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Original Article

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Assessment of Whole-Body Vibration Exposure in Mining Earth-moving Equipment and Other Vehicles Used in Surface Mining

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Abstract

This study characterized whole-body vibration exposures in a set of vehicles that operate in open-pit mines and compared three different daily exposure parameters based on the ISO 2631-1:1997 and ISO 2631–5:2004 standards. Full-shift, 6 to 12-hour, continuous whole-body vibration measurements were collected from 11 representative types of vehicles in terms of hours of operation and number of vehicles used. For each type of vehicle, the exposure parameters (A(8), VDV(8), and $S_{ed}(8)$) were calculated for each axis (*x*, *y*, and *z*), and in addition, shear or horizontal (∑*xy*) and vector sum (∑*xyx*) whole-body vibration exposure. Findings showed that: (i) substantially higher shear and vector sum whole-body vibration exposures indicated relatively high levels of exposure on the non-predominant axis; (ii) the predominant axis of exposure varied across the different type of vehicles; (iii) there were differences in whole-body vibration exposure parameters regarding the standards-based predictions of potentially adverse health outcomes (the impulsive exposure parameters VDV(8) and $S_{ed}(8)$ were higher and reduced acceptable vehicle operation times by one-half to two-thirds relative to A(8) exposures); and (iv) based on the predominant exposures and the time to reach daily vibration action limits, the operation of most mining vehicles would be limited to less than 8 hours a day. Differences in whole-body vibration exposure parameters impact the prediction of potentially

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adverse health outcomes and may introduce some uncertainty regarding how to best characterize a vehicle operator's actual exposure.

Keywords: daily exposure metrics; daily vibration action limits; health risk predictions; heavy equipment vehicles; mining vehicle operators; open-pit mine; predominant axis

Introduction

Whole-body vibration is present in many industries and it has been recognized as an important health hazard for operators of industrial vehicles and professional drivers (Bovenzi, 2006; Langer *et al.*, 2015). A range of vehicles are used extensively in large scale surface mining operations, exposing drivers regularly to whole-body vibration during their daily activities (Eger *et al.*, 2006; Eger *et al.*, 2008; Smets *et al.*, 2010; Chaudhary *et al.*, 2015). Mining fleets include large capacity haul trucks, graders, hydraulic and electric shovels, scrapers, front loaders, bulldozers, wheel dozers, and water trucks. Because of strict production demands, the mining sector operates year-round with few or no interruptions 24 hours a day, 7 days a week, and almost 365 days a year. Equipment operators consistently work 12-hour shifts with limited breaks and approximately 90% of their shift time is spent driving (Wolfgang and Burgess-Limerick, 2014).

The operators of these vehicles suffer high rates of musculoskeletal disorders (MSDs), which is believed to be related to their exposure to vibration (Bovenzi, 2006). In 2015, in the United States, the incidence rate of MSDs in the mining sector was 12.9 per 10 000 full-time equivalent workers, well above the average rates measured across all occupations (Bureau of Labor Statistics, 2016). Epidemiological studies have reported an association between long-term exposure to whole-body vibration and risk of negative health outcomes such as MSDs, in particular, low back and neck pain (Burdorf and Sorock, 1997; Bovenzi, 2006; Okunribido *et al.*, 2007; Vanerkar *et al.*, 2008).

Many different factors affect an operator's exposure to vibration, including the type of vehicle and its features (type, size, suspension, maintenance, seating design, and tire conditions); the tasks completed by the vehicle type; the nature of the operations performed; and the job organization. Individual characteristics (operator's anthropometry and posture), operating conditions (roads, tasks), and work organization (shifts, work-cycle) may also affect an operator's exposure to whole-body vibration (Blood *et al.*, 2012; Milosavljevic *et al.*, 2012; Thamsuwan *et al.*, 2013; Wolfang and Burgess-Limerick, 2014). Studies conducted in this industry have reported that driving over rough surfaces for extended periods while sitting in a poorly suspended seat can expose drivers to mechanical vibration and multiple impulsive shocks resulting in high occupational exposure to whole-body vibration and health risks (Eger *et al.*, 2008; Smets *et al.*, 2010; Skandfer *et al.*, 2014; Wolfang and Burgess-Limerick, 2014; Chaudhary *et al.*, 2015)

Whole-body vibration exposures can be measured and analyzed according to the ISO standard 2631-1:1997, which uses the axis with the highest frequency-weighted vibration exposure to predict the potential for adverse health outcomes. The ISO 2631-1:1997 standard suggests two methods for evaluating whole-body vibration: (i) the weighted root mean square (r.m.s.) acceleration (A_w in m/s^2), and (ii) the vibration dose value (VDV in m/s$^{1.75}$) when the presence of mechanical shocks can be identified (crest factors >9.0).The lower limits for ISO 2631-1 health caution guidance zone exposure levels, 0.5 m/s^2 for $A_w(8)$, and 9.1 m/s$^{1.75}$ for VDV(8), were used for an 8-hour daily exposure to whole-body vibration. These lower limit health caution guidance zone exposure levels can vary slightly depending on the country's standards and formulas used.

In addition, the ISO 2631–5:2004 standard was introduced for evaluation of exposure to multiple mechanical shocks/peaks. This ISO standard states the guideline on the calculation of cumulative acceleration dose (D_k) and the daily equivalent static compression dose ($S_{ed}(8)$ in MPa). $S_{ed}(8)$ values less than 0.5 MPa are expected to have a low probability of adverse health outcomes after a lifetime of work exposure to shocks (Milosavljevic *et al.*, 2010; Lewis and Johnson, 2012). For consistency, the term "action limits" is used here to refer to these lower limit exposure levels which span the two ISO standards

The purpose of this study is to characterize whole-body vibration exposures in a fleet of surface mine vehicles, mostly earth-moving equipment using ISO 2631-1:1997 and ISO 2631–5:2004 whole-body vibration exposure metrics and to determine the potential for adverse health outcomes by comparing the various exposure metrics.

Methods

Study site

The whole-body vibration exposure measurements were collected from a fleet of vehicles utilized daily in an open-pit surface coal mine located in the Northeastern region of Colombia (Table 1). The mine operates a fleet of approximately 500 pieces of earth-moving mining equipment and vehicles. Daily tasks in the mine include exposing the coal seams by extracting overburden (non-coal containing ground material) with hydraulic and electric shovels; transporting this overburden using 240-ton and 320-ton trucks; extracting and aggregating the coal from these seams with bulldozers, front loaders, and wheel dozers; loading the coal into 190-ton trucks and transporting it; and continuously spraying the road surfaces from water trucks to minimize dust.

Whole-body vibration and GPS measurements

In consultation with the participating company, 11 of the most representative types of vehicles in terms of hours of operation and number of vehicles were selected for the study (Table 2). For each vehicle type, the sampling plan was to measure at least two different vehicles. On each sample day, the equipment and vehicles to be measured were selected based on the mining operations planned for that day. Up to 24 hours of continuous whole-body vibration exposure data were collected per day from each piece of earth-moving equipment and vehicle. Most earth-moving equipment and vehicles typically operated on 12-hour shifts while hydraulic and electric shovels operated on 6-hour shifts. Therefore, one day of measurements consisted of two or three shifts of vehicle operation, which corresponded to two to three operators per measurement period per vehicle. Measurement protocols were approved by the Human Subject Committee at Pontificia Universidad Javeriana and all workers gave their oral consent to participate in the study.

Whole-body vibration exposure data were collected with two systems, each one installed simultaneously in two vehicles. One system used an 8-channel data recorder (Model DA-40; Rion Co., LTD.; Tokyo, Japan) and the other used a 4-channel data recorder (Model DA-20; Rion Co., LTD.; Tokyo, Japan) according to ISO 2631-1 and 2631–5 standards (International Standard Organization, 1997, 2004). Raw, unweighted tri-axial whole-body vibration measurements were collected at 1280 Hz per channel using a seat pad ICP accelerometer (Model 356B41; PCB Piezotronics; Depew, NY). All accelerometer calibrations were verified prior to data collection. Vehicle speed was collected using a GPS logger (Model DG-100; GlobalSat; Chino, CA) simultaneously with the whole-body vibration exposure measurements (Blood *et al.*, 2012). Vehicle speed and location data were recorded once every second. The whole-body vibration and GPS systems were installed during a regularly scheduled break, subsequently checked 10 to 12 hours later, and retrieved 24 hours after installation during a break.

A total of 846 hours of whole-day whole-body vibration exposure data were collected from 38 vehicles, capturing the exposure of 123 mining equipment operators (Table 2). All the vehicles were regularly maintained with a range of one to eight years in service at the time of the measurements. Road conditions varied from uneven off-road surfaces consisting of natural strata in the mines to dirt roads connecting the mines to the production and delivery areas. The speed of the earth-moving equipment and vehicles varied based on the type of vehicle and the tasks performed. Hydraulic and electric shovels were primarily stationary. Dozers, loaders, and tractors performed tasks within limited areas and did not travel very far during their operations. Trucks traveled the longest distances and were stationary during loading and unloading operations. In general, the average speed of the various types of earth-moving equipment and vehicles

Table 1. Type of mining earth-moving equipment and vehicles along with their main tasks

Type of mining equipment	Tasks
Hydraulic and electric shovel	▪ Digging into the overburden material ▪ Loading the material into 240-ton and 320-ton trucks.
Bull dozer and wheel dozer	▪ Extracting and aggregating coal from the coal seams.
Front loader	▪ Loading coal into 190-ton trucks.
Grader	▪ Preparing and maintaining haul roads.
Scraper	▪ Removing the topsoil and transporting it to storage areas.
190 Ton truck	▪ Transporting coal to crushing plants or stockpiling areas.
240-Ton and 320 ton truck	▪ Transporting the overburden to dump sites for final disposal.
Water truck	▪ Watering haul roads to keep road dust down.

Table 2. Measuring conditions for data acquisition and descriptive measures by vehicle

	Mining earth-moving equipment and vehicles			Mining earth-moving equipment and vehicles operators			
Type of mining equipment	Percentage of total operating hours per year[a]	Hours measured	Number of equipment sampled	Number of operators sampled	Average years of experience as operator	Operators' average age in years (*SD*)	Operators' average BMI, kg/m²
Hydraulic shovel	5.5%	57	3	7	9.9	38.3 (5.2)	27.6
Electric shovel	2.4%	40	2	9	19.9	44.8 (11.2)	29.2
Bull dozer	13.1%	99	4	14	11.3	40.8 (9.6)	28.5
Front loader	2.5%	60	2	9	19.3	43.4 (8.9)	29.2
Wheel dozer	7.4%	83	4	15	22.4	49.0 (5.7)	29.1
Grader	5.9%	53	3	9	15	43.9 (9.2)	28.8
Scraper	1.7%	66	5	10	17.6	44.8 (9.0)	28.3
240 Ton truck	20.6%	108	3	14	10.8	38.2 (8.6)	28.3
Water truck	5.6%	79	4	10	12.2	36.6 (10.4)	25.9
320 Ton truck	25.8%	147	6	18	6	32.8 (7.4)	29.7
190 Ton truck	9.5%	54	2	8	9.3	37.8 (12.5)	28.9
Total		846	38	123			

[a]Based on annual mine operation data from 2013.

were based on the terrain conditions and operational requirements.

Whole-body vibration and GPS signal processing

Whole-body vibration and GPS data were transferred to a PC immediately following the 24-hour measurements and then processed using a custom LabVIEW routine (LabVIEW version 2013; National Instruments). The LabVIEW routine synchronized the whole-body vibration and GPS data and appropriately weighted the continuous whole-body vibration signals per ISO 2631-1 (Zuo and Nayfeh, 2003) and ISO 2631–5 standards. Data were parsed into 123 measurements associated with a distinct operator's shift.

Before calculating the daily vibration exposure summary measures, a data program evaluated the raw whole-body vibration data second-by-second for bad or erroneous data. The bad or erroneous data was predominantly the result of signal noise from communication devices in the vehicle cabin, but was sometimes due to temporary strain-induced shorts in the connectors or non-vehicle-related transient shocks saturating and overloading the accelerometers (e.g. the operator entering the vehicle and dropping down on the seat accelerometer when sitting). To identify and eliminate these data, second-by-second and peak, mean and standard deviation values for each one second epoch were calculated. Then, based on the data distribution of these parameters, the outlier values for each parameter could be readily identified. This outlier analysis indicated that any one second epoch that had a peak, mean or standard deviation value above 19.8 m/s^2, 4.6 m/s2, or ± 1.2 m/s^2, respectively, likely represented bad data. This procedure and the error threshold values were validated with a subset of measurements with known errors. Using a computer program with a visual interface, the known bad data and little to no real data would be highlighted when the error thresholds were set at the levels identified in the outlier analysis using these threshold values, less than 0.5% of the data was removed.

Calculating the whole-body vibration exposure and GPS metrics

The whole-body vibration exposure parameters were calculated from the good second-by-second data and normalized to represent 8 hours of vehicle operation (e.g., A(8), VDV(8), and S_{ed}(8)). The ISO 2631-1 parameters A(8) and VDV (8) were calculated for each axis (x, y, and z), for the shear whole-body vibration exposures (Σxy—vector sum of the x and y axes), and for the vector sum whole-body vibration exposures (Σxyz—vector sum of the x, y, and z axes).

The amount of time in hours the various types of mining equipment could be operated before reaching the daily action limit values found in the ISO standards were calculated using the following formulas.

$$\text{Time to A}(8)\text{Action Limit} = 8 \bullet \left(\frac{A(8)}{0.5 m/s^2} \right)^2$$

$$\text{Time to VDV}(8)\text{Action Limit} = 8 \bullet \left(\frac{VDV(8)}{9.1 m/s^{1.75}} \right)^4$$

$$\text{Time to S}_{ed}(8)\text{ Action Limit} = 8 \bullet \left(\frac{S_{ed}(8)}{0.5 MPa} \right)^6$$

The data analysis focused on characterizing the vehicle speeds and whole-body vibration exposures by vehicle type and by the different exposure parameters. Median values across the small number of operators per vehicle represented the central tendency and minimum and maximum values represented the variability.

Results

The data indicated that the predominant axis of exposure varied across vehicles, with associations between exposure and speed, which was both a function of the terrain (on-road or off-road) and the task the mining equipment performed (Table 3). Whole-body vibration metrics within types of mining equipment showed significant variability, particularly for Sed(8) (Figures 1–3). Vehicles with slower speeds (average speed less than 3 kilometers per hour) presented predominant exposures in the *x*-axis. The tasks of these vehicles typically involved fore-aft stop-and-go actions aligned in the *x*-direction. Vehicles with moderate speeds (3 to 12 kilometers per hour) had predominant exposures in the *y*-axis (lateral). These vehicles typically worked on rough, off-road terrain. Vehicles with higher speeds had predominant exposure in the *z*-axis (vertical). These vehicles' tasks typically involved transportation on dirt roads. Exposure metrics for the non-predominant axis were relatively large, often greater than 50% of the predominant axis value. With the exception of the electric shovel, all vector sum A(8), VDV(8), and Sed(8) exposures were above their respective action limits. In addition, the exposures differed by exposure metrics with no single type of mining equipment having the highest values for all of the vector sum metrics (A(8), VDV(8), and Sed(8)).

With the exception of the Hydraulic Shovel, all equipment operation times to reach the daily action limits based on the VDV(8) exposures were less than 8 hours (Table 4). In general, the time the equipment could be operated before reaching the daily action limits was predominantly much shorter for VDV(8) in comparison to the more traditional A(8) metric, which indicates that the exposures in this study population were more likely impulsive in nature.

With the exception of the Electrical Shovel, the equipment operation times to reach daily action limits were relatively similar between VDV(8) and $S_{ed}(8)$, the majority of the equipment operation times to reach daily action limits were under two hours for both parameters.

Discussion

The purpose of this study was to characterize continuous and impulsive whole-body vibration exposures from a representative sample of vehicles used in surface mining of coal. Based on full-shift measurements, we calculated three whole-body vibration exposure parameters, A(8), VDV(8), and $S_{ed}(8)$, as per the ISO 2631-1:1997 and ISO 2631–5:2004 standards. We collected the mining whole-body vibration exposure data during typical work hours and regular operational conditions. The major findings of this study were (i) the relationship between type of vehicle function with the predominant axis of exposure and its speed; (ii) relatively high metrics for the non-predominant axis of exposure; (iii) differences across whole-body vibration exposure metrics in the prediction of adverse health outcomes; and (iv) the high impulsive exposures.

Action levels according to axes of exposure

The large number of mining vehicles with exposures above VDV(8) action limit indicates that the impulsive whole-body vibration exposures were more prevalent and predominant. Based on the ISO 2631-1 standard which recommends that whole-body vibration exposures be assessed by the predominant axis, 5 out of 11 types of mining equipment were above ISO A(8) action limits and 10 out of 11 were above VDV(8) action limits.

When considering the vector sum exposures, exposure prediction was relatively consistent across whole-body vibration parameters. In that, all 11 types of mining equipment were above action limits for vector sum VDV(8) exposures and 10 of 11 vehicles were above action limits for A(8) and Sed(8) exposures. Many of the vector sum-based equipment operation times were less than half the counterpart predominant axis times. This indicates that the exposures were across multiple axes rather than a single axis of exposure.

Unlike previous studies (Kumar, 2004; Eger *et al.*, 2006; Eger *et al.*, 2008; Smets *et al.*, 2010; Burgess-Limerick and Lynas, 2016), our predominant (*z*-axis) A(8) whole-body vibration exposures in the 190-, 240-, 320-Ton trucks were not found to result in exposures above

Table 3. Median (min – max) daily whole-body vibration exposures by parameter and axis arranged in ascending order of vehicle speed

Mining equipment	# of meas	Average speed (km/h)	0.5 m/s²					9.1 m/s$^{1.75}$					0.5 MPa
			A(8)					VDV(8)					Sed(8)
			1.4x	1.4y	z	Σxy	Σxyz	1.4x	1.4y	z	Σxy	Σxyz	Σxyz
Hydraulic shovel	7	1.0	0.4 (0.28–0.55)	0.29 (0.21–0.42)	0.19 (0.16–0.35)	0.51 (0.35–0.70)	0.56 (0.38–0.78)	10.6 (8.7–22.3)	8.8 (7.1–11)	6.4 (4.3–10.3)	12 (9.5–22.6)	12.1 (10.2–22.7)	0.56 (0.39–1.01)
Electric shovel	9	2.0	0.29 (0.25–0.45)	0.26 (0.21–0.30)	0.24 (0.22–0.29)	0.39 (0.33–0.53)	0.47 (0.40–0.61)	7.0 (5.5–26.1)	6.1 (4.6–10.1)	7.4 (5.7–10)	8.0 (6.1–26.1)	10.4 (7.7–26.2)	0.45 (0.23–0.89)
Bull dozer	14	2.4	0.6 (0.47–0.80)	0.56 (0.46–0.87)	0.44 (0.29–0.76)	0.82 (0.67–1.18)	0.91 (0.75–1.4)	13.9 (11.4–17.2)	12.7 (10.5–18.4)	9.9 (6.8–16.0)	15.9 (13.3–21.2)	16.6 (13.5–22.8)	0.63 (0.47–1.02)
Front loader	9	2.9	0.57 (0.42–0.67)	0.57 (0.43–0.71)	0.27 (0.22–0.37)	0.82 (0.60–0.92)	0.87 (0.64–0.98)	13.7 (10.8–15.1)	12.9 (11.7–36)	8 (6.5–10.8)	16.2 (14.1–36.1)	16.4 (14.5–36.1)	0.64 (0.46–3.35)
Wheel dozer	15	3.7	0.60 (0.28–0.79)	0.83 (0.45–1.15)	0.36 (0.18–0.61)	1.02 (0.53–1.39)	1.08 (0.56–1.50)	15.3 (8.4–30.4)	20.5 (12.1–36.2)	9.1 (4.8–18.6)	22.3 (12.7–36.7)	23.6 (12.8–36.8)	0.83 (0.41–2.55)
Grader	9	6.8	0.41 (0.24–0.53)	0.58 (0.33–0.82)	0.48 (0.31–0.57)	0.73 (0.41–0.98)	0.89 (0.52–1.14)	10.9 (8.9–18.4)	14 (9.3–23.9)	10.8 (9.2–13.8)	15.4 (13.0–24.1)	16.6 (13.6–24.3)	0.94 (0.59–1.24)
Scraper	10	12.0	0.51 (0.38–0.94)	0.69 (0.51–0.96)	0.65 (0.51–0.83)	0.86 (0.64–1.21)	1.10 (0.82–1.47)	12.3 (9.0–55.7)	14.8 (11.7–19.8)	14.4 (11.6–16.3)	16.9 (12.6–55.8)	19.3 (14.4–55.8)	0.84 (0.50–1.75)
240 Ton truck	14	12.8	0.34 (0.28–0.48)	0.31 (0.35–0.68)	0.41 (0.35–0.70)	0.48 (0.39–0.66)	0.64 (0.49–0.87)	9.7 (7.5–23.1)	9.6 (5.7–33.7)	10.3 (7.2–16.1)	11.8 (8.7–35.4)	13.9 (9.6–35.5)	0.81 (0.32–3.09)
Water truck	10	14.0	0.36 (0.26–0.48)	0.38 (0.23–0.54)	0.48 (0.23–0.48)	0.52 (0.35–0.72)	0.72 (0.46–0.95)	9.6 (8.2–25.6)	9.9 (6.2–22.5)	11.8 (8.4–13.2)	11.6 (8.9–25.8)	14.5 (10.4–26.2)	0.88 (0.49–3.33)
320 Ton truck	18	16.8	0.40 (0.26–0.51)	0.34 (0.39–0.66)	0.43 (0.33–0.53)	0.55 (0.38–0.78)	0.71 (0.56–0.87)	10.2 (7.4–24.1)	8.7 (7.2–31.4)	10.1 (8.3–13.8)	12.2 (8.7–31.5)	14.9 (11.6–31.6)	0.73 (0.38–2.06)
190 Ton truck	8	20.2	0.38 (0.26–0.50)	0.30 (0.24–0.52)	0.48 (0.27–0.69)	0.50 (0.35–0.68)	0.70 (0.50–0.81)	9.1 (7.0–23.8)	6.6 (5.6–26.4)	11 (9.8–12.2)	10.4 (7.6–29.5)	13 (11.9–29.6)	0.52 (0.32–2.37)

Σxy is the vector sum of the x and y axes and represents the shear-based exposures and Σxyz is the vector sum exposure of all three axes. The shaded cells under each parameter indicate the predominant exposure axis for each vehicle. Recommended action limits are provided above each exposure parameter.

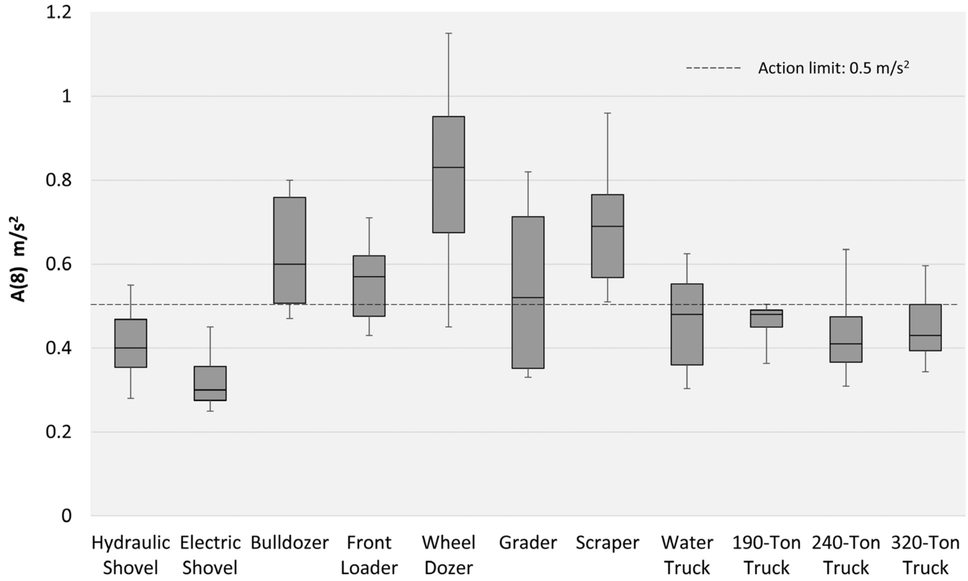

Figure 1. Median (min – max) whole-body vibration exposures by equipment type, the solid lines represent the action limits for predominant axis A(8) exposures.

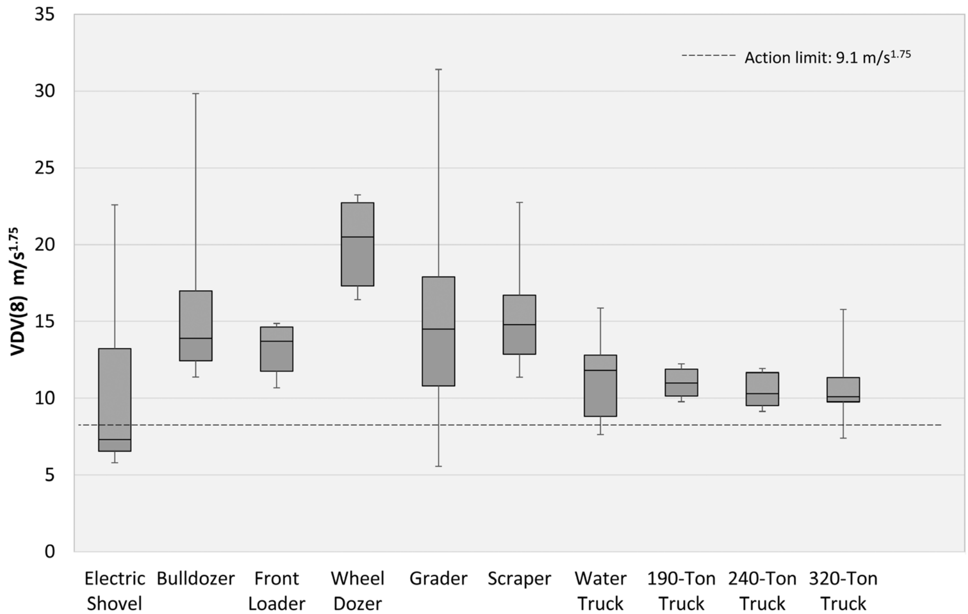

Figure 2. Median (min – max) whole-body vibration exposures by equipment type, the solid lines represent the action limits for predominant axis VDV(8) exposures.

ISO action limits; however, our VDV(8) results appear to be similar to the VDV(8) results of others (Smets *et al.*, 2010; Burgess-Limerick and Lynas, 2016). Despite the differences in the predicted potential for adverse health outcomes with A(8) exposures, our results coincide with Eger *et al.* (2006), in identifying the *z*-axis as the predominant exposure axis for the large haul trucks. The *z*-axis has been previously recognized as the most critical direction for low back pain in drivers (Rehn *et al.*, 2005).

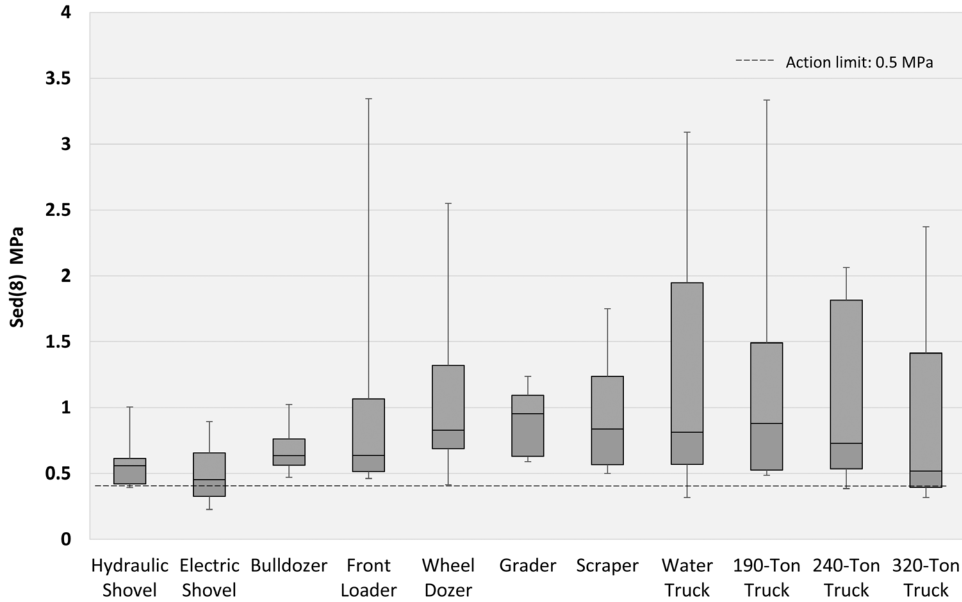

Figure 3. Median (min – max) whole-body vibration exposures by equipment type, the solid lines represent the action limits for Sed (8) exposures (note S_{ed} is a vector sum exposure).

Some of these conflicting results in vibration exposure levels might be explained by potential differences in work tasks and operating conditions under each study, but also may be due to differences in measurement methods. While previous studies measured short intervals of exposure in each task (e.g., 4 minutes) and then averaged the daily exposure over the variety of task (Kumar, 2004; Eger *et al.*, 2006; Eger *et al.*, 2008; Smets *et al.*, 2010); our study captured the entire shift bymeasuring for two or three full shifts in a 24-hour period. Our approach, due to the longer measurement durations, may result in a more accurate estimate of the actual whole-body vibration exposure due to accurately collecting and characterizing the daily duty cycle of both the activity and inactivity of mining equipment (Burgess-Limerick and Lynas, 2016).

The longer duration measurements also created some challenges, mainly in the form of erroneous signal transients and noise from the various sources described in the methods. In removing this noise and interference, we lost less than 0.5% of the original data. With the elimination of the suspected signal transients and noise, some "real" data may have also be eliminated. However, given the long duration of our recordings (8–12 hours), the multiple peaks over that period and the small amount of data removed (less than 0.5%), the impact on the impulsive exposure parameters VDV(8) and Sed (8) should have been minimal. Almost all of the VDV(8) whole-body vibration exposures were above action limits and were in line with whole-body vibration exposures reported in other studies. For example, bulldozers, graders, and front loaders were found to expose operators to similar vibration levels as reported in previous studies (Eger *et al.*, 2006; Eger *et al.*, 2008). For these types of earth-moving equipment, the studies also concur in the identification of the *x*-axis as the predominant axis of exposure.

The relationship between vehicle speed and predominant axis of exposure

Previous studies have reported that the vibration exposure experienced by drivers is determined by several variables including the function of the mining equipment, the terrain, and vehicle speed (Chen *et al.*, 2003; Wolfang and Burgess-Limerick, 2014; Langer *et al.*, 2015). Our results show that the predominant axis of exposure was related to the function of the mining equipment and the terrain on which the equipment operated, both of which contributed to the vehicle's average speed. In the mine, the equipment which was mainly operated off-road with a fair amount of stop-and-go activity, presented the x-axis as the predominant axis of exposure and a lower average vehicle speed. In vehicles primarily operating off-road without much stop-and-go activity, the y-axis was the predominant axis of exposure and had a slightly higher average speed. Finally, vehicles that mainly operated on gravel roads, presented the z-axis as the predominant axis of exposure and had the highest average speeds. The apparent relationship between vehicle function, vehicle speed, and predominant axis of exposure

Table 4. Median (min – max) time in hours equipment could be operated until reaching the daily exposure action limit (action limit values listed above each parameter)

	# of meas	Predominant axis		Σxyz		
		0.5 m/s²	9.1 m/s$^{1.75}$	0.5 m/s²	9.1 m/s$^{1.75}$	0.5 MPa
		A(8)	VDV(8)	A(8)	VDV(8)	Sed(8)
Hydraulic shovel	7	12.7 (6.5–25.1)	4.3 (0.2–9.8)	6.4 (3.3–13.6)	2.6 (0.2–5.1)	4.2 (0.1–34.8)
Electric shovel	9	22.6 (9.8–32)	18.9 (5.6–112.9)	8.9 (5.4–12.4)	4.8 (0.1–15.5)	40.6 (0.2–916.3)
Bull dozer	14	5.6 (3.1–9.1)	1.5 (0.6–3.3)	2.4 (1–3.5)	0.7 (0.2–1.7)	1.9 (0.1–11.7)
Front loader	9	6.2 (4.4–11.3)	1.6 (1.1–4.0)	2.6 (2.1–4.8)	0.8 (0–1.3)	1.9 (0–13)
Wheel dozer	15	2.9 (1.5–10)	0.3 (0–2.6)	1.7 (0.9–6.4)	0.2 (0–2.1)	0.4 (0–24.8)
Grader	9	8.8 (3–18.8)	1.3 (0.2–7.4)	2.9 (1.5–7.5)	0.6 (0.2–2.1)	0.2 (0–3.6)
Scraper	10	4.2 (2.2–7.6)	1.1 (0.4–3.0)	1.7 (0.9–3.0)	0.4 (0–1.3)	0.4 (0–8)
240 Ton truck	14	11.7 (4.2–26.7)	4.9 (0.8–21.1)	4.9 (2.7–8.2)	1.5 (0–6.6)	0.6 (0–124.4)
Water truck	10	8.6 (2.9–7.6)	2.9 (1.8–10.9)	3.9 (2.2–9.5)	1.3 (0.1–4.7)	0.3 (0–9.5)
320 Ton truck	18	10.7 (4.1–16.3)	5.1 (0.2–18.2)	4.0 (2.6–6.3)	1.1 (0.1 – 3.0)	0.8 (0–38.6)
190 Ton truck	8	8.6 (6.1–37.4)	3.8 (2.5–6.1)	4.1 (3.0–7.9)	1.9 (0.1–2.8)	6.5 (0–125.6)

Data grouped by the predominant axis (grey cells from Table 3) and vector sum exposures.

is important in that it may lead to different controls to reduce the whole-body vibration exposures. For the slower moving earth-moving equipment where the *x*- and *y*-axis exposures predominate, there are commercially available seats where the seat pan can be unlocked to allow *x*-axis fore-aft translation and/or y-axis side-to-side translations. For the mining equipment moving at moderate to high speeds where the *z*-axis was the predominant axis of exposure, seats should be selected which effectively attenuate the vertical movement of the driver. There are commercially available semi-active and active suspension seats which have been shown to better attenuate vertical whole-body vibration exposures than the industry-standard air-suspension seats.

Whole-body vibration exposure parameters and differences in adverse health outcomes prediction

An intuitive way to compare these whole-body vibration exposure parameters is the vehicle operation time to reach daily action limits. As shown in the left portion of Table 4, based on the predominant axis whole-body vibration parameters A(8) and VDV(8), there were differences in risk prediction and vehicle operation times to reach action limits. Seven types of mining equipment could be operated for greater than 8 hours a day based on A(8) predominant axis exposures but only one could be operated longer than 8 hours a day based on VDV(8) predominant axis exposures. In general, acceptable vehicle operation times based on VDV(8) exposures were one-third to one-half as long when compared to A(8) exposures, indicating that the impulsive whole-body vibration exposures were more prevalent and predominant.

As shown in the right part of Table 4, the acceptable vehicle operation times based on the vector sum exposure were even more restrictive; vehicle operation times based on vector sum A(8) and VDV(8) exposures were essentially cut in half compared to the predominant axis exposures. The amount of vehicle operation was reduced by 30 to 60% for A(8) and by 20 to 66% for VDV(8), when the vector sum exposure was used instead of the predominant axis exposure. Again, VDV(8) exposures were more restrictive than the A(8) exposures, with the majority of the acceptable vehicle operation times being less than 2 hours for the vector sum VDV(8) exposures. With the exception of the electric shovel, the acceptable vehicle operation times were relatively similar between the vector sum VDV(8) and $S_{ed}(8)$ measures.

The more restrictive vehicle operation times based on vector sum VDV(8) and $S_{ed}(8)$ exposures point to impulsive exposures being more predominant and prevalent. These results are not surprising given that the operating conditions of the mining equipment (rough surfaces, vehicle suspension, driving speed, vehicle load) can increase operators' exposure to peaks and impulsive exposures, and these shock-related exposures can be underestimated using the r.m.s methods to calculate A(8). Previous studies have also reported differences in the prediction of the potential for adverse health outcomes when the A(8) exposure parameters are estimated according to the ISO 2631-1:1997 and compared to $S_{ed}(8)$ in the ISO 2631–5:2004 standards (Paddan and Griffin, 2002). It has been suggested that, due to not accurately catching the peak impulsive exposures, the A(8) exposures in the ISO 2631-1:1997 standard tend to underestimate risks from exposure to whole-body vibration. Due to these parameter-based discrepancies, questions have emerged regarding the suitable method for quantification of the permitted daily exposure duration (Smets *et al.*, 2010; Zhao and Schindler, 2014).

Using a biomechanical basis for whole-body vibration exposures

There is some uncertainty as to how to best represent a mining equipment operator's whole-body vibration exposures since there are three possible axes for the exposure, fore-aft translations (*x*-axis), side-to-side translations (*y*-axis), and up-and-down movements (*z*-axis). As shown in Table 3, not all of the mining equipment showed large it differences among axes making difficult to use the ISO 2631-1:1997 for evaluating the potential for adverse health outcomes based on the predominant axis. As reported by Smets (2010), the predominant axis approach can be acceptable when there are considerable differences between axes. However, under conditions of similar magnitudes, vibration exposure calculated based on the predominant axis approach may result in an underestimation of the adverse health outcome (Smets *et al.*, 2010).

Instead of just considering the predominant direction of the whole-body vibration exposures it may be meaningful to also think of the exposures, in terms of biomechanical pathways. The up-and-down *z*-axis exposures can represent the risks associated with the compressive forces to the spine, the vector sum of the *x*- and *y*-axes exposures can represent risks associated with shear forces, and the vector sum of all axes can represent the cumulative risks of both exposure pathways. In the slow to intermediate speed vehicles (0 to 12 km/h), the shear whole-body vibration exposures were almost twice as high as the *z*-axis compressive exposures indicating shear was the predominant exposure. In contrast, in the vehicles that travelled above 12 km/h, the shear and compressive exposures were equivalent, indicating both exposures may be important and the vector sum measure may be the best parameter for interpreting the health effects of the exposures of the fastest travelling mining equipment. However, one challenge is that the European Union (2002) has developed daily action and exposure limits for acceptable vibration exposures based on the use of predominant axis whole-body vibration exposures, whereas the ISO 2631-1 suggests the use of vector sum exposures when there is more than one predominant whole-body vibration exposure axis (Thamsuwan *et al.*, 2013). Finally, a limitation of the current ISO 2631-1 standard is that no guidance is given to determine when a whole-body vibration exposure should be based on a predominant axis versus using a vector sum approach when there is more than one predominant axis.

Strengths and limitations

This study's results should be interpreted in light of its strengths and limitations. First, as the trucks were not randomly selected from the mining fleet, potential sampling biases may have affected our findings. However, multiple measurements were collected from each type of surface mining equipment to hopefully reduce the potential biases. Secondly, as whole-body vibration exposure was measured during a 12-hour shift without collecting the duration and distribution of specific tasks, we were unable to determine the contribution of a particular task (i.e. loading, unloading, driving, dumping, etc.). However, the full-shift whole-body vibration characterization provides representative daily exposures with a realistic task distribution and duty cycle. In addition, as the full-shift exposure measurements may have captured transient events (i.e. motion artifact during driver's ingress and egress of the vehicle), such transient shocks not associated with driving were identified and eliminated based on the peak, mean, and standard deviation. The removed transient acceleration accounted for approximately 0.5% of total raw acceleration data. Because the transient events were checked based on a statistical distribution but not actual non-driving activity, some driving-related transient events may also have been removed. Nonetheless, as the proportion of the excluded data was small (less than 0.5%), the results still indicated high impulsive exposures existed. Through testing, we know our error correction methods resulted in just a slight underestimation of *z*-axis VDV(8) and Sed(8) exposures. A third limitation would be the observed range of road conditions during the daily tasks which may affect vibration exposure. We identified significant impulsive peaks in our data which have previously been associated with uneven road surfaces in other studies. Therefore, the role of road surfaces should be considered in future studies. Finally, driver posture was not measured or recorded and thus it was not possible to evaluate how posture may have mediated or contributed to an operator's exposure to whole-body vibration.

Despite the limitations mentioned above, so far, this is one of the more comprehensive studies in the mining sector in terms of exposure data collected and type of surface mining equipment. The 846 hours of whole-body vibration data covered 123 operators, exposure over a full-shift, a variety of vehicles and mining equipment speed under typical operating conditions of an open-pit coal mine. Therefore, our whole-body vibration exposure data may reduce the uncertainty of the true daily exposure and reflect the actual risk of adverse health consequences to the surface equipment operators in the mine we measured and likely represent the exposures of surface mining equipment operators in general.

Conclusion

The findings from this study indicated surface mining equipment operators are exposed to high levels of both continuous and impulsive whole-body vibration. Comparisons between whole-body vibration exposure parameters calculated based on the ISO 2631-1:1997 and ISO 2631–5:2004 standards indicate substantial differences in the prediction of the risk of adverse health effects between average r.m.s exposures (A(8)) and cumulative impulsive exposures (VDV(8) and $S_{ed}(8)$). Often there was more than one predominant axis of exposure and the health risk predictions between predominant axis exposures differed dramatically when compared to the vector sum exposures. The detailed results from this study may be used to explore the effectiveness of potential engineering controls in reducing continuous and impulsive whole-body vibration as well as monitoring their effect on a particular axis or axes of exposure. In addition, differences in whole-body vibration exposure parameters impact the prediction of health effects and may introduce some uncertainty regarding how to best represent surface mining equipment operators' actual exposure. Future research should longitudinally evaluate vehicle whole-body vibration exposures to determine whether any of the whole-body vibration exposure measures are better suited to model and predict adverse health outcomes.

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Declaration

The authors declare no conflict of interest relating to the material presented in this manuscript.

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