2} \quad (9)$$

where W_{hi} is the weighting factor for the i th one-third-octave band developed from Table A. 1 (ISO 5349-1), and a_{hi} is the RMS acceleration measured in the i th one-third-octave band, in m/s^2.

$$a_{wh}\_Total = \sqrt{(awhx)^2 + (awhy)^2 + (awhz)^2} \quad (10)$$

$$A(8) = a_{wh}\_Total\sqrt{(T/TO)} \quad (11)$$

where T is the total daily duration of exposure to the vibration a_{wh}, *and* T_O *is the reference duration of 8 h (28,800 s)*.

4. Results

4.1. Whole-body vibration exposure

Tables 2 and 3 show WBV levels according to a_w and VDV. The dominant axis of exposure is italicized or bold and italicized. Table 2 shows that the majority of a_w levels were below the HGCZ of 0.50 m/s^2 (European Directive2002/44/EC) and to a lesser extent, 0.45 m/s^2 (ISO/ANSI). The predominant axis of vibration was the Z-axis (vertical direction) for ten of thirteen days of recorded WBV. Nevertheless, high mean a_w levels were noted for Subjects 1, 2, 4, and 5 from two of the four quarries where the roughest roadways were observed. These roadways were muddy at times, undulating with ruts and potholes. In the only case ***Above*** the HGCZ case, the mean recorded level was 5.64 m/s^2 for the X-axis (fore-aft direction) for Subject 5, which was 5–6 times the exposure level (upper boundary) of the HGCZ for the ISO/ANSI and European standards. Together with other information, it appears these high a_w and VDV peaks were associated with the haul truck traveling into the pit loading area down a pronounced grade sliding at times, on a wet and slippery road surface caused by rain earlier in the day and later from watering of the roadway along its entire length for dust abatement. This caused difficulty in controlling the haul truck while braking to reduce speed on its descent into the pit. The four *Within* cases showed levels ranging up to 0.72 m/s^2.

Mean crest factors for the seven participating subjects and 13 days of data collection were higher than nine for all three axes on the order of two to three times. In light of high crest factors, VDV was also selected to describe levels of vibration. Values of VDV, which are more indicative of jarring/jolting events, for the same days and subjects are shown in Table 3. Similarly, as with a_w, most of the VDV levels were below the HGCZ. Incidences of VDV *Within* and ***Above*** are shown for the same quarries and subjects, with the Z or vertical direction as the dominant axis for vibration level in all but two cases. Subjects 1, 4, and 5 showed VDV levels of 16, 11, and 13 m/s$^{1.75}$ and were *Within* the HGCZ for both the ISO/ANSI and European Directive. Considering Subjects 4 and 5, VDV values were ***Above*** the HGCZ for both the ISO/ANSI and European Directive. In fact, Subject 5 showed a VDV at 81 m/s$^{1.75}$ for the X-axis – nearly four to five times the exposure limit values of 16 m/s$^{1.75}$ (ISO/ANSI) and 21 m/s$^{1.75}$ (European). Moreover, on Day 2 of data recording, Subject 4 presented VDVs at or above the HGCZ.

Similarly, mean seat transmissibility levels were reviewed for the seven subjects using the a_w and VDV methods. The mean transmissibilities were similar for the X and Y directions with values at four times the unity reference value for X and three times the unity value for Y. For the Z direction, the a_w computation resulted in values ranging from 0.80 to 1.30; whereas, values by the VDV method ranged from 0.66 to 2.05 (Fig. 1). The higher seat transmissibility values were shown for 100-ton (nominal) truck capacity vehicles that operated on the roughest roadway surfaces observed.

4.2. Hand-arm vibration exposure

Levels for a_w for measures on the steering wheel and shifter for two-day periods were below the HGCZ boundary levels of 2.5 m/s^2 and 5.0 m/s^2. Table 4 shows that mean levels for all seven subjects ranged from a low of 1. 01 m/s^2 to a high of 2.17 m/s^2 for the steering wheel and 0. 52 m/s^2 to a high of 1.92 m/s^2 for the shifter. The 8-h equivalent A(8) values were a little lower in magnitude, with a low of 0.94 m/s^2 to a high of 2.03 m/s^2 for the steering wheel and 0.47 m/s^2 to a high of 1.80 m/s^2 for the shifter. Here, it is assumed that no vibration exposure exists for periods for which there is no data. Thus, A(8) values are lower.

4.3. Whole-body vibration exposure by haul truck activity

Vibration exposures for different haul truck activities were determined using the trigger markers and WBV analysis procedures described in Section 3 Methods. Fig. 2 through 4 portray mean a_w accelerations (not normalized to an 8-hr shift, yet with the HGCZ as a reference) for all seven subjects according to activity for each orthogonal axis – X-, Y-, and Z-axes. Considering Fig. 2, a_w levels for all but one subject were shown to be low in light of the HGCZ and EAV of 0.45 and 0.50 m/s^2 for the ISO-ANSI and European directive, respectively. Subject 5 from Quarry 1 shows the case where the highest a_w level occurred in view of the HGCZ ELV of 0.9 and 1.15 m/s^2, respectively. Moreover, Subject 5 - traveling empty showed the highest and most extreme vibration, whereas dumping and traveling loaded were the next in order. Loading showed the lowest exposure value, but yet appeared above the ELV of the ISO/ANSI standard. Subjects 2 and 4 were employed at the same quarry as Subject 5, but WBV levels substantially lower than those for Subject 5. Primary reasons for this were the different routes and conditions encountered on separate sampling days. Traveling empty showed WBV exposure levels that were two to three times the value for the upper boundary of the HGCZ (EU Directive 2002/44/EC) and (ISO/ANSI), respectively. The reader should recall that the X-axis represents movement or vibration in the fore-aft direction. In Fig. 3, the mean a_w were all lower than the EAV of the HGCZ for all seven subjects. Looking at Fig. 4, the mean a_w for the Z-axis are shown for the seven subjects. Here Subjects 6 and 7 showed a_w below the HGCZ. However, the remaining 5 Subjects showed levels *Within* the HGCZ for the traveling empty activity. Subjects 1, 2, and 4 exhibited values ranging from 0.63 to 0.70 m/s^2 for the traveling loaded activity. Subjects 2, 4, and 5 showed levels from 0.47 to 0.60 m/s^2 for the dumping activity. (It should be noted that dumping included short distances, when entering and exiting the dumpsite, where the haul truck was traveling empty and loaded). All mean a_{wz} were considerably low for the loading activity.

Similarly, Fig. 5 through 7 present mean VDV exposures (not normalized to an 8-hr shift) for the X-, Y-, and the Z-axes during dumping, loading, traveling empty, and traveling loaded haul truck activities for all seven subjects. Notice in Fig. 5 that the mean VDV_x values showed the highest value of 22 for Subject 7 in the loading area. The highest values for all activities, except for Subject 7 during loading, were again noted for Subject 5, where conditions were some of the poorest in terms of ruts, muddy, slippery conditions, and potholes. VDV_x levels for Subject 5 were 14 for dumping, 11 for loading, 19 for travel empty, and 15 for travel loaded. Regarding VDV_y, levels were among the lowest for all seven subjects and the four activities. Finally, Fig. 7 shows the VDV_z exposure levels for the seven subjects and four haul truck activities. Mean VDV_z levels represented here, although somewhat higher than those shown for the VDV_y, are significantly low.

5. Discussion

Mayton et al. (2014) compared WBV exposures of haul trucks (HTs) and front-end wheel loaders (FELs) operating at two crushed stone operations with existing ISO/ANSI and EUGPG vibration standards. They also evaluated, among other issues, the influence of factors such as nominal load capacity (50–70 short tons), vehicle age, and seat transmissibility. Decreases in transmissibility were evident with increases in HT size and age (1–22 years for 5 haul trucks). Increasing HT size and age showed decreasing transmissibility. Similarly, the present study showed some evidence of lower haul truck seat transmissibility (Z-axis) for older haul trucks compared to newer ones. Moreover, Mayton et al. (2014) presented findings within the HGCZ of HT for dominant-axis a_w levels that were most often the Y-axis, lateral, or side-to-side direction. Of the 275 HT intervals of recorded vibration (not normalized to an equivalent 8-hr shift), 129 were within the HGCZ and 146 of 275 were below the HGCZ. Of those within the HGCZ, 56% of the 129 incidents were due to vibration in the vertical or Z-axis, whereas 44% were the lateral Y-axis. For this study, vibration in the Z-axis or vertical direction was generally dominant.

The highest nominal capacity trucks in the current study showed the mean A(8) a_w and VDV levels were all below the HGCZ. When looking at haul truck activity, only the VDV_x exposures during loading appeared high for five of the seven subjects. In contrast, mean VDV_y and VDV_z levels were significantly lower than those for the VDV_x in all four activities. In addition, mean A(8) values for a_w in the Mayton et al. (2014) study of six subjects operating a haul trucks at two quarries showed WBV dominant in the Y-axis or side-to-side direction, in all but two instances, where the levels within the HGCZ were associated with the X-axis. Dominant axis levels within the HGCZ ranged from 0.51 m/s^2 squared to 0.99 m/s^2. A(8) VDV were similar except that 36% (5 of 14) of the levels within the HGCZ were associated with the Z-axis, whereas the remaining levels were associated with the Y-axis. In a half dozen cases, levels appeared above the EL exceeding the ISO/ ANSI standards in these cases. In these cases levels of VDV, within or above the HGCZ, ranged from 12 to 20.

Findings from the Mayton et al. (2014) study contrasted with findings from this recent study where a majority of a_w levels fell outside or below the HGCZ of 0.50 m/s^2 and 1.15 m/s^2 (EU Directive 2002/44/EC) and, to a lesser extent, 0.45 m/s^2 and 0.90 m/s^2 (ISO/ANSI). In the current study, the Z-axis (vertical direction) was the dominant axis of vibration. There were, however, instances of high a_w levels which occurred for Subjects 1, 2, 4, and 5 from two of the four quarries where the roughest roadways were observed. In the only ***Above*** case, the recorded a_{wx} level was 5.64 m/s^2 for Subject 5, which was 5–6 times the exposure level (upper boundary) of the HGCZ for the ISO/ANSI and EU Directive 2002/44/EC standards. The four exposure levels *Within* showed a_{wy} ranging up to 0.72 m/s^2.

Mean crest factors for the seven participating subjects and 13 days of data collection were higher than 9 for all three axes on the order of 2–3 times. In light of high crest factors, VDV was also selected to describe levels of vibration. Subjects 1, 4, and 5 showed VDV levels of 16 $m/s^{1.75}$, 11 $m/s^{1.75}$, and 13 $m/s^{1.75}$, respectively, and were *Within* the HGCZ for both the ISO/ANSI and European Directive. Considering Subjects 4 and 5, VDV values were ***Above*** the HGCZ for both the ISO/ANSI and European Directive. In fact, Subject 5 showed a VDV_x at 81 $m/s^{1.75}$ for the X-axis – nearly 4 to 5 times the exposure limit values of 16 $m/s^{1.75}$ (ISO/ANSI) and 21 $m/s^{1.75}$ (EU Directive 2002/44/EC). Moreover, Subject 4 on Day 2 of data recording presented VDV_y at or above the HGCZ.

High a_{wx} and VDV_x levels were identified for Subject driver 5 that exceeded the ISO/ANSI HGCZ by more than 5 to 6 times the exposure level for an 8-h shift. Levels of a_{wy}, a_{wz}, VDV_y, and VDV_z appeared below the same HGCZ. The review of trigger and available GPS data together with field notes from the researcher riding along in the passenger seat of the haul truck pointed to a_{wx} and VDV_x peaks that occurred for the traveling empty activity. Consequently, researchers concluded that these high levels occurred as the haul truck descended down grade into the pit loading area, sliding at times, on a wet and slippery road surface caused by rain during the day and when the rain had stopped, over watering of the roadway for dust abatement. Drivers, subsequently, requested that watering not be done for the entire length of the roadway, but that segments of the roadway be left un-watered. This would allow haul truck drivers to maintain better control of the vehicle when descending into the pit (Mayton et al., 2016).

Similarly, mean seat transmissibility levels were considered for the seven subjects using the a_w and VDV methods. The mean transmissibilities were similar for the X- and Y- directions by a magnitude of 4 for X and 3 for Y. For the Z direction, the a_w computation resulted in values ranging from 0.80 to 1.30; whereas, values by the VDV method ranged from 0.66 to 2.05 (Fig. 1). The higher seat transmissibility values were shown for 100-ton (nominal) truck capacity vehicles that operated on the roughest roadway surfaces observed.

5.1. Ways to reduce WBV exposure

Tiemessen et al., 2007 reported on a study using a systematic review of the research literature to identify preventive strategies for reducing vibration exposure and result in decreasing musculoskeletal disorders (MSDs). Their goal was to examine evidence-based, preventive strategies that helped in reducing vibration exposure for drivers and also contributed to lowering the incidence of low back pain (LBP) from WBV exposure. They identified various factors directed toward reducing exposure intensity, exposure duration, and the number of exposure intervals for total exposure duration. They categorized these factors into two groups: 1) design considerations and 2) skills and behavior. The type of seat and seat suspension, cabin suspension, location of cabin, tire condition, pressure, and type, and load of the vehicle and vehicle maintenance are factors associated with design considerations. The weight, posture, and experience of the driver, seat adjustment, driving speed, track condition, working schedule, and fitness as evaluated by an occupational health physician are factors associated with the skills and behavior category. All factors combined from both categories were noted to have a positive (or lowering) effect on vibration magnitude. In comparison to the design considerations category, factors associated with the skills and behavior category may be a more preferred option for mine/quarry managers and safety personnel to explore in the short-term. These factors are generally less costly and more easily implemented and may consequently be of greater interest for short-term planning. On the other hand, design consideration factors may be more suited to the long-term interests and planning of a mine/quarry operation. Since many factors contribute to vibration exposure, it would be prudent for a successful intervention program that lowers exposures to include elements from both categories. The success or effectiveness of such an intervention program is more likely to occur by limiting the scope and focus to a specific group of drivers or a single driver. In summary, Tiemessen et al., 2007 assert that the development and implementation of intervention programs is necessary to curtail the incidence of LBP in drivers/operators exposed to WBV and investigating the success of these programs is also of key importance.

5.2. Limitations

Data collection was at times abbreviated or limited by malfunctioning instrumentation or defective data storage cards and changes in mining conditions that occur over time or randomly with onsite operations. Constraints of time and funding did not permit the inclusion of data on haul trucks operating with nominal capacities of 150–200 and 200 to 250 short tons for comparison with the other truck capacities sampled. Additionally, the sample size was small.

6. Conclusions

Studies have reported that WBV is a contributing factor in the development of musculoskeletal disorders, low back pain, and other injuries among workers exposed to a vibration environment. Drivers/operators are also exposed to hand-arm vibration (HAV) transmitted from the engine, vehicle transmission, and movement of the vehicle to both the steering column and the gear shift lever. Both WBV and HAV can contribute to fatigue and affect health and job performance. The findings of this study indicate that a_w measures and VDV levels, when compared to the ISO/ANSI and EU Directive2002/44/EC standards, were mostly below levels identified for the HGCZ. Although, there were several instances of WBV levels that appeared *Within* the HGCZ solely in the Z-axis (vertical direction), those exceeding the ELV were recorded for the X-axis (fore-aft direction). These cases showed high or extreme a_{wx} and VDV_x levels and were associated with Quarries 1 (in particular) and 2. Hence, it is not surprising that the rough haul road conditions at these mines/quarries were associated with the WBV levels within or exceeding the HGCZ of ISO/ANSI and EU Directive2002/44/EC. Roadway maintenance at these quarries was available, but at the time of data collection, somewhat limited or inadequate owing to the availability of appropriate equipment and mining conditions. On the other hand, roadways at the other two mines/quarries exhibited smoother surfaces and were well maintained. Hence, these factors were evident in the data with the lower a_w and VDV levels. Five of seven subjects showed mean a_{wz} exposures to levels *Within* the HGCZ for the traveling empty activity, which prior research has shown to the worst of the four haul truck activities considered. VDV_x was the highest recorded level at 22 $m/s^{1.75}$ for Subject 7 during loading. Aside from this case, the highest levels, a_{wz} and $VDV_{x,}$ for all activities were noted for Subject 5. These levels were the result of operating conditions that included haul roads with numerous ruts, potholes, muddy and slippery conditions (particularly for the descent into the pit loading area due to rain part of the day and watering the roadway for dust abatement). Nonetheless, more data is needed with perhaps additional controls to gain a better understanding of the cases where WBV levels were especially high *Within* and ***Above*** the HGCZ.

Levels of HAV for measures taken on the steering wheel and shifter were all below the HGCZ boundary levels of 2.5 m/s^2 and 5.0 m/s^2. The 8-h equivalent A(8) values for the seven total participants showed that HAV exposure is not an issue for these drivers/operators when handling steering and shifting control devices. Haul truck drivers did not contact or handle the shifter except to back up and move forward in dumping and loading areas and occasionally down-shift or up-shift when traveling.

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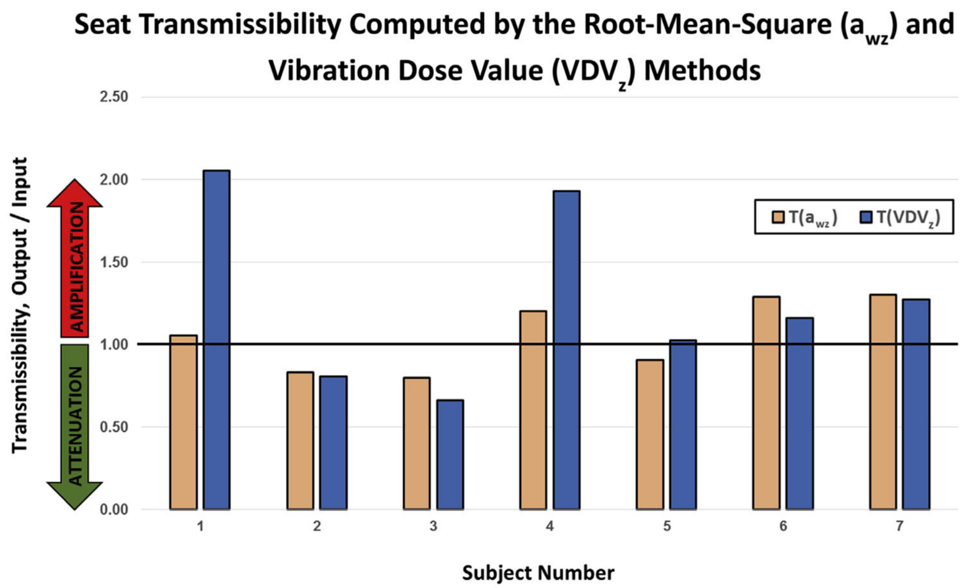
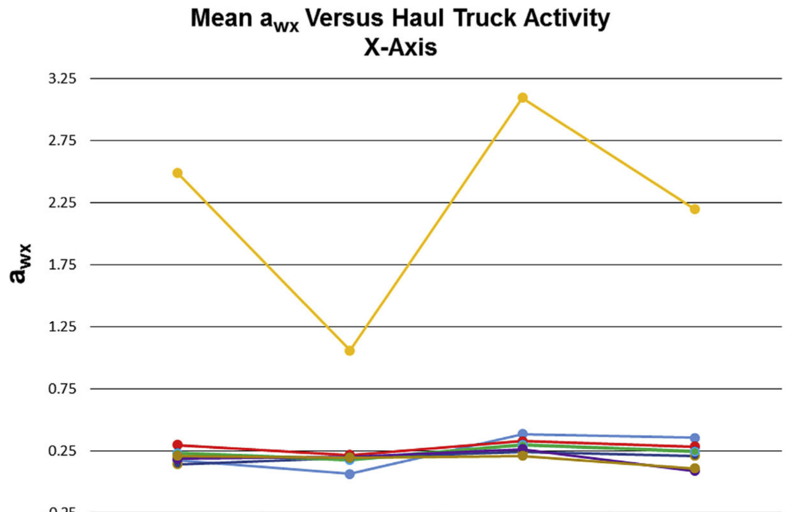


Fig. 1.

Overall mean transmissibility levels comparing root-mean-square acceleration (a_w, m/s^2) and VDV methods in the Z-direction for the seven participating haul truck drivers/ operators.



	Dumping/Travel	Loading/Travel	Travel Empty	Travel Loaded
Subj 1	0.18	0.07	0.39	0.35
Subj 2	0.30	0.22	0.33	0.29
Subj 3	0.15	0.19	0.24	0.21
Subj 4	0.23	0.18	0.30	0.25
Subj 5	2.49	1.06	3.09	2.20
Subj 6	0.19	0.20	0.27	0.09
Subj 7	0.21	0.20	0.21	0.11

Fig. 2.

Levels of whole-body vibration for the X-axis expressed as mean a_w (m/s^2 for haul truck activities of dumping&travel, loading&travel, travel empty, and travel loaded.

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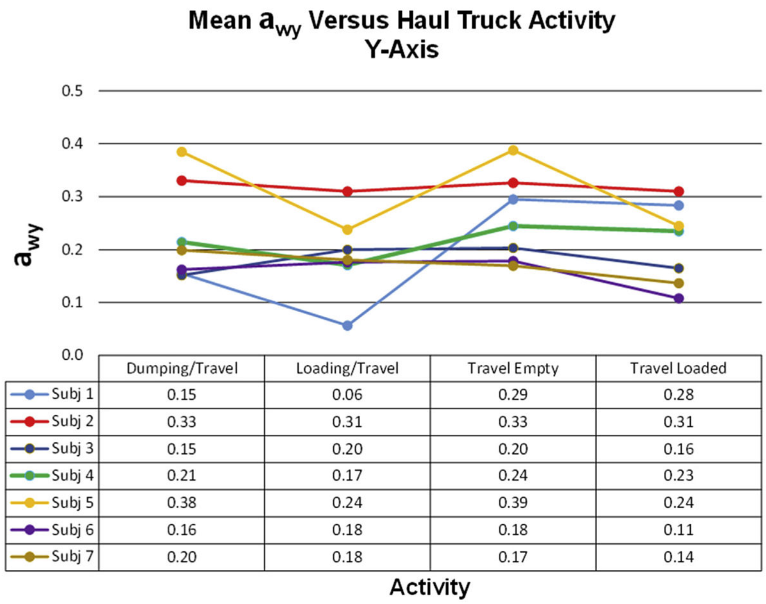
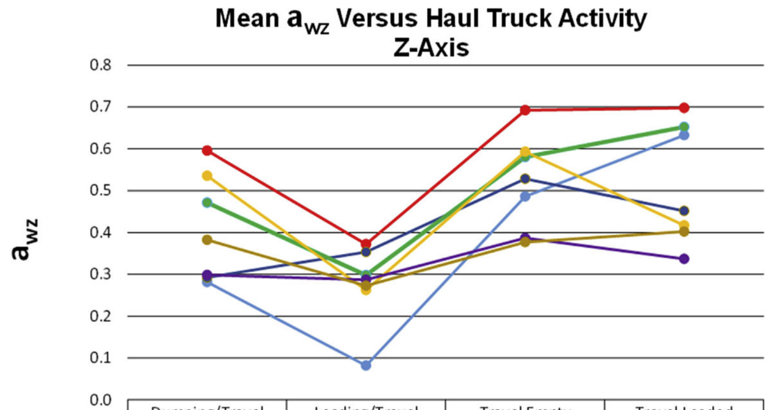


	Dumping/Travel	Loading/Travel	Travel Empty	Travel Loaded
Subj 1	0.15	0.06	0.29	0.28
Subj 2	0.33	0.31	0.33	0.31
Subj 3	0.15	0.20	0.20	0.16
Subj 4	0.21	0.17	0.24	0.23
Subj 5	0.38	0.24	0.39	0.24
Subj 6	0.16	0.18	0.18	0.11
Subj 7	0.20	0.18	0.17	0.14

Fig. 3.

Levels of whole-body vibration for the Y-axis expressed as mean a_w (m/s^2) for haul truck activities of dumping&travel, loading&travel, travel empty, and travel loaded.

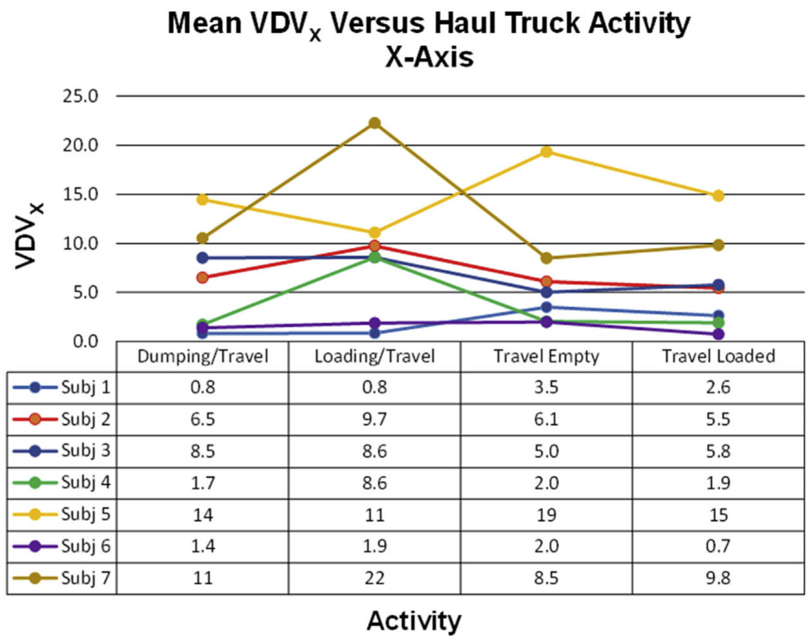


	Dumping/Travel	Loading/Travel	Travel Empty	Travel Loaded
Subj 1	0.28	0.08	0.49	0.63
Subj 2	0.60	0.37	0.69	0.70
Subj 3	0.29	0.35	0.53	0.45
Subj 4	0.47	0.30	0.58	0.65
Subj 5	0.54	0.26	0.59	0.42
Subj 6	0.30	0.29	0.39	0.34
Subj 7	0.38	0.27	0.38	0.40

Activity

Fig. 4.

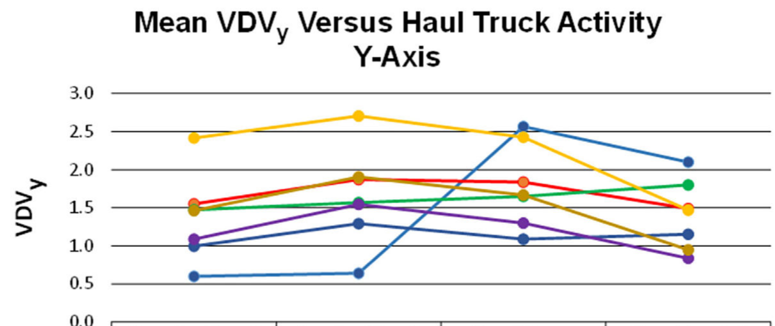
Levels of whole-body vibration for the Z-axis expressed as mean a_w (m/s^2) for haul truck activities of dumping&travel, loading&travel, travel empty, and travel loaded.



	Dumping/Travel	Loading/Travel	Travel Empty	Travel Loaded
Subj 1	0.8	0.8	3.5	2.6
Subj 2	6.5	9.7	6.1	5.5
Subj 3	8.5	8.6	5.0	5.8
Subj 4	1.7	8.6	2.0	1.9
Subj 5	14	11	19	15
Subj 6	1.4	1.9	2.0	0.7
Subj 7	11	22	8.5	9.8

Fig. 5.

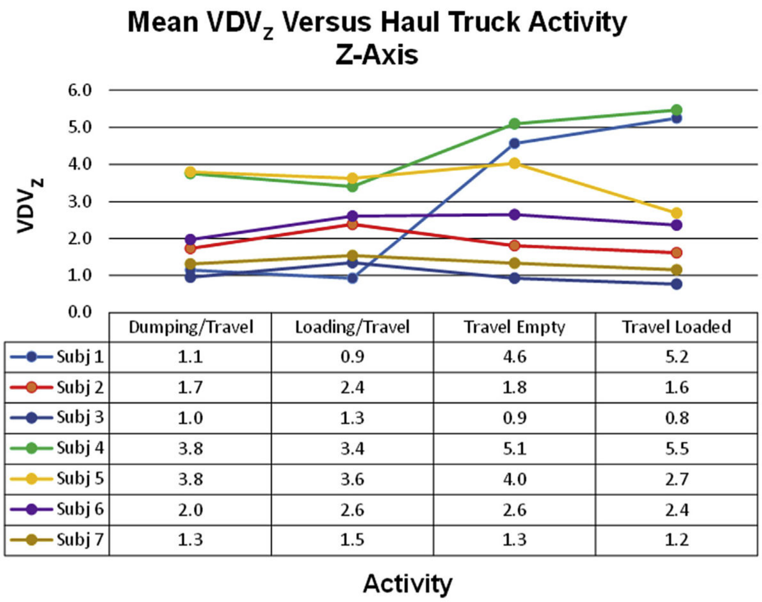
Levels of whole-body vibration for the X-axis expressed as VDV (m/s$^{1.75}$) for haul truck activities of dumping&travel, loading&travel, travel empty, and travel loaded.



	Dumping/Travel	Loading/Travel	Travel Empty	Travel Loaded
Subj 1	0.6	0.6	2.6	2.1
Subj 2	1.6	1.9	1.8	1.5
Subj 3	1.0	1.3	1.1	1.2
Subj 4	1.5	1.6	1.7	1.8
Subj 5	2.4	2.7	2.4	1.5
Subj 6	1.1	1.5	1.3	0.8
Subj 7	1.5	1.9	1.7	0.9

Fig. 6.

Levels of whole-body vibration for the Y-axis expressed as VDV (m/$s^{1.75}$) for haul truck activities of dumping&travel, loading&travel, travel empty, and travel loaded.



	Dumping/Travel	Loading/Travel	Travel Empty	Travel Loaded
Subj 1	1.1	0.9	4.6	5.2
Subj 2	1.7	2.4	1.8	1.6
Subj 3	1.0	1.3	0.9	0.8
Subj 4	3.8	3.4	5.1	5.5
Subj 5	3.8	3.6	4.0	2.7
Subj 6	2.0	2.6	2.6	2.4
Subj 7	1.3	1.5	1.3	1.2

Fig. 7.

Levels of whole-body vibration for the Z-axis expressed as VDV (m/s$^{1.75}$) for haul truck activities of dumping&travel, loading&travel, travel empty, and travel loaded.

Table 1

Description of haul trucks and subjects evaluated for whole-body and hand-arm vibration exposure at four mine/quarry operations.

Commodity	Haul Truck (Make – Model)	Year of Mfr.	Nominal Class (Short Tons)	Operating Hours	Subject #	Age (years)	HT exp. (years)
Limestone	CAT – 777D	1996	100	51,476	1	56	0.25
Sandstone	CAT – 773D	1997	50	18,821	2	57	4
Limestone	CAT – 773D	1997	50	28,208	3	39	3.5
Limestone	CAT – 777D	1997	100	52,676	4	25	0.25
Limestone	CAT – 777D	2005	100	21,403	5	54	22
Copper	Liebherr – T282B	2010	400	4969	6	56	17.5
Copper	Liebherr – T282B	2007	400	21,791	7	52	6.5

HT: haul truck.

Table 2

Whole-body vibration exposures evaluated by weighted, root-mean-square (a_w) accelerations for axes x, y, and z, and vector summations for haul truck drivers at four mines/quarries.[a]

Quarry	Subject #	Day No.	Total sampling time (min)	A(8) a_w X-axis (m/s^2)	A(8) a_w Y-axis (m/s^2)	A(8) a_w Z-axis (m/s^2)	A(8) a_w vector sum (m/s^2)	ISO/ANSI 8-hr shift equivalent HGCZ dominant axis	EUGPG 8-hr shift equivalent HGCZ dominant axis
1	1	1	501	0.44	0.35	*0.61*	1.00	*Within*	*Within*
2	2	1	369	0.35	0.38	*0.52*	0.89	*Within*	*Within*
		2	245	0.34	0.42	*0.49*	0.90	*Within*	Below
3	3	1	356	0.23	0.23	0.35	0.57	Below	Below
		2	355	0.25	0.24	0.37	0.61	Below	Below
1	4	1	478	0.28	0.24	*0.47*	0.70	*Within*	Below
		2	495	0.67	*0.72*	0.65	1.52	*Within*	*Within*
	5	1	468	*0.51*	0.51	0.48	1.12	*Within*	*Within*
1		2	489	***5.64***	0.29	0.34	7.91	***Above***	***Above***
4	6	1	368	0.25	0.20	0.31	0.54	Below	Below
		2	397	0.26	0.21	0.31	0.56	Below	Below
	7	1	358	0.21	0.19	0.28	0.49	Below	Below
		2	319	0.23	0.22	0.35	0.57	Below	Below

[a]Weighted acceleration levels for the total sample times were normalized to full 8-hr shift equivalent levels to compare with the ISO health guidance caution zone (HGCZ) action and limit boundary level conditions of ISO2631-1 and the European Union Directive 2002/44/EC presented in the European Union good practices guide (EUGPG).

Table 3

Whole-body vibration exposures evaluated by vibration dose values (VDV) for axes x, y, and z, and vector summations for haul truck drivers at four mines/quarries.[a]

Quarry	Subject #	Day No.	Total sampling time (min)	A(8) VDV X-axis ($m/s^{1.75}$)	A(8) VDV Y-axis ($m/s^{1.75}$)	A(8) VDV Z-axis ($m/s^{1.75}$)	A(8) VDV Vector sum ($m/s^{1.75}$)	ISO/ANSI 8-hr shift equivalent HGCZ dominant axis	EUGPG 8-hr shift equivalent HGCZ dominant axis
1	1	1	501	6.7	5.4	*16*	20	*Within*	*Within*
2	2	1	369	4.7	4.9	6.4	11	Below	Below
		2	245	4.1	5.0	5.6	11	Below	Below
3	3	1	356	3.2	3.3	4.2	8	Below	Below
		2	355	3.0	2.9	4.0	7.1	Below	Below
1	4	1	478	5.4	4.8	*11*	15	*Within*	*Within*
		2	495	21	***24***	23	50	***Above***	***Above***
	5	1	468	12	12	*13*	27	*Within*	*Within*
		2	489	***81***	4.3	5.4	114	***Above***	***Above***
4	6	1	368	3.6	2.5	3.7	7.2	Below	Below
		2	397	3.4	2.6	3.5	6.9	Below	Below
	7	1	358	2.9	2.4	3.5	6.3	Below	Below
		2	319	3.3	2.8	4.2	7.4	Below	Below

[a]Levels were normalized to full 8-hr shift equivalent levels to compare with the ISO health guidance caution zone (HGCZ) action and limit boundary level conditions of ISO2631-1 and the European Union Directive 2002/44/EC presented in the European Union good practices guide (EUGPG).

Table 4

Hand-arm vibration exposures evaluated by vector summations of the weighted RMS accelerations for haul truck drivers at four mines/quarries. Levels are compared with the ISO health guidance caution zone (HGCZ) action and limit boundary level conditions of ISO2631-1 and the European Union Directive 2002/44/EC presented in the European Union good practices guide (EUGPG).

Quarry	Subject #	Day No.	Total sampling time (min)	Steer a_w Vector Sum (m/s^2)	Shifter a_w Vector Sum (m/s^2)	A(8) Steer a_w Vector Sum (m/s^2)	A(8) Shifter a_w Vector Sum (m/s^2)	ISO 2631-1 8-hr shift equivalent HGCZ dominant axis	EUGPG 8-hr shift equivalent HGCZ dominant axis
1	1	1	237	1.75	1.92	1.64	1.80	Below	Below
2	2	1	369	2.06	1.85	1.93	1.73	Below	Below
		2	245	1.89	1.59	1.77	1.41	Below	Below
3	3	1	356	1.51	1.35	1.41	1.26	Below	Below
		2	355	1.42	1.30	1.33	1.21	Below	Below
1	4	1	88	2.17	0.95	2.03	0.95	Below	Below
		2	269	1.94	1.08	1.81	1.01	Below	Below
	5	1	468	1.89	1.18	1.77	1.10	Below	Below
		2	489	2.14	1.36	2.00	1.28	Below	Below
4	6	1	368	1.14	0.51	1.07	0.47	Below	Below
		2	397	1.24	1.10	1.16	1.03	Below	Below
	7	1	358	1.01	0.52	0.94	0.48	Below	Below
		2	319	1.02	0.55	0.96	0.51	Below	Below