Northeastern University
Bouvé College of Health Sciences

WHOLE BODY VIBRATION EXPOSURE AND INJURY PREVENTION OF HEAVY EQUIPMENT OPERATORS IN OPEN PIT COAL MINES

FINAL REPORT

1.0 Cover Page

Grant Title: Whole Body Vibration Exposure and Injury Prevention of Heavy Equipment Operators in Open Pit Coal Mines

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Principle Investigator: Jack Tigh Dennerlein, Ph.D.

Contact Information: 360 Huntington Avenue, 301-RB
Boston, MA 02115
+1 617 373 5428
j.dennerlein@northeastern.edu

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List of Acronyms

A(8)	Daily (8 hour) Time-Weighted Average Vibration
BMI	Body Mass Index
Dk(8)	Daily (8-hour) Acceleration Dose for each axis
EU	European Union
HEV	Heavy Equipment Vehicles
ISO	International Organization for Standardization
JMP	Statistical Software
LabVIEW	Laboratory Virtual Instrument Engineering Workbench – Programming Software
LBP	Low Back Pain
MSD	Musculoskeletal Disorders
***Sed*(8)**	Daily (8-hour) Static Compressive Dose: compression dose-oriented exposure
VDV(8)	Daily (8-hour) Vibration Dose Value: a measure of *cumulative* mechanical shock
WBV	Whole Body Vibration

2.0 Executive Summary:

Miners who operate heavy equipment vehicles (HEV) in open pit mines have a high prevalence of musculoskeletal disorders (MSD), which may be related to their experiencing whole body vibration (WBV), especially shock impulse vibration. The overall objective of this study was to characterize whole body vibration exposures using newer metrics of whole body vibration that capture the more impulsive exposures expected for these operators, relate these exposures to the health outcomes of the workers, and then test feasible approaches for reducing exposure to whole body vibration among heavy equipment vehicle operators in mines. We accomplished this with three aims.

First, we collected over 846 hours of whole-day whole body vibration exposure data from 38 vehicles capturing the exposure of 123 heavy equipment vehicles operators in a large, coal producing, open-pit surface mine. Full-shift, 6 to 12-hour, continuous whole body vibration measurements were collected from 11 of the most representative types of the mine's fleet vehicles in terms of hours of operation and number of vehicles. Findings showed that mining heavy equipment vehicles operators are exposed to high levels of both continuous and impulsive whole body vibration.

- The impulsive exposure parameters daily Vibration Dose Value (*VDV(8)*) and daily static compressive dose (*Sed*(8)) were above action limits and reduced heavy equipment vehicles operation times (time exposed before reaching the action limit) by one-half to two-thirds relative to daily time-weighted average vibration *A(8)* exposures.
- Exposures were similar in multiple axes, not just in the traditional vertical direction.
- The direction (axis) with the highest amplitude of vibration exposure varied across the different heavy equipment vehicles, which is most likely related to the different tasks the vehicles complete within the mine. Dozers, for example, act like brooms going back and forth pushing aggregate into piles (fore and aft). Shovels then transfer these piles (rotation of the shovels create lateral movements) into the trucks that then travel some distance over temporary dirt roads to move the aggregate to different locations in the mine (traditional vertical directions).

Second, we tested the association between estimated whole body vibration exposure and absenteeism related to back pain (as defined by the mine's medical staff in accordance with the definition of dorsalgia (back pain) from the international classification of disease (ICD-9) of the World Health Organization) in 2,302 operators of mining heavy equipment vehicles. Findings showed that whole body vibration was positively and significantly associated to back-pain absenteeism. Moreover,

- We found statistically significant associations between back pain absenteeism and all three types of the estimated exposure metrics for accelerations in all three axes within our adjusted models.
- A small change in exposure relative to the full range of exposures in the cohort can significantly change the risk of absenteeism. Therefore, from a theoretical point of view opportunities to reduce risk appear to exist; however, the practicalities of doing so remain unclear and need to be explored further.

Third, we tested current seat suspension technology and their effects in reducing exposures to whole body vibration. We tested a simple technology (an air-filled bladder seat cushion) in vehicles operating in the mine and two more sophisticated technologies (a passive air suspension seat with passive mechanical lateral and fore/aft suspension and an electromagnetic active suspension seat with active linear motors to reduce vertical axis vibrations and passive mechanical elements to reduce fore/aft vibrations), in a laboratory using the field measurements from three different vehicle types to establish the loading protocol. Findings showed that the engineered seat designs reduced the vibration exposure; however, the reduction was relatively small. Specifically,

- Air-filled bladder seat cushion demonstrated almost no reduction in exposures in the vehicles operating in the mine.
- A passive air suspension seat with passive mechanical lateral and fore/aft suspension showed limited whole body vibration attenuation in the laboratory.
- An electromagnetic active suspension seat with passive mechanical fore/aft suspension significantly attenuated the vertical whole body vibration component in the laboratory.

The impact of this research includes new knowledge about (1) whole body vibration exposures and (2) the associations between these exposures and work-related absenteeism in a cohort of surface mine workers. In addition, the research demonstrates that innovative engineering technology can reduce vibrations in the vertically direction; however, currently available technology has difficulties in reducing accelerations in the horizontal plane of the seat, specifically vibrations in the fore/aft and lateral directions. Other controls, both engineering and administrative, may be necessary to reduce exposures to whole body vibration, and hence prevent low back pain related absences at work.

3.0 Problem Statement and Objective:

3.1 Problem Statement:

Focus Area:

Health: Ergonomic-Related Conditions and Surveillance of Health Conditions in Miners.

Miners who are operators of heavy equipment vehicles (heavy equipment vehicles) in open pit mines have a high prevalence of musculoskeletal disorders. While sedentary for most of the day, these miners are exposed to whole body vibration, especially shock impulse vibration, due to the operation of heavy equipment vehicles during mining operations. Whole-body vibration (whole body vibration) is one of the leading risk factors for the development of low back musculoskeletal disorders and other general health outcomes among professional vehicle operators. [1, 2] Epidemiological and physiological studies demonstrate consistent associations between occupational back pain and exposure to whole body vibration from professional driving [3] with the risk of injury increasing as whole body vibration duration increases.[1] In addition, it has been proposed that the presence of obesity increases the risk of injury related to vibration. [4-6] Thirty-three percent of the heavy equipment vehicles operators in the study mine are obese, increasing their risk for whole body vibration injury. This factor may be related to the sedentary aspects of their job. With a dedicated and ageing working population, operators of such large mines face challenges in reducing the cost and burden of the injuries and illnesses that exist within their work environments. This study used a comprehensive, large scale, multi-year database to determine specific exposure dose associations between whole body vibrations and workers' musculoskeletal disorders as well as identify specific approaches, including both engineering and administrative controls, to assist mine operators in improving the health and safety of the heavy equipment vehicles operator.

3.2 Objectives

The broad objective for this research was to characterize whole body vibration exposures to develop feasible and effective approaches for reducing exposure to whole body vibration among heavy equipment vehicle operators in mines.

Specific Aim 1: To characterize workers' peak and impulsive shock whole body vibration exposure during the operation of heavy equipment vehicles in the mine's heavy equipment vehicles fleet. In a cross-sectional and representative sample of heavy equipment vehicles, we characterized whole body vibration exposure using daily time-weighted average vibration exposure *A(8)*; the daily Vibration Dose Value (*VDV(8)*), which is a time-weighted measure more sensitive to cumulative and impulsive vibration exposures; and, the daily static compressive dose *Sed*(8), a raw continuous measure designed to better characterize and capture impulsive exposures, which is an ISO 2631-5 whole body vibration parameter derived from the acceleration dose (Dk(8)) of each axis.

Specific Aim 2: Utilizing four years of employee occupational health records (2010-2013), heavy equipment vehicles operating logs, and the new set of whole body vibration measurements from Aim 1 to:

- Estimate each employee's cumulative annual whole body vibration exposure utilizing three different metrics for whole body vibration exposure: A(8), VDV(8) and Sed(8).

- Use these whole body vibration exposure metrics to assess the associations between whole body vibration and musculoskeletal disorders related absenteeism recorded in the database, test the hypothesis that exposure to whole body vibration in these heavy equipment vehicles operators is associated with their days away from work due to musculoskeletal disorder diagnoses.

Specific Aim 3: To complete a pilot exploratory study to examine the effects of newly developed engineering controls, including two different seats' suspension systems (a passive air suspension seat with passive mechanical lateral and fore/aft suspension and an electromagnetic active suspension seat with passive mechanical fore/aft suspension), and an air bladder seat cushion (passive air-filled), have on reducing whole body vibration exposures in the laboratory and the field. For the two seat suspension systems, this pilot study was conducted using a six degree of freedom vibrating platform playing recorded vibrations from Aim 1. The air bladder was tested in both the laboratory and the field in the mine.

4.0 Research Approach:

The research approach for this study included detailed exposure assessment, epidemiological modeling using a large employee cohort (~3,200 employees), and evaluation of potential engineering that can reduce whole body vibration exposures within the mining sector. In addition to traditional time-weighted average exposures, we examined the specific cumulative and peak exposures associated with dynamic loads (impulsive shocks) associated with haul trucks receiving loads from a hydraulic shovel.

4.1 Background

In 2015, the incident rate of musculoskeletal disorders in the mining sector in the US was 0.129 events per 100 full-time workers. Epidemiological and physiological studies have demonstrated consistent associations between occupational-related back pain and exposure to whole body vibration (whole body vibration) from professional driving.[5, 7] While many musculoskeletal disorders risk factors exist in the mining industry, whole body vibration (whole body vibration) experienced by operators of heavy equipment vehicles is of main concern because whole body vibration has been associated with an increased risk for the development of musculoskeletal disorders. [8, 9] Whole body vibration exposure has been related to back complaints among vehicle operators. [7, 10, 11] Moreover, a high incidence of long term absenteeism due to intervertebral disc disorders, similar to the disorders observed in our partner mine's operators, has been reported in operators exposed to whole body vibration. [12] Finally, a higher risk of developing back disorders in those exposed compared to those not exposed to driving heavy equipment vehicles has been reported. [1, 13, 14]

New approaches and additional metrics to whole body vibration exposure that capture cumulative whole body vibration exposure and impulsive shock impacts, which are very typical in the open pit mining industry and the operation of heavy equipment vehicles, do exist. The typical approach to quantify whole body vibration exposure has been simply to calculate a time weighted average of the amplitude of the vibration signal and normalize the exposure to an eight hour day (*A(8)*). With the *A(8)* measure, there is no information about the exposure to cumulative vibration and shock impulses. The newer metrics include the Vibration Dose Value (*VDV*), which is more sensitive to impulsive vibration exposures and reflects the total, instead of the average, vibration; and the Static compressive dose (*Sed*), which was an ISO 2631-521 whole body vibration parameter derived from the acceleration dose (Dk). Unlike the *VDV*, which is a cumulative, time-weight average exposure measure, the *Sed* was designed to measure impulsive exposures from the raw, continuously collected vibration data. We expect the operators of the heavy equipment vehicles to have high amounts of shock impulse types of whole body vibration exposures (Figure 1). These newer metrics are better predictors of low back pain and risk of injury. [15, 16]

Figure 1. Typical heavy equipment vehicles (HEV), a shovel and load truck during a shock impulse loading scenario, not well captured with traditional whole body vibration exposure metrics

Risk factors for musculoskeletal disorders are often multifactorial in nature and result from a combination of physical, organizational/psychosocial, and individual factors, many of which are present for the heavy equipment vehicles operators in open pit coal mines. [3, 17, 18] As a result, ecological approaches such as multiple component interventions that address several of these factors together are often the most effective in reducing injury and absenteeism rates. [19, 20] Organizational factors that often are associated with improved or better outcomes include people-oriented culture, safety and ergonomic practices, and safety leadership.[21, 22]

Specific individual factors that influence musculoskeletal disorders outcomes include age, time in job, and obesity, which are all of concern for this coal mine work force that has an increasing median age of 38 years in 2007 to 39 in 2009 with a proportion 35% of obese (BMI>30) workers in 2009. Several conceptual models exist that attempt to describe the complex relationships between obesity, occupational hazards, and work-related health outcomes.[4, 23, 24] One model suggests that obesity interacts with the injury mechanism increasing the risk of injury. There is evidence that obese workers are at a higher risk for work-related musculoskeletal disorders and injury, especially those associated with exposure to vibration.[4]

Study Site

Due to the dimensions of the mining operation, large-scale surface mining in the United States and around the world operates similar type of large capacity heavy equipment and earthmoving vehicles. In general, mining equipment fleets comprise mainly haul trucks, shovels, bulldozers, graders and drillers from the United States and Australia equipment manufactures. Worldwide, large-scale surface mining also utilizes state-of-the-art technology such as global positioning satellites (GPS), productivity monitoring systems, and computerized dispatching technologies improve operating efficiency.[25]

The Cerrejón mine is an open-pit coal mine located in the northeastern region of Colombia. It has several active pits that produce 33 million tons of coal per year. The mining production process involves the exploration, extraction, transportation, ship loading, and export of coal. The method of mining is top slicing with deep hole drilling and blasting. Hydraulic and electric shovels load the overburden for final disposition into 240-ton and 320-ton trucks until the coal seams are exposed. Once the coal seams are visible, the coal is extracted and piled by bulldozers, front loaders and wheel dozers. Then, coal is loaded into 190-ton capacity trucks and carry out to the crushing plants before being loaded into a train that transports the coal to the mine's port where it is then loaded on ships for export. The mining operation involves a fleet of approximately 500 earthmoving and mining equipment including loaders, track-type tractors, 190-ton trucks, 240-ton trucks, 320-ton trucks, wheel tractor scrapers, graders, electric and hydraulic shovels, water tanker trucks, and wheel dozers.

The Heavy Equipment Vehicle (heavy equipment vehicles) operators in the Cerrejón mine report a high prevalence and incidence of absenteeism due to specific back musculoskeletal disorders (musculoskeletal disorders). According to the mine report, in 2007, the incidence of absenteeism among the heavy equipment vehicles operators due to cervical disc disorders (M50), back pain (M54) and other intervertebral disc disorders (M51) was 9.6 cases per 100 Full Time Equivalents (FTEs). This is quite high compared to administrative workers at Cerrejón who have an incident rate of 0.74 cases per 100 FTEs. In the US for coal operators, the rate of nonfatal lost-time injuries per 100 full-time equivalent employees at surface work locations in 2015 was 1.3 (full-time equivalent (FTE) employees which equal 2,000 hours worked per year)[26].

Our previous research:

<u>Estimating *A(8)* whole body vibration exposure in heavy equipment vehicles:</u> [27] During previous studies with this mine, we collected measurements of whole body vibration on some of their heavy equipment vehicles fleet using an off-the-shelf measurement system that provided only the time weighted whole body vibration amplitude normalized to an eight hour day, *A(8)*, which lacks cumulative shock [*VDV(8)*] information and the new ISO 2631-5 metrics on raw, continuous, and shock impulse vibration exposures [*Sed*(8)]. As part of their work flow, operators were required to drive different types of heavy equipment vehicles. Exposure data on the number of hours of operation per operator in the years 2007, 2008, and 2009, and type of vehicle were tracked by the Production Department at the mine. From these measurements, individual axis and vector sum median whole body vibration exposures were calculated for each heavy equipment vehicles. Each operator's driving log was used to calculate the yearly and three-year time weighted average daily vibration exposures [*A(8)*]. Based on the 2002 European Vibration Directive, the only currently enforced vibration standard, the median yearly equivalent daily (calculated as the median of the average daily exposure in one year) vibration exposure levels for most of the operators were just below the level that requires employers to control whole body vibration (whole body vibration) risk (EU Directive recommended exposure level: 0.5 m/s^2). Most drivers clustered at levels just below the limit. However, when we examined and calculated the *A(8)* using the three years' worth of driving logs, the exposure for 119 (7.2%) operators was above this action limit. Based on employees' health and operational records, the characteristics of the vehicles, the type of roads, and our past experiences, we anticipated that the *VDV* (exposure limit 9.1 $m/s^{1.75}$) and the *Sed* (exposure limit 0.5 MPa) metrics would be above the respective limits.

Evaluating engineering controls to reduce whole body vibration exposure in long haul trucking: A panel of 16 drivers drove a semi-truck twice, once with a new electromagnetic active vibration cancelation (EAVC) seat suspension technology (an earlier version of the one tested in this study that did not have passive lateral suspension) and once with a new air-ride seat, a passive suspension system, over a standardized 60km route that included four common road types encountered by semi-truck drivers. An eight-channel data recorder (model DA-40; Rion Co., LTD.; Japan) collected whole body vibration exposures per ISO 2631-1 and ISO 2631-5 standards. Raw, unweighted tri-axial whole body vibration measurements were collected at 1,280 Hz using a tri-axial seat pad ICP accelerometer mounted on the driver's seat and from an identical, magnet mounted tri-axial accelerometer on the truck floor.

The new EAVC seat technology transmitted 36% to 63% of the floor-measured vibration to the seat of the operator, whereas the air-ride seat transmitted 94% to 115% showing that, in some cases, the seat amplified the vibration instead of absorbing it. Whole body vibration exposures were dependent on road type. For the traditional air-ride seats, the driving times ranged between 2.6 and 11.3 hours per day, most being shorter than the typical 8-hour working day. For the EVAC seat, the acceptable driving hours ranged from 4.7 to 20.7 hours depending on the road conditions, nearly a two-fold difference with many being greater than the typical 8-hour work day (truckers can drive up to 11 hours per day).

Evaluating engineering controls to reduce whole body vibration exposure in bus drivers: [28] A newly developed integrated air-bladder seat cushion was recently evaluated in a bus driver's seat and the whole body vibration attenuation performance of the integrated air-bladder seat cushion was compared to stock foam supplied with the bus seat. Sixteen bus drivers drove a 12.1 meters-long low-floor coach bus over a 60km standardized route two times, and z-axis average weighted whole body vibration exposures were measured and compared between the two different seat cushion treatments, the stock foam and the integrated air-bladder cushion. When comparing seat cushion treatments over the whole route, the integrated air-bladder cushion reduced whole body vibration exposures by 24 ± 2% ($p < 0.0001$) relative to the seat's stock foam. When the buses traveled at low speeds over 4 meters-wide by 0.10 meters-high speed bumps, there were no differences in seat cushion performance; however, when traveling at moderate-to-high speeds on city streets and freeways, the whole body vibration attenuation performance of the integrated air-bladder was significantly better.

4.2 Research Strategy

Our goal was to reduce worker disability and improve the health of mine workers through testing for, and describing associations between, specific work-related exposures to whole body vibration (whole body vibration) and workers' musculoskeletal disorders and their related absenteeism. *Our central hypothesis was that exposure to whole body vibration creates a physical strain on the body that then leads to detrimental health effects for miners*.

Our approach was to examine whole body vibration exposure associated with impulse shock of acquiring and dumping loads with open-pit mine vehicles, such as the hydraulic shovels and load trucks. Using newer exposure metrics, we documented cumulative and peak impulsive whole body vibration exposures and tested for associations between absenteeism and other health outcomes within the employee database.

4.2.1 Aim 1: Research Tasks: Measuring whole body vibration including shock impulse

We used multiple whole body vibration measurement systems to measure and analyze tri-axial whole body vibration exposures per ISO 2631-1 and 2632-5 standards for the 11 different types of heavy equipment vehicles operated in the mine. From each vehicle type we collected full-shift measurements from at least three different operators. The 11 different heavy equipment vehicles include a loader, track-type tractor, 190-ton truck, 240-ton truck, 320-ton truck, wheel tractor scraper, motor grader, electric shovel, water tanker truck, hydraulic shovel, and wheel dozer. The vehicles and drivers measured were a convenience sample.

To record the whole body vibration data, we used an 8-channel data recorder (Model DA-40; Rion Co., LTD.; Japan) per ISO 2631-1 and 2631-5 standards.[21,46] Raw, unweighted tri-axial whole body vibration measurements were collected at 1,280 Hz per channel using a seat pad ICP accelerometer (Model 356B40; PCB Piezotronics; Depew, NY) mounted on the driver's seat and simultaneous tri-axial measurements were collected with an identical accelerometer magnetically mounted to the truck floor under the driver's seat. All accelerometer calibrations were verified prior to data collection. We simultaneously collected GPS data to analyze the whole body vibration exposure data by vehicle speed and location in the mine, similar to previous studies. [47]

Data processing. The vibration data was processed and analyzed using an interactive LabVIEW program to calculate standard exposure parameters. The ISO 2631-1 whole body vibration parameters calculated include the root mean square average weighted vibration (*Aw*); the Vibration Dose Value (*VDV*), which is more sensitive to impulsive vibration exposures and reflects the total cumulative, as opposed to average, vibration; and the Static compressive dose (*Sed*), which was an ISO 2631-5 [2004] whole body vibration parameter derived from the acceleration dose (Dk). As outlined in the ISO 2631-1 and ISO 2631-5 whole body vibration standards, all vibration exposures (*Aw*, *VDV*, *Sed*) were normalized to reflect 8 hours of driving (e.g. *Aw*(8), *VDV(8), Sed*(8)) and the vector sum exposures for each parameter were derived using the following equation: vector sum = $((a * Exp(8)_x)^n + (b * Exp(8)_y)^n + (c * Exp(8)_z)^n)^{1/n}$; where *x, y*, and *z* represent the three axes in 3-dimensional space, with *z* being vertical, *x* being fore/aft, and *y* being lateral directions (Figure 2) and *Exp* being the whole body vibration exposure.

Figure 2. Coordinate system used to measure whole body vibration, as defined by ISO 2631–1:1997

We also calculated the Seat Effective Amplitude Transmissibility (*SEAT*) values for the *A(8)*, *VDV(8)*, and *Sed*(8) vibration exposures metrics.[29] The *SEAT* values indicate the percentage of the floor-measured vibration transmitted to the seat of the operator.

4.2.2 Aim 2: cumulative exposures to whole body vibration and association between whole body vibration exposure and absenteeism

For Aim 2, we tested the associations between back pain absenteeism and an estimate of exposure for a cohort of drivers of heavy equipment vehicles over a four year period. We *estimated the vibration exposure from two sets of data, 1) driving logs for the four year periods defining the specific vehicle types and 2) summary metrics from whole body vibrations made in the vehicle types from a non-concurrent time period (Aim 1).*

Study population. The study population were drivers of heavy equipment vehicles (heavy equipment vehicles) of a large open-pit mine in Cerrejón, Colombia. The database included workers with information on both working hours in heavy equipment vehicles and absenteeism related to back-pain between the years 2010 and 2013. We excluded 121 workers who reported absenteeism related to back-pain during year 2010 to start with a population free of recent absenteeism. In addition, 100 women were excluded because there may be important culturally-determined physical work differences between sexes inside and outside the workplace for which we could not readily adjust. Lastly, we excluded 212 workers with no information on sex or BMI (Figure 3).

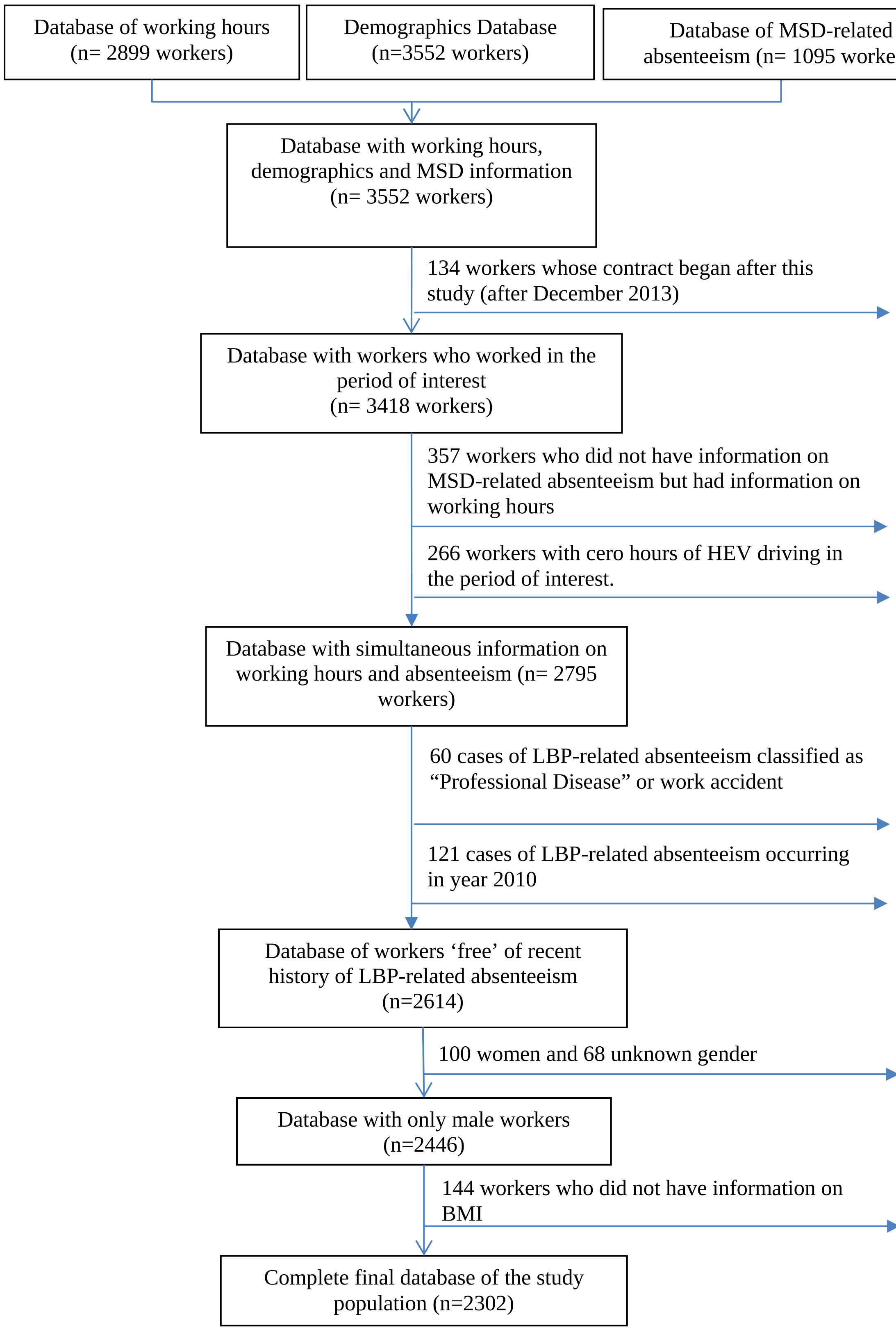

Figure 3. Inclusion and Exclusion Criteria for the Cohort

Estimated Exposure Metrics. We estimated three exposure metrics for each month based on the cross-sectional whole body vibration assessment of 119 operators in 43 different vehicles representing 11 different types of heavy equipment vehicles. Operators exposure throughout the years of observation were estimated utilizing the exposure assessment data collected in Aim 1 during the months of June and July of 2014, and utilizing the multiyear administrative data from the mine employee database, which had operating logs for each employee defining the total number of hours worked in each type of heavy equipment vehicles per month from years 2010 to 2013.

The duration of exposure expressed as the percentage of operational time, was calculated as the total number of hours an operator drove a vehicle for the study period divided by the total number of hours worked during the study period. Driving logs with the amount of hours of operation per operator and type of vehicle per month were provided by the mine, which it is used for the company to administrate HEVs fleet and control production in the mine.

In order to estimate the exposure, we assumed that the whole body vibration measured during June-July 2014 was similar in nature and magnitude to the exposure experienced by operators from 2010 to 2013. Although the areas where the mining process was conducted from 2010 to 2014 might vary from those during the whole body vibration exposure data collection in 2014, we considered that these values may not change significantly given the level of standardizing of the mining process in terms of production levels, vehicles conditions, and type of roads.

The average whole body vibration exposures associated with the aggregate of each worker-vehicle combination were estimated using: the standard weighted daily root mean square (r.m.s.) acceleration (A(8); the daily vibration dose value (VDV(8)) which was considered a measure of, impulsive mechanical shocks; and the daily equivalent static compression dose (Sed(8)). The ISO standard 2631-1:1997 was used to estimate A(8) and VDV(8); and the ISO 2631-5:2004 was used to estimate Sed(8). For each axis and vector sum, a time-weighted formula was used to estimate the Aw metric (based on *A(8)*); and cumulative formulae were used to estimate the *VDV* (based on *VDV(8)*) and *Sed* metrics (based on *Sed*(8)) (Equations 1, 2 and 3).

Equation 1. Monthly weighted vibration (Aw_t) and average monthly-equivalent weighted vibration for the period of interest (Aw)

$$Aw_t = \sqrt{\sum_i A(8)_i^2 \frac{T_{i,t}}{\sum_i T_{i,t}}}; \qquad Aw = \sqrt{\sum_t A_t^2 \frac{T_t}{176}}$$

Where Aw_t is the weighted exposure for the month t of a worker; i is the type of heavy equipment vehicles; $A(8)_i$ is the weighted exposure associated to the heavy equipment vehicles i; $T_{i,t}$ is the exposure time of a worker on each type of heavy equipment vehicles i during the month t.

Aw is the weighted exposure for the complete 4-year period of analysis; T_t is the total number of hours of exposure during the month t. Exposures are adjusted to 176 hours worked per month, which is the standard of working hours per month in the company.

Equation 2. Monthly cumulative vibration (VDV_t) and cumulative vibration for the period of interest (VDV)

$$VDV_t = \sqrt[4]{\sum_i VDV(8)_i^{\;4} \; \frac{T_{i,t}}{8}} = \sqrt[4]{\sum_i VDV_i^{\;4} \; \frac{T_{i,t}}{T_{measured}}} \; ; \; VDV = \sqrt[4]{\sum_t VDV_t^4 * T_t}$$

Where VDV_t is the cumulative exposure of a worker for the month t across vehicles; $VDV(8)_i$ is the cumulative exposure associated to the heavy equipment vehicles i; $T_{i,t}$ is the exposure time of a worker on each type of heavy equipment vehicles i during the month t.

VDV is the cumulative exposure for the complete 4-year period of analysis; T_t is the total number of hours of exposure during the month t. For *VDV* a normalization term is not necessary since by definition *VDV* is cumulative in contrast to Aw.

Equation 3. Monthly cumulative vibration (Sed_t) and cumulative vibration for the period of interest (Sed)

$$Sed_t = \sqrt[6]{\sum_i Sed(8)_i^{\;6} \; \frac{T_{i,t}}{8}} = \sqrt[6]{\sum_i Sed_i^{\;6} \; \frac{T_{i,t}}{T_{measured}}} \; ; \; Sed = \sqrt[6]{\sum_t Sed_t^6 * T_t}$$

Where Sed_t is the cumulative exposure of a worker for the month t across vehicles; $Sed(8)_i$ is the cumulative exposure associated to the heavy equipment vehicles i; $T_{i,t}$ is the exposure time of a worker on each type of heavy equipment vehicles i during the month t.

Sed is the cumulative exposure for the complete 4-year period of analysis; T_t is the total number of hours of exposure during the month t.

We scaled the estimated vibration metrics to obtain a more intuitive interpretation of the regression association models between exposure metrics of whole body vibration and back pain -related absenteeism. The exposures were multiplied by a factor such that one-unit increase in the scaled exposure metric would represent a change in the action limit from 8 hours to 4 hours. In Aw, for example, according to ISO 2631-1 there is a threshold of exposure of 0.707 m/s^2 and 0.5 m/s^2 to reach EU action limits for 4 and 8 hours of vehicle operation respectively, hence an increase of 0.207 m/s^2 represents a decrease of the time to the action limit from 8 hours to 4 hours. In this case, the exposures for every person per month were multiplied by 4.83 (1/0.207). In this way, the hazard ratio can be interpreted as the number of times the risk of absenteeism increases for a 0.207 m/s^2 increase in exposure. In the case of VDV, the 8-hour action limit is 9.1 $m/s^{1.75}$ and the 4-hour action limit is 10.825 $m/s^{1.75}$, therefore exposures were multiplied by 0.58 (1/1.725); and for the case of S_{ed}, the 8-hour action limit is 0.5 MPa and the 4-hour action limit is 0.561 MPa exposures were multiplied by 16.39 (1/0.061). These 4-hour action limits were calculated by scaling the 8-hour exposure to a four-hour exposure according to the ISO 2631 standard.

Outcome. The operators' absenteeism records were matched to operators' exposures by the company prior to analyses. The absenteeism records included workers reporting absenteeism due to musculoskeletal disorders codes (M00 to M99), according to the International Classification of Disease (ICD) during years 2010 to 2013. For each code, the database included the initial date of absenteeism and the last date of absenteeism.

The outcome in the present study was time to first episode of back pain (ICD version 10, code M54)-related absenteeism. This code includes according to ICD the following conditions: Radiculopathy, cervicalgia, sciatica, lumbago with sciatica, low back pain, pain in the thoracic spine, other back pain and unspecified back pain. Absenteeism in the company must be approved by the general physician after consultation. The physician must be affiliated to a recognized health service provider. One of the health service provider is located within the company and is where most frequently workers look for health services.

Data analysis. To test the hypothesis that the estimated exposure to whole body vibration in these heavy equipment vehicles operators was associated with time to absenteeism related to back-pain, we used Cox Regression models that provided Hazard Ratios. Two types of models were used: time-varying models, in which exposures vary month-to-month throughout the years of observation, and non-time-varying models, in which there is only one summary metric of exposure during the years of observation (Aw, VDV and Sed in equations 1, 2 and 3 above). In the case of time-varying models, monthly exposures can be the exposures of each month (Aw_t, VDV_t, and Sed_t, in equations 1, 2 and 3 above), or the exposures accumulated to each month (i.e., Aw, VDV and Sed,). These regression models estimate Hazard Ratios (HR), which represent the relative risk of having a new episode of absenteeism related to back-pain of someone with high vibration exposures (enough to reach the 4-hour action limit) compared to someone with low vibration exposures (enough to reach the 8-hour action limit). For all models, we controlled for the effect of age (years), seniority at the company (years in the company regardless of the job), body mass index (Kg/m^2), presence of absenteeism related to other musculoskeletal disorders (ICD codes M00 to M99, except for M54 which corresponds to back-pain), and total duration of exposure to whole body vibration (months) in the period of observation.

4.2.3 Aim 3: Research Tasks: Evaluating whole body vibration control technologies

We completed a pilot and exploratory study to examine the effects that three engineering controls, an air-filled bladder seat cushion and two seat suspension technology, may have on reducing whole body vibration exposures thus can be used for primary health preventions activities. We tested the air-filled bladder seat cushion given that it has been reported its effectiveness in reducing whole body vibration exposure up to 25% in city bus applications that also have impulsive shock exposures.[33] In contrast, the active seat suspension technology, uses a highly responsive electromagnetic linear actuator to continuously and nearly instantaneously control up-and-down vibration-induced motion. [39,51]

In a repeated-measures design, a total of 8 health adult subjects (6 men and 2 women) participated in this laboratory-based study. All the subjects have driving experience with no pre-existing musculoskeletal disorders in the upper extremities and low back. The subjects' average age was 38 ranging from 28 to 52 years. The experimental protocol was approved by the University's Human Subjects Committee and all subjects provided their written consent prior to their participation in the study.

Experimental Apparatus

Whole Body Vibration Simulation: A six degree of freedom (6-DOF) motion platform (MB-E-6DPF, Moog Inc., East Aurora, NY) played back field-measured vibration profiles from three types of mining heavy equipment vehicles. The 6-DOF motion platform consisted of 6 electric linear servo actuators and has been used in previous laboratory-based studies (e.g. Rahmatalla et al., 2008; Blood et al., 2015).

The 24-minute field-measured vibration profiles consisted of data collected from three mining heavy equipment vehicles (8 minutes per heavy equipment vehicles): 240-ton haul truck (T240), bulldozer, and scrapper (Table 1 and Figure 4). These vehicles were chosen base on their significant operation times and predominant WBV axes identified during Aim 1. These three vehicles account 38% of the total mining vehicle operation times at the study site. Furthermore, they have different predominant axes:

- Bulldozer: fort/aft (x-axis) dominant;
- Scrappers: lateral (y-axis) dominant with significant lateral vibration (i.e. above ISO action limits for *A(8)* and *VDV(8)*).
- T240 truck: vertical (z-axis) dominant;

Table 1. Vibration profiles from three mining heavy equipment vehicles types (24 minutes total – 8 minutes/heavy equipment vehicles)

Segment Order	Description	Duration (sec)
1	T240: Truck	480
2	Bulldozer	480
3	Scrapper	480

The vibration profiles from each vehicle was selected to represent a realistic whole body vibration characterized by its average weighted vibration (A8) and *VDV(8)* values as well as the predominant exposure axis measured during the full shift (~12 hours) in the study sites.

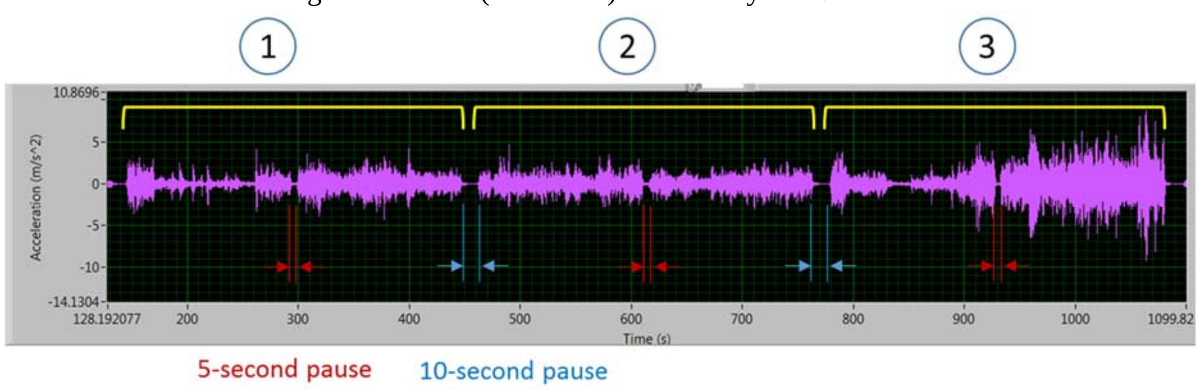

Figure 4. Sample vibration profiles: 240-ton haul truck (1), bulldozer (2), and scrapper (3). Each vehicle vibration profile is 480 seconds in length; there were 5-second mid-point pauses within each vibration profile (red lines and arrows) and 10-second pauses between vibration profiles (blue lines and arrows).

Engineering controls evaluated
Three engineering controls (two different suspension seats and an air bladder seat cushion) were tested in this laboratory-based study:

- A passive air suspension seat with passive mechanical lateral and fore/aft suspension
- An electromagnetic active suspension seat with passive mechanical fore/aft suspension
- An integrated air-filled bladder seat cushion

The passive air suspension seat (MSG 95; Grammer Seating; Hudson, WI) was equipped with a pneumatic passive suspension (vertical z-axis) and mechanical spring-based passive suspensions for lateral (y-axis) and fore/aft (x-axis) (Figure 5). This commercially-available seat is an industry standard for off-road vehicles such as agriculture and construction heavy equipment vehicles.

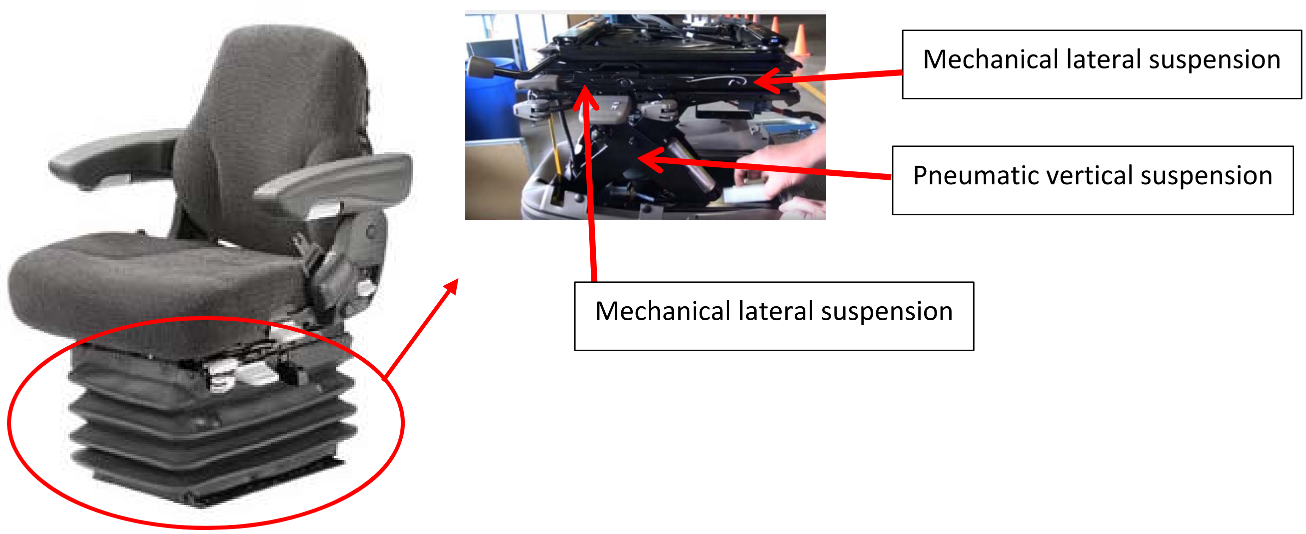

Figure 5. Grammer MSG95 Series. Picture from https://usa.grammer.com/usa/seating-solutions/construction-seating/msg95-series.html

The electromagnetic active suspension seat (BoseRide; Bose Corporation; Framingham, MA) was equipped with electromagnetic linear actuator (vertical z-axis) and mechanical spring-based passive suspension for fore/aft (x-axis) only. The highly responsive electromagnetic linear actuator can continuously and nearly instantaneously control up-and-down vibration induced motion (Figure 6). The seat has a built-in microprocessor, which uses seat position and acceleration information to control the electromagnetic linear actuator. This controls the seat travel and counteracts the road-induced vibration disturbances. As a result, this active suspension seat also attenuates the impulsive exposures, which is common in off-road vehicles.

Figure 6. Anatomy of the electromagnetic active seat suspension system (BoseRide® System). The main components include the linear electromagnetic actuator used to suspend and control the vertical movement of the seat and fore/aft passive mechanical suspension.

The integrated air-filled bladder seat cushion consisted of two air reservoirs: one on the seat back and the other on the seat pan (Figure 7). These two bladders were connected with three channels. When a driver is exposed to impulsive vibration, the air at the seat pan reservoir is blown out to the seat back reservoir and then instantaneously reciprocate back to the seat pan reservoir. This air bladder seat cushion is known to be effective in reducing whole body vibration exposure up to 25% in city bus applications that also have impulsive shock exposures.

Figure 7. Air-filled bladder with two reservoirs (one on the back and one on the pad) installed on a seat. The air at the seat pan reservoir is blown out to the seat back reservoir and then instantaneously reciprocate back to the seat pan reservoir.

As our aim was to systematically evaluate different engineering controls (vertical, lateral, fore/aft suspensions, and air-filled bladder cushion). We chose six different seat suspension combinations (Table 2) to determine whether:

- The active suspension seat was more effective in reducing whole body vibration exposures as compared to passive suspension seat (Condition 2 vs. 5);
- The -active fore/aft suspension was effective in reducing whole body vibration (keeping the vertical suspension active) (Condition 1 vs. 2);
- The active lateral suspension was effective in reducing whole body vibration (keeping the vertical suspension passive) (Condition 4 vs. 5);
- The integrated air-filled bladder seat cushion was effective in reducing whole body vibration (Condition 5 vs. 6). Given that the air-filled bladder was one of the engineering controls to test separately, the evaluation was conducted keeping the vertical, fore/aft and lateral suspension passive in order to measure the isolate effect of the air-filled bladder cushion;
- The effectiveness of passive fore/aft suspension would differ between active and passive vertical suspension system (Condition 1 vs. 3)

Table 2. Description of the conditions evaluated in the laboratory.

Condition		Vertical suspension		Fore/aft suspension	Lateral suspension	Air-filled bladder seat cushion
		Active	Passive			
1	Seat 1 (Bose)	X		X		
2		X				
3			X	X		
4	Seat 2 (Grammer)		X		X	
5			X			
6			X			X

A tri-axial seat-pad accelerometer (Model 356B40; PCB Piezotronics; Depew, NY) mounted on the seats measured whole body vibration exposures according to International Organization for Standardization (ISO) 2631-1 whole body vibration standards. An identical tri-axial accelerometer magnetically mounted to the floor of the motion platform measured the floor vibrations. Raw un-weighted acceleration data were simultaneously collected on floor and seat at 1,280 Hz using an eight-channel data recorders (Model DA-40; Rion Co. LTD; Tokyo, Japan).

A custom-built LabVIEW program (v2014; National Instruments; Austin, TX) calculated the whole body vibration exposure parameters per ISO 2631-1 and 2631-5 standards as follows:

ISO 2631-1 parameters

- Root mean square (r.m.s) weighted average acceleration (*Aw*) calculated at the seat pan, floor, and head (m/s^2):

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

where $a_w(t)$ is the instantaneous frequency-weighted acceleration at time, t and T is the duration of the measurement in seconds.

- Vibration dose value (*VDV*), which is more sensitive to impulsive vibration and reflects the total, as opposed to average vibration, over the measurement period at the seat pan and floor of the motion platform ($m/s^{1.75}$):

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

ISO 2631-5 parameters

- Acceleration dose value (D_k) in m/s^2:

$$D_k = \left[\sum_{k=x,y,z} A_{ik}^6\right]^{\frac{1}{6}} \quad (3)$$

where A_{ik} *is the* i^{th} peak of the response acceleration $(a_{ik}(t))$ and k represents the axis, x, y, *or* z.

- Average daily dose value (D_{kd}) to which a driver will be exposed (m/s^2):

$$D_{k\mathrm{d}} = D_k\left(\frac{t_d}{t_m}\right)^{\frac{1}{6}} \quad (4)$$

$$\begin{aligned} &where \\ &\quad D_k\ is\ theacceleration\ dose\ value\ in\ equation\ (3) \\ &\quad t_d\ is\ the\ duration\ of\ the\ daily\ exposure, and \\ &\quad t_m is\ the\ period\ over\ which\ D_k\ has\ been\ measured. \end{aligned}$$

- Daily equivalent static spinal compression dose (*Sed*) in mega pascals (MPa):

$$S_{ed} = \left[\sum_{k=x,y,z} (m_k D_{k\mathrm{d}})^6\right]^{\frac{1}{6}} \quad (5)$$

$$\begin{aligned} &where \\ &\quad D_{k\mathrm{d}}: average\ daily\ dose\ value\ in\ equation\ in\ (4) \\ &\quad m_x = 0.015\ \mathrm{MPa}/(m/s^2) \\ &\quad m_y = 0.035\ \mathrm{MPa}/(m/s^2) \\ &\quad m_z = 0.032\ \mathrm{MPa}/(m/s^2) \end{aligned}$$

To enable comparisons across all measurements, all the parameters ($A_w, VDV,\ S_{ed}$) were normalized to reflect 8 hours of exposure to whole body vibration (e.g. $A(8),\ VDV(8),$ and $S_{ed}(8)$).

Statistical data analysis

Given the small sample size and non-normality of whole body vibration exposure data, Wilcoxon signed-rank tests (JMP Ver. 11 Pro, SAS Institute; Cary, SC) tested for differences in whole body vibration exposures between the different seat suspensions settings. Statistical significance was noted when p-values were less than 0.05.

5.0 Summary of Accomplishments:

5.1.1 Aim 1. Characterization of heavy equipment vehicles exposure in mining vehicles

We collected over 846 hours of whole-day whole body vibration exposure data from 38 vehicles capturing the exposure of 123 heavy equipment vehicles operators in a large coal producing open-pit surface mine. Full-shift, 6 to 12-hour continuous whole body vibration measurements were collected from 11 of the most representative types of vehicles in terms of hours of operation and number of vehicles in order to characterize whole body vibration exposures in an open-pit coal mine fleet. Findings showed that mining operators are exposed to high levels of both continuous and impulsive whole body vibration:

- The impulsive exposure parameters *VDV(8)* and *Sed*(8) were above the exposure limits and reduced heavy equipment vehicles operation times to reach these exposure limits by one-half to two-thirds relative to *A(8)* exposures.
- Exposures were similar across the three axes, not only in the traditional vertical direction.
- The direction (axis) with the highest amplitude of vibration exposure varied across the different heavy equipment vehicles, which is most likely related to the different tasks the vehicles complete within the mine.

Heavy equipment vehicles mining operators are exposed to high levels of both continuous and impulsive whole body vibration (Figures 8-10). Comparisons between whole body vibration exposure parameters calculated based on the ISO 2631-1:1997 and ISO 2631-5:2004 standards, and on the EU whole body vibration Directive action limits, indicated substantial differences in the prediction of the risk of adverse health effects between average root mean square (r.m.s) exposures (*A(8)*) and cumulative impulsive exposures (*VDV(8)* and *Sed*(8)).

Based on the predominant axis of exposure and the vector sum exposures, the amount of time the heavy equipment vehicles could be operated until reaching ISO daily vibration action limits (*A(8)*=0.5 m/s^2; *VDV(8)*= 9.1 $m/s^{1.75}$) is often shorter than a 12-hour shift (Table 3). Comparing the *A(8)* and *VDV(8)* whole body vibration exposure parameters, heavy equipment vehicles operation time was considerably shorter for cumulative-impulsive *VDV(8)* whole body vibration exposures in comparison to the more traditional average-continuous *A(8)* whole body vibration exposures. Large heavy equipment vehicles operation time differences also existed between the predominant axis and the vector sum whole body vibration exposures. The cumulative-impulsive *VDV(8)* whole body vibration exposures reduced acceptable heavy equipment vehicles operation times by one-half to two-thirds relative to average-continuous *A(8)* exposures. In addition, vector sum whole body vibration exposures were much more restrictive in heavy equipment vehicles operation times and cut acceptable vehicle operation times in half.

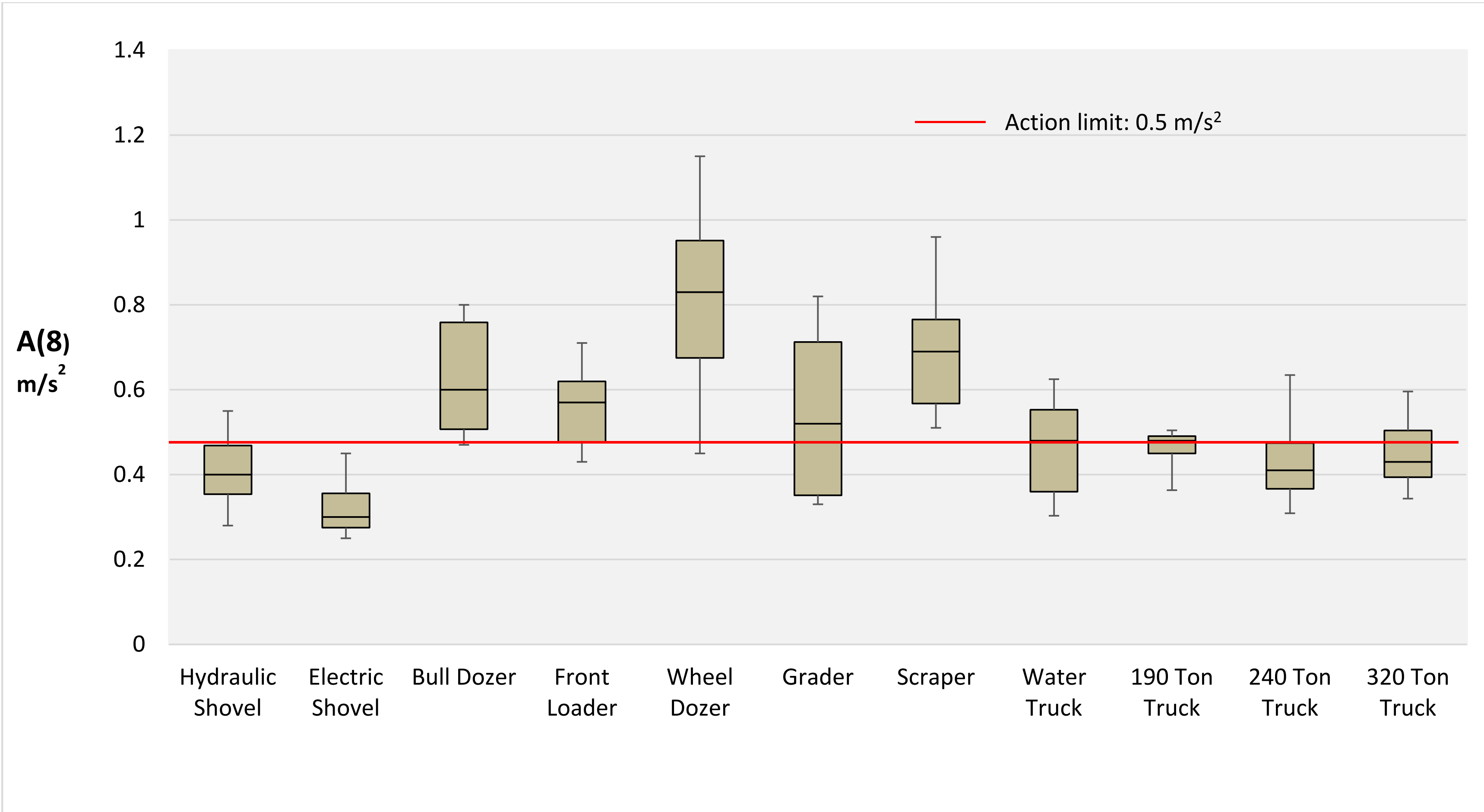

Figure 8. Median (min – max) daily average-continuous *A(8)* whole body vibration exposure by type of vehicle for the predominant axis. The line that divides the box into two parts represents the median values of *A(8)* for each type of vehicle; the upper and lower whiskers represent the highest and lowest exposure values; and the box limits represent the inter-quartile range (25% to 50%) of exposure values for each type of vehicle.

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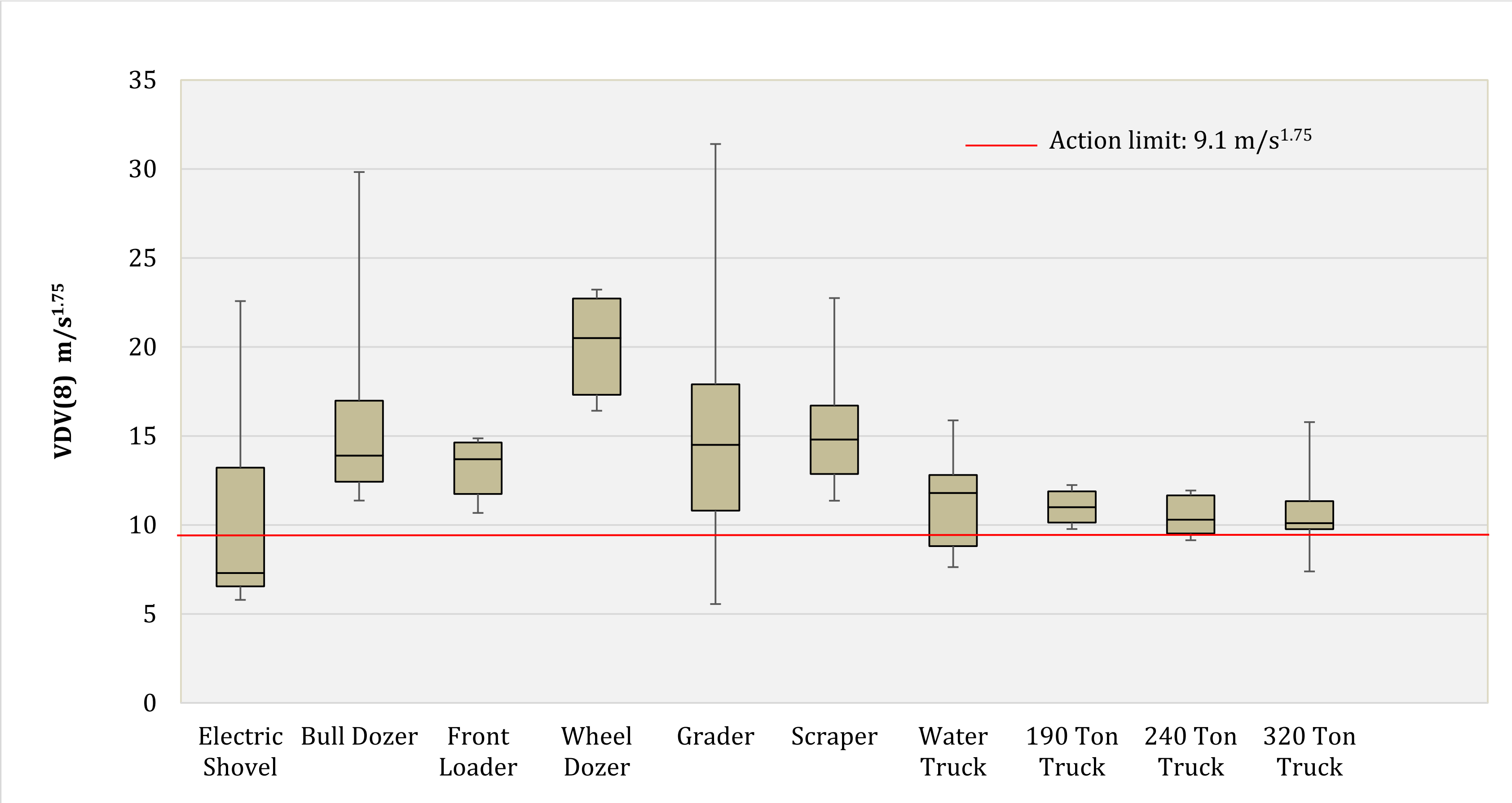

Figure 9. Median (min – max) cumulative-impulsive *VDV(8)* whole body vibration exposure by type of vehicle for the predominant axis. The line that divides the box into two parts represents the median values of *VDV(8)* for each type of vehicle; the upper and lower whiskers represent the highest and lowest exposure values; and the box limits represent the inter-quartile range (25% to 50%) of exposure values for each type of vehicle.

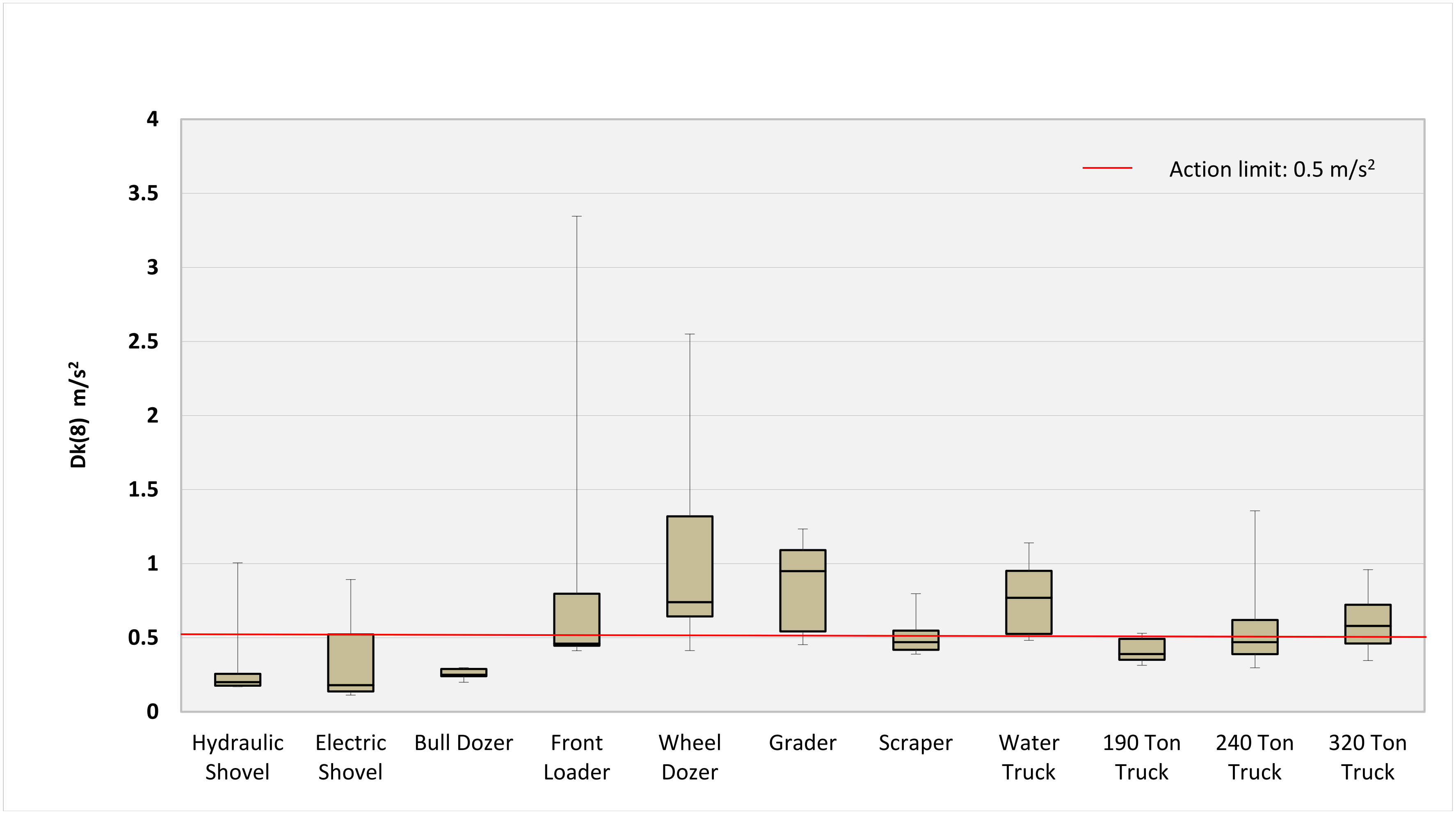

Figure 10. Median (min – max) Static Compressive Dose Value Dk(8) whole body vibration exposure (single axis components of *Sed*) by type of vehicle for the predominant axis. The line that divides the box into two parts represents the median values of Dk(8) for each type of vehicle; the upper and lower whiskers represent the highest and lowest exposure values; and the box limits represent the inter-quartile range (25% to 50%) of exposure values for each type of vehicle.

Table 3. Median (min, max) time in hours equipment could be operated until reaching the ISO daily vibration action limit (*A(8)* = 0.5 m/s^2 and *VDV(8)* = 9.1 $m/s^{1.75}$). Data grouped by metrics calculated based on the predominant axis and vector sum exposures.

	# of measure-ments	Axis	Predominant Axis		Σxyz		
			0.5 m/s^2 *A(8)*	**9.1 $m/s^{1.75}$ *VDV(8)***	**0.5 m/s^2 *A(8)***	**9.1 $m/s^{1.75}$ *VDV(8)***	**0.5 MPa *Sed*(8)**
Hydraulic Shovel	7	X	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	X	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	X	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	X	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	Y	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	Y	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	Y	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	Z	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	Z	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	Z	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	Z	8.6 (6.1 - 37.4)	3.8 (2.5 - 6.1)	4.1 (3 - 7.9)	1.9 (0.1 - 2.8)	6.5 (0 - 125.6)

5.1.2 Aim 2: Association between back-pain related absenteeism and estimates of whole body vibration exposures

We tested the association between estimates of whole body vibration exposure and back-pain-related absenteeism in 2302 operators of mining HEV who operated an array of different heavy equipment vehicles. Findings showed that whole body vibration was positively and significantly associated to absenteeism. In addition,

- Estimates of exposure metrics varied greatly across the cohort of operators during the study periods (Table 4).
- We found significant positive associations between estimates of whole body vibration and back-pain related absenteeism for all of our exposure metrics for accelerations in all three axes (Table 5). For both the A(8) and the *VDV* metrics, the strongest associations were for vibration exposure metrics in the vertical axes. For example, the risk of absenteeism was 12.39 times higher, when

the *A(8)*-based exposure metric increased by 0.207 m/s^2 for the vertical (z) axis in the time varying cumulative exposure models, compared to only 2.80 times higher for lateral (y) axis.

- A small change in exposure relative to the full range of exposures in the cohort can significantly change the risk of absenteeism. Therefore, from theoretical point of view opportunities to reduce risks appear to exist; however, the practicalities of doing so remain unclear and need to be explored further.
- The present study for the first time presents evidence directly linking exposure estimates of whole body vibration and absenteeism in the mining industry using direct measurements over a hundred workers combined with working-hours logs for over a thousand workers.

The statistical modeling approach resulted in differences in the results. Time-varying regression models, particularly those capturing cumulative exposures changing from month to month showed stronger associations with back-pain-related absenteeism in comparison to non-time-varying regression models that used single summary metrics per worker. This result suggests that the patterns of exposure from month to month can indeed provide useful information about the relation between whole body vibration exposure and back-pain-related absenteeism.

When interpreting the absenteeism risk presented in Table 5, it should be noted the unit increase in the exposure metric is different for each exposure metric (that is *A(8)* versus *VDV* or *Sed*) based on the difference between the 4 and 8 hour action limits for each vibration metric. These differences are not linear across the three metrics and hence it is difficult to compare the associations between the three different metrics. We did not complete any tests comparing the different types of metrics; rather our goal was to see which ones were related to the outcomes. These data suggest that they are all associated with the back-pain outcome.

Table 4. Estimated Cumulative and monthly exposure of whole body vibration (n=2302)

Metric	(1) *Minimum* exposure observed in a *person across months* along the total period of assessment (4 years). $\bar{x}$, m (SD), [min-max]	(2) *Maximum* exposure observed in a *person across months along the total period of assessment (4 years).* $\bar{x}$, m (SD), [min-max]	(3) Cumulative exposure observed *across workers*. $\bar{x}$, m (SD), [min-max]
A	***(m/s²)***	***(m/s²)***	***Aw, Weighted 4-year period (m/s²)***
Ax	0.07, 0 (0.09), [0-0.42]	0.42, 0.39 (0.12), [0.0007-0.75]	0.36, 0.35 (0.10), [0.0007-0.62]
Ay	0.07, 0 (0.09), [0-0.44]	0.43, 0.37 (0.16), [0.0007-0.97]	0.36, 0.32 (0.13), [0.0007-0.83]
Az	0.07, 0 (0.09), [0-0.38]	0.41, 0.43 (0.09), [0.0004-0.71]	0.35, 0.38 (0.08), [0.0004-0.64]
Σ*A*	0.13, 0 (0.16), [0-0.67]	0.74, 0.70 (0.19), [0.001-1.28]	0.64, 0.62 (0.16), [0.001-1.11]
VDV	***(m/s^1.75)***	***(m/s^1.75)***	***VDV, Cumulative 4-year period (m/s^1.75)***
VDVx	7.28, 0 (8.36), [0-28.41]	26.10, 24.91 (4.63), [1.02-39.59]	109.40, 114.34 (33.66), [0.08-210.65]
VDVy	7.74, 0 (9.00), [0-33.13]	29.34, 28.26 (6.38), [1.19-49.08]	120.69, 124.37 (38.59), [0.09-258.98]
VDVz	6.02, 0 (6.92), [0-22.82]	21.94, 22.64 (3.23), [0.64-31.80]	92.19, 98.59 (26.46), [0.05-170.85]
Σ*VDV*	10.19, 0 (11.67), [0-37.32]	37.37, 36.73 (6.06), [1.41-54.69]	155.71, 165.34 (45.22), [0.11-289.03]
Sed	***(MPa)***	***(MPa)***	***Sed, Cumulative 4-year period (MPa)***
Sed	0.50, 0 (0.58), [0 -1.89]	1.68, 1.70 (0.33), [0.16-2.12]	4.21, 4.35 (1.10), [0.03-6.27]

$\bar{x}$: mean; m: median; Σ: Vector sum across vibration axis (x, y and z).

Table 5. Hazard Ratios (HR) and 95% lower and upper confidence intervals (LCI – UCI) for each estimated whole body vibration metric.

		Unadjusted	Adjusted Models		
			Non-time varying	Non-cumulative time varying metrics	Cumulative time varying metrics
	Increase of exposure metric	Hazard Ratio (LCI UCI)	Hazard Ratio (LCI UCI)	Hazard Ratio (LCI UCI)	Hazard Ratio (LCI UCI)
Ax(8)	0.207 m/s^2	1.15 (0.87 - 1.52)	**3.27 (2.52-4.23)**	**2.92 (2.44-3.51)**	**4.63 (3.8-5.63)**
Ay(8)	0.207 m/s^2	**1.29 (1.06 - 1.57)**	**2.03 (1.69-2.44)**	**2.14 (1.86-2.46)**	**2.8 (2.36-3.32)**
Az(8)	0.207 m/s^2	0.82 (0.6 - 1.13)	**9.89 (7.02-13.93)**	**4.93 (3.91-6.21)**	**12.39 (8.94-17.18)**
∑A(8)	0.207 m/s^2	1.13 (0.95 - 1.35)	**2.39 (2.04-2.81)**	**1.99 (1.78-2.22)**	**3.04 (2.61-3.54)**
VDVx(8)	1.725 $m/s^{1.75}$	0.99 (0.98 - 0.99)	**1.06 (1.05-1.07)**	**1.21 (1.17-1.24)**	**1.11 (1.1-1.12)**
VDVy(8)	1.725 $m/s^{1.75}$	0.99 (0.98-0.99)	**1.03 (1.02-1.04)**	**1.13 (1.11-1.16)**	**1.06 (1.06-1.07)**
VDVz(8)	1.725 $m/s^{1.75}$	0.98 (0.97-0.99)	**1.12 (1.1-1.14)**	**1.34 (1.28-1.41)**	**1.18 (1.16-1.2)**
∑VDV(8)	1.725 $m/s^{1.75}$	0.99 (0.98-0.99)	**1.04 (1.04-1.05)**	**1.14 (1.12-1.17)**	**1.08 (1.07-1.09)**
Sed (8)	0.061 MPa	0.99 (0.98-0.99)	**1.04 (1.03-1.05)**	**1.09 (1.08-1.11)**	**1.07 (1.06-1.08)**

Hazard Ratios indicate the increase of risk of absenteeism for an increase in the exposure metric equal to the value in the first column, which is the difference between 4 hour and 8 hour action limits as defined by the European Union standards in attempt to standardize the HR across the different metrics.
Adjusted models included Age, BMI, Seniority, Other MSD, and Total exposure duration (Months driving).
LCI: Lower 95% confidence interval;
UCI: Upper 95% confidence interval;
Bolded values indicate statistically significant results with alpha set at 0.05: that is the 95th percentile confidence interval does not contain 1.

Research Tasks: Evaluating whole body vibration control technologies

We tested current technology and their effects in reducing exposures to whole by vibration. We tested a simple technology in vehicles operating in the mine and more sophisticated technologies in the laboratory using the field measurements from three different vehicle types. Findings showed reduction in the exposure; however, the amount was relatively small. Specifically

- Air bladder demonstrated almost no reduction in exposures in the vehicles.
- A passive fore-aft lateral suspension systems showed limited whole body vibration attenuation in the laboratory.
- An active suspension seat significantly attenuated the vertical whole body vibration component.

The passive integrated air-filled cushion was tested in 12 vehicles covering four types of heavy equipment vehicles (T-240 Truck, scraper, bulldozer, and caterpillar tractor), and 36 heavy equipment vehicles operators. We collected approximately 230 hours of full-shift whole body vibration exposure. However their effectiveness in the mining heavy equipment vehicles may be limited due to the fact that while these air-filled cushions were effective in reducing vertical vibrations, many mining heavy equipment vehicles experience horizontal and lateral vibrations and the air cushion is less effective in reducing the impact of vibrations in the non-vertical axes.

The laboratory tests showed that whole body vibration exposures varied by mining vehicle types. Truck T-240 tons showed relatively lower vibration exposures while the scrappers had higher whole body vibration exposures. Bulldozers and scrappers had significant Y-axis (lateral) whole body vibration exposures, above the ISO 2631-1 standards recommended action limits on both *A(8)* and *VDV(8)*. The daily static compressive dose *Sed*(8) indicated that the scrapper operators may be exposed to higher impulsive shock exposures compared to T-240 trucks and bulldozer operators.

The HEV vibrations pass through the seat to the operator. The *SEAT* values indicate the percentage of the floor-measured vibration transmitted to the seat of the operator. The seat dynamics act to absorb the vibration (or even to amplify it). The *SEAT* value for the *A(8)* showed that Bose active vertical suspension had superior attenuation performance (50-60% reduction) to passive vertical suspension with or without the air cushion (attenuated less than 10%), while fore/aft and lateral suspension showed limited attenuation (Figure 11). Thus, only 40% of the vibration measured at the floor level is transmitted to the operator on the vertical axis.

The *SEAT* value for the *VDV(8)* indicated that both fore/aft and lateral passive suspensions had limited attenuation performance. Bose active vertical suspension had superior attenuation performance (approx. 50% reduction) to passive vertical suspension with or without the air cushion (attenuated less than 7-20%) (Figure 12).

The *SEAT* value for the Dk(8), which represents the single axis components of *Sed*, showed that both fore/aft and lateral suspension attenuated the average daily dose values [Dk(8)], indicating that these suspensions may only attenuate very high shocks. Bose active suspension continues to outperform in attenuating impulsive exposures (Figure 13). In general, Bose active suspension system significantly attenuated the vertical whole body vibration components while the passive fore-aft and lateral suspension systems showed limited whole body vibration attenuation performance.

Previous studies have identified amplification at the seat in comparison to the floor, especially in the lateral axis (y)[30,31]. Several potential explanations for the amplification of the whole body vibration (SEAT values greater that 100%) exist. One explanation is that the higher seat position relative to the road/floor, lateral/fore-aft accelerations are amplified, and then due to lack of a working suspension or for these axes are not attenuated. Another explanation is the passive seat mechanical properties may amplify the floor accelerations through the excitation of resonant frequencies. Finally, some suggest that the foam of the seat pad itself is very poor in attenuating the accelerations and may also be an underdamped system for low frequency lateral vibration again amplifying the accelerations of the floor.

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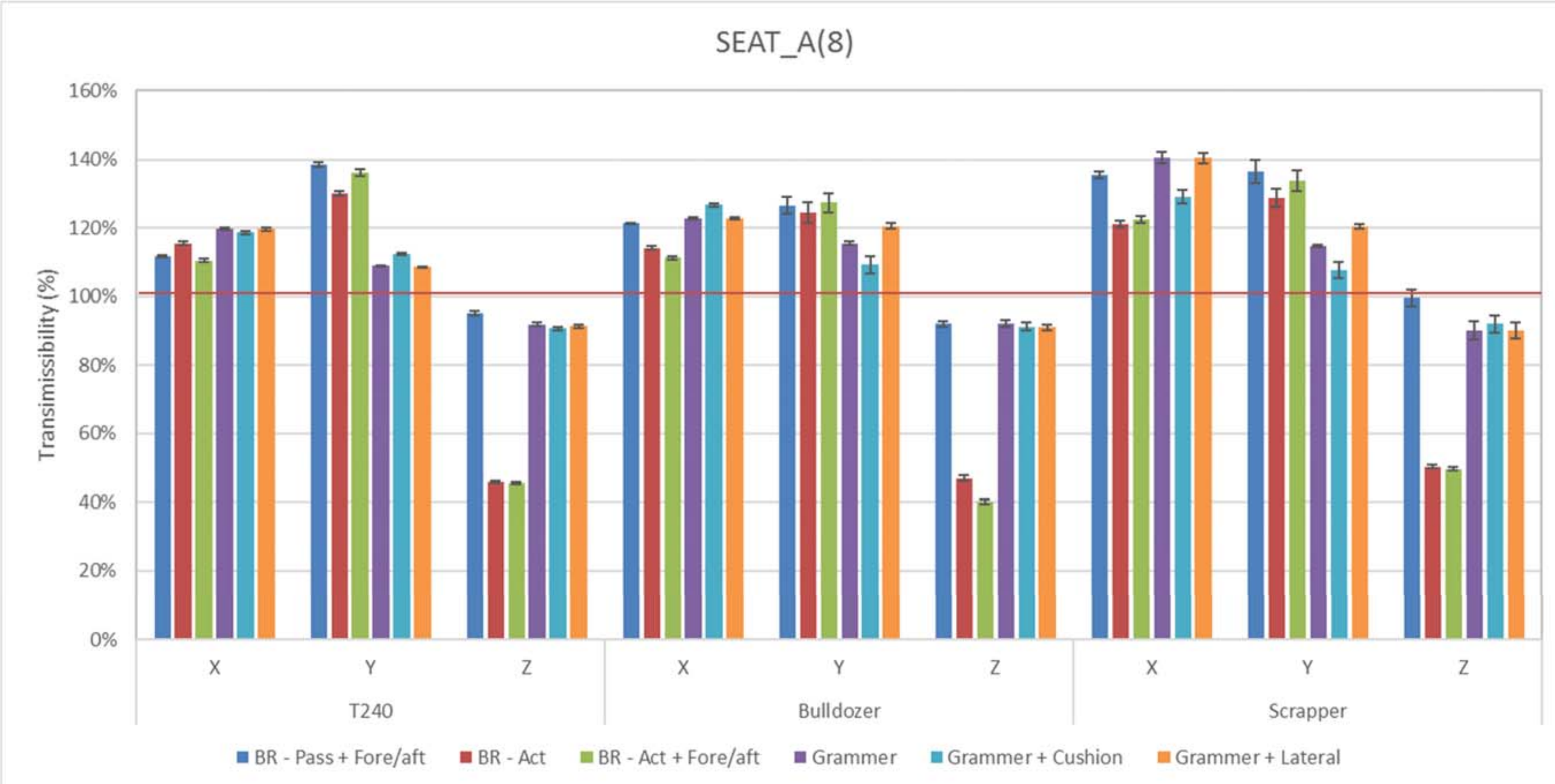

Figure 11. Seat Effective Amplitude Transmissibility (*SEAT*) values for the *A(8)* whole body vibration exposure parameter for three types of heavy equipment vehicles and for the technologies tested at the vibrating platform. Values below 100% indicate that the seat condition tested reduced the vehicle vibration.

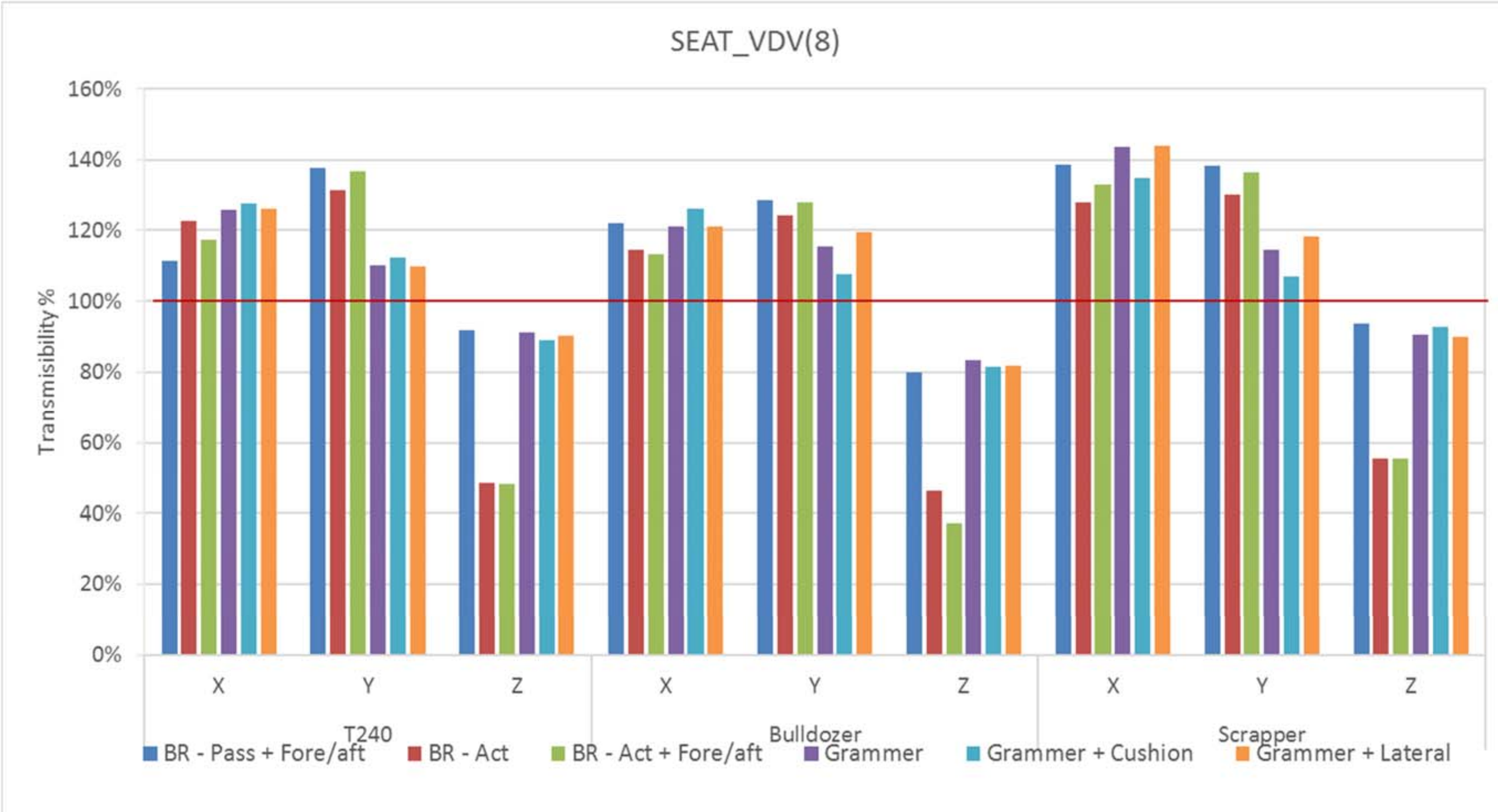

Figure 12. Seat Effective Amplitude Transmissibility (*SEAT*) values for the *VDV(8)* whole body vibration exposure parameter for three types of heavy equipment vehicles and for the technologies tested at the vibrating platform. Values below 100% indicate that the seat condition tested reduced the vehicle vibration

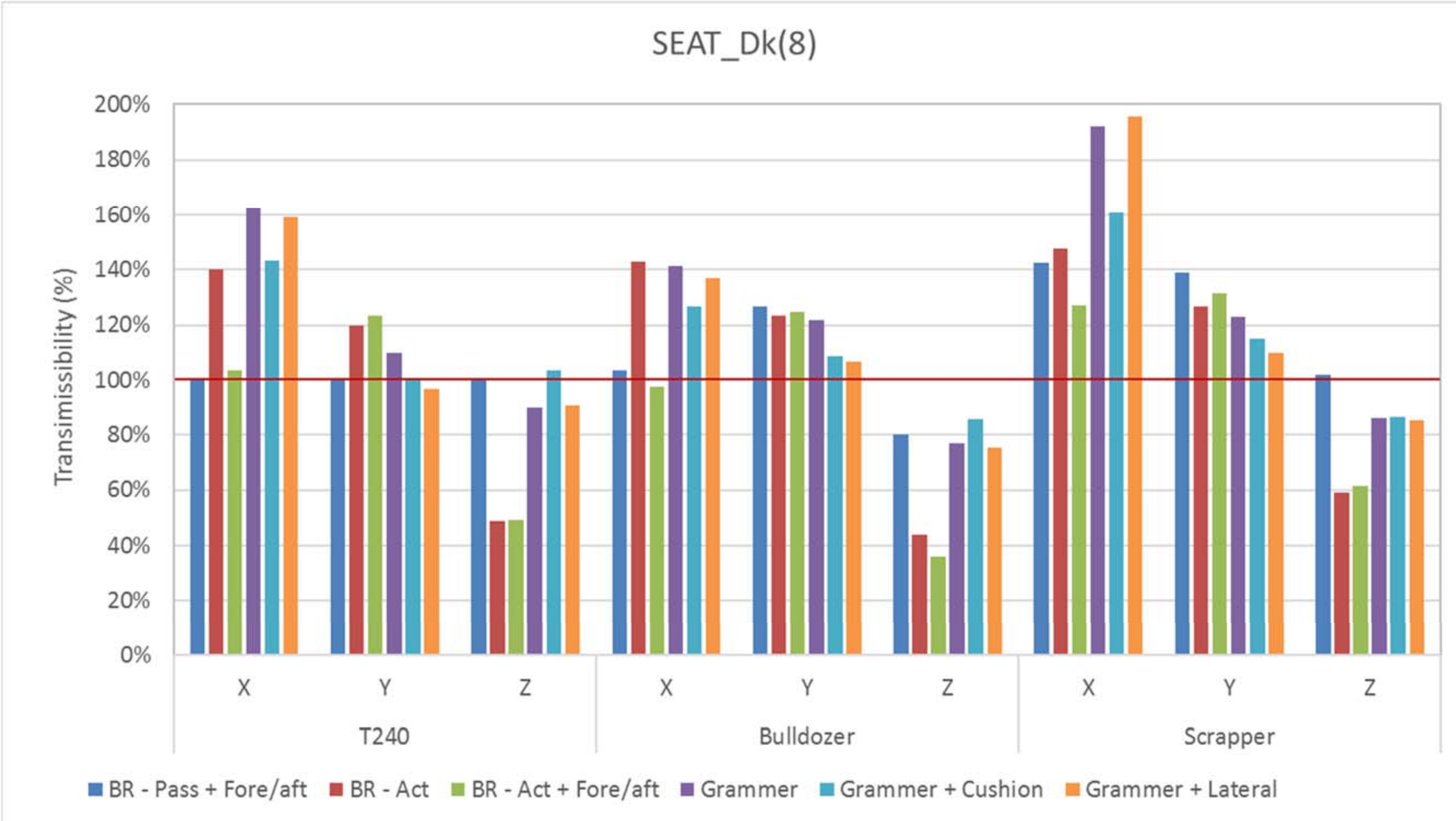

Figure 13. Seat Effective Amplitude Transmissibility (*SEAT*) values for the Dk(8) whole body vibration exposure parameter for three types of heavy equipment vehicles and for the technologies tested at the vibrating platform. Values below 100% indicate that the seat condition tested reduced the vehicle vibration.

6.0 Dissemination Efforts and Highlights:

Aim 1. Characterization of heavy equipment vehicles exposure in mining vehicles.

Our efforts of dissemination included publications on peer-reviewed journals and participation on national and international scientific conferences (Table 8). Our first peer-reviewed manuscript presenting the characterization of whole body vibration for the heavy equipment vehicles was just accepted to the Annals of Occupational Hygiene journal. Additionally, two Proceeding Papers were accepted for oral presentation and published at the at the International Ergonomics Association (IEA) International Congress (Melbourne, Australia. 2015) and at the Human Factors and Ergonomics (HFES) International Annual Meeting (Washington DC, September 2016) respectively. The papers titled "Assessment of Continuous and Impulsive Whole Body Vibration Exposures in Heavy Equipment Mining Vehicles" and "Influence of Speed in Whole Body Vibration Exposure in Heavy Equipment Mining Vehicles" were published in these proceedings.

Results regarding the whole body vibration for the heavy equipment vehicles were also accepted for oral presentation at the West Virginia Coal Association Conference (May 13-15, 2015); the 6th American Conference on Human Vibration in Milwaukee, WI in June, 2016. In addition, an oral presentation discussing the prediction of health risks in heavy equipment vehicle operators based on average-continuous and cumulative impulsive whole body vibration exposures, was also conducted at the 9th International Scientific Conference on the Prevention of Work-Related Musculoskeletal Disorders (PREMUS) held in Toronto, Canada in June 2016. A poster contrasting the daily average-continuous *A(8)* and cumulative-impulsive *VDV(8)* whole body vibration exposures and their impact on maximum daily operation hours, was also presented at the American Public Health Association (APHA) Conference in October 2016 in Denver, CO.

Additionally, an abstract was submitted and is pending acceptance from the American Industrial Hygiene Conference and Expo (AIHce), 2017.

6.1.2 Aim 2. Testing the associations between whole body vibration and musculoskeletal disorders related absenteeism.

We presented preliminary results at the 25th Epidemiology in Occupational Health Conference (EPICOH) held in Spain in September 2016. An oral presentation based on our preliminary results from testing the hypothesis that exposure to whole body vibration in these heavy equipment vehicles operators is associated with absenteeism due to musculoskeletal disorders, was conducted.

We drafted a peer-reviewed manuscript examining the potential associations between whole body vibration exposure and absenteeism related to musculoskeletal disorders. Using a database of health records provided by Cerrejón and the results from Aim 1, we estimated the cumulative whole body vibration exposure of 2302 employees. Utilizing three whole body vibration exposure metrics (*A(8)*; *VDV(8)*; *Sed*(8)) calculated based on the ISO 2631-1:1997 and ISO 2631-5:2004 standards, we examined potential associations between whole body vibration and musculoskeletal disorders related absenteeism. In this peer-reviewed manuscript, we reported our findings from testing the hypothesis that exposure to whole body vibration in these heavy equipment vehicles operators is associated with their days away from work due to musculoskeletal disorder diagnoses. The manuscript is under internal review and will be submitted to the Occupational and Environmental Medicine journal by March 2017.

6.1.3 Aim 3 Research Tasks: Evaluating whole body vibration control technologies

We presented the preliminary results to Bose Engineering team on October 2016. Currently, the team is drafting the third manuscript, which evaluates how well the two engineering control technologies tested in the laboratory were suited for the mining heavy equipment vehicles. We anticipate this peer-reviewed manuscript will be submitted by May 2017.

6.1.4. Summary of presentations and scientific conferences

In summary, we have presented several conference abstracts and have one manuscript under review all presenting the results of this study (Table 8). We have one paper fully drafted under internal review before submission to a journal and another under preparation.

Table 8. Summary of presentations and scientific conferences

Aim	Type of publication	Title	Authors	Current Status
Aim 1.	Peer-reviewed paper	Assessment of Whole Body Vibration Exposure in Heavy Equipment Mining Vehicles	Marin et al.	Accepted for publication. Annals of Occupational Hygiene
	Conference Proceeding	Assessment of Continuous and Impulsive Whole Body Vibration Exposures in Heavy Equipment Mining Vehicles	Johnson et al. (2014)	Proceedings 19th Triennial Congress of the International Ergonomics Association (IEA), Melbourne, Australia, 9-14 August 2015
		Influence of Speed in Whole Body Vibration Exposure in Heavy Equipment Mining Vehicle	Marin et al. (2016)	Human Factors and Ergonomics (HFES) International Annual Meeting (Washington DC, September, 2016)
	Oral presentation	Whole Body Vibration Exposure in Heavy Equipment Mining Vehicle	Barrero et al. (2015)	West Virginia Coal Association Conference (May 13-15, 2015);
	Oral presentation	Influence of Speed in Whole Body Vibration Exposure in Heavy Equipment Mining Vehicle	Johnson et al. (2016)	Sixth American Conference on Human Vibration. Milwaukee, WI. June, 2016.
	Oral presentation	Health risks in heavy equipment vehicle operators based on average-continuous and cumulative impulsive whole body vibration exposure	Johnson et al. (2016)	9th International Scientific Conference on the Prevention of Work-Related Musculoskeletal Disorders (PREMUS). Toronto, Canada
	Poster	Impact of daily average-continuous *A(8)* and cumulative-impulsive *VDV(8)* whole body vibration exposures impact on maximum daily operation hours	Marin et al. (2016)	American Public Health Association (APHA) Conference. October 2016 in Denver, CO.
Aim 2.	Peer-reviewed paper	Whole-body vibration and absenteeism due to low back pain among heavy equipment vehicle mining operators: the metric matters	Barrero et al.	In preparation. (Under internal review)
	Oral presentation	Association between exposure to whole body vibration and absenteeism due to musculoskeletal disorders among heavy equipment vehicles operators (preliminary results)	Barrero et al. (2016)	25th Epidemiology in Occupational Health Conference (EPICOH). Spain, September 2016.
Aim 3.	Peer-reviewed paper	Evaluation of Seating Alternatives to Reduce Whole Body Vibration in Mining heavy equipment vehicles Operators	Kim et al.	In preparation.

7.0 Conclusions and Impact Assessment

Aim 1 showed that heavy equipment vehicles mining operators are exposed to high levels of both continuous and impulsive whole body vibration. Our findings showed that: 1) substantially higher vector sum whole body vibration exposures indicated the presence of more than one predominant axis of exposure; 2) 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 *Sed*(8) were higher and reduced acceptable heavy equipment vehicles operation times by one-half to two-thirds relative to *A(8)* exposures; and 3) based on the predominant axis and vector sum, impulsive exposures and the time to reach daily vibration action limits, the operation of most heavy equipment vehicles would be restricted to less than 4 and 2 hours a day, respectively.

The research strategy and results of this study may aid further evaluation of potential engineering controls to continuous and impulsive whole body vibration as well as monitoring their effect on a particular axis or axes of exposure. Differences in whole body vibration exposure parameters must be examined in future studies because they impact the prediction of health effects and may introduce some uncertainty regarding how to best represent heavy equipment vehicles operators' actual exposure.

Aim 2 showed that whole body vibration was positively and significantly associated to absenteeism. The risk of absenteeism was the highest for the vertical axes within the A(8) and VDV metrics.. A small change in exposure relative to the full range of exposures in the cohort can significantly change the risk of absenteeism. Therefore, from a theoretical point of view, opportunities to reduce risks appear to exist; however, the practicalities of doing so remain unclear and need to be explored further.

The evaluation of engineering controls tested in the laboratory showed that Bose active suspension seat significantly attenuated the vertical whole body vibration components while the passive fore-aft and lateral suspension systems showed limited whole body vibration attenuation performance. The evaluation of these two newly and different seating technologies in specific occupational settings allowed the identification of at least one that appears to have potential to reduce exposures in the specific conditions of the heavy equipment vehicles mining operations.

8.0 Recommendations for Future Work.

This project results in several recommendations for future work to improve the health and safety of heavy equipment vehicles operators in the mining industry.

First, future work should develop, test, and evaluate the efficacy of new seat suspension technologies to reduce whole body vibration exposures. The findings of this study clearly demonstrate high exposure levels. The current state-of-the-art approaches do little to reduce the exposure to these hazards. New technology is emerging that appears to drastically reduce the vertical exposures. These might be very promising in reducing the risk for low back pain based on the findings from Aim 2; however, the non-vertical axis exposure remains high. Advances are necessary to address the horizontal and lateral loads typically found in these non-highways road applications.

Second, future work can explore administrative controls through qualitative and quantitative research of the workers to better understand the job demands and psychosocial factors associated with these disorders. For example, the data used in Aim 2 indicate there are specific driving patterns associated with risk of injury. Some key informant interviews as well as worker surveys can assist in determining some approaches for intervention.

Third, this study showed that seating interventions could be effective engineering controls to reduce whole body vibration exposures, which is known to be a risk factor for adverse musculoskeletal health outcomes including low back pain. Therefore, it is a logical next step to study whether the reduced exposure to occupational whole body vibration will reduce associated risk for musculoskeletal disorders. Using the extensive field-collected whole body vibration data, we plan to study whether some of the more effective seating interventions (e.g. active suspension seat) will reduce biomechanical and physiological loading on driver’s musculoskeletal systems. As we have been granted 2-year research grant from Alpha Foundation (PI: Jeong Ho Kim), we are currently conducting a laboratory-based study to determine whether there are differences in reducing whole body vibration exposure and associated biomechanical loading on the low back and neck among different seating interventions for the long term goal of reducing whole body vibration-related musculoskeletal injuries especially in the low back and neck regions.

Finally, future work can extend the evaluation of the engineering controls explored in this project from the laboratory to the actual mine operations of the vehicles. These interventions need to address the high levels of exposure via new seat suspensions and administrative controls limiting the overall exposure.

On a final note, while we were in the field taking measurements for this project, there was a great opportunity to address other hazards in this population. The two obvious physical hazards include air-borne particles regarding lung diseases and noise regarding hearing loss. All operators wear personal protection equipment for both. In addition, the cabs have positive air pressure to reduce dust. With the large health data base and hearing conservation program, other exposure – dose response relationships can be explored. In addition, issues associate with shift work and sleep wellbeing exist in the mine. With 12-hour shifts for a 24/7 operation, drivers are faced with long days as well as long commutes to the remote location of the mine.

9.0 References:

1. Teschke, K.N., H. Davies, and S. Ju, *Whole body vibrations and back disorders among motor vehicle drivers and heavy equipment operators: a review of the scientific evidence.*, 1999.
2. Troup, J.D., *Clinical effects of shock and vibration on the spine.* . Clin Biomech. :, 1988. **3**(4): p. 232-235.
3. Ariëns, G.A., et al., *High quantitative job demands and low coworker support as risk factors for neck pain: results of a prospective cohort study.* Spine, 2001. **26**(17): p. 1896-901; discussion 1902-3.
4. Schulte, P.A., et al., *Work, Obesity, and Occupational Safety and Health.* American Journal of Public Health, 2007. **97**(3): p. 428-436.
5. Pope, M.H., M. Magnusson, and D.G. Wilder, *Low back pain and whole body vibration.* . Clin Orthop Relat Res., 1998. **354**: p. 241-248.
6. Bernard, T., *Musculoskeletal disorders and workplace factors.*, 1997: Washington, D.C. p. 97-141.
7. Bovenzi, M. and A. Betta, *Low-back disorders in agricultural tractor drivers exposed to whole-body vibration and postural stress.* Appl Ergon, 1994. **25**(4): p. 231-41.
8. Kumar, S., *Vibration in operating heavy haul trucks in overburden mining.* Appl Ergon, 2004. **35**(6): p. 509-20.
9. Howard, B., R. Sesek, and D. Bloswick, *Typical whole body vibration exposure magnitudes encountered in the open pit mining industry.* Work, 2009. **34**(3): p. 297-303.
10. Rehn, B., C. Ahlgren, and B. Jarvholm, *Musculoskeletal symptoms among drivers of all-terrain vehicles.* Journal of Sound and Vibration., 2002. **253**: p. 21-29.
11. Schwarze S NG, D.H., Hartung E. Dose–response relationship between whole-body, v.a.l.d.d.a.f.s.o.d.o.d.v.J. of, and S.a.V. 1998;215:613-628., *Dose–response relationship between whole-body vibration and lumbar disk disease – a field study on 388 drivers of different vehicles.* . Journal of Sound and Vibration., 1998. **215**: p. 613-628.
12. Boshuizen, H.C., C.T. Hulshof, and P.M. Bongers, *Long-term sick leave and disability pensioning due to back disorders of tractor drivers exposed to whole-body vibration.* Int Arch Occup Environ Health, 1990. **62**(2): p. 117-22.
13. Leelavathy, K.R. and S. Raj, *Whole Body Vibration and Back Disorders among Vehicle Operators.* European Journal of Scientific Research, 2011. **Leelavathy K RR, Raj S. . Whole Body Vibration and Back Disorders among Vehicle Operators.**

European Journal of Scientific Research 2011;61(3):328-340.(3): p. 328-340.

14. Waters, T., et al., *The impact of operating heavy equipment vehicles on lower back disorders.* Ergonomics. , 2008. **51**(5): p. 602-636.
15. Bovenzi, M., *A longitudinal study of low back pain and daily vibration exposure in professional drivers.* Ind Health, 2010. **48**(5): p. 584-95.
16. Bovenzi, M., *Metrics of whole-body vibration and exposure-response relationship for low back pain in professional drivers: a prospective cohort study.* Int Arch Occup Environ Health, 2009. **82**(7): p. 893-917.
17. Sorensen, G., et al., *The role of the work context in multiple wellness outcomes for hospital patient care workers.* J Occup Environ Med, 2011. **53**(8): p. 899-910.
18. Dennerlein, J.T., *Ergonomics/Musculoskeletal Issues.*, in *International Encyclopedia of Public Health.*, Q.S. Heggenhougen K, eds., Editor 2008, Academic Press: San Deigo, CA.
19. Kennedy, C.A., et al., *Systematic review of the role of occupational health and safety interventions in the prevention of upper extremity musculoskeletal symptoms, signs, disorders, injuries, claims and lost time.* J Occup Rehabil, 2010. **20**(2): p. 127-62.
20. Tullar, J.M., et al., *Occupational safety and health interventions to reduce musculoskeletal symptoms in the health care sector.* J Occup Rehabil, 2010. **20**(2): p. 199-219.

21. Amick, B.C., et al., *Measuring the Impact of Organizational Behaviors on Work Disability Prevention and Management.* Journal of Occupational Rehabilitation, 2000. **10**(1): p. 21-38.
22. Berolo, S., R.P. Wells, and B.C. Amick, 3rd, *Musculoskeletal symptoms among mobile hand-held device users and their relationship to device use: A preliminary study in a Canadian university population.* Appl Ergon, 2011. **42**(2): p. 371-8.
23. Schulte, P.A., et al., *Interaction of Occupational and Personal Risk Factors in Workforce Health and Safety.* American Journal of Public Health, 2012. **102**(3): p. 434-448.
24. Schulte, P.A., et al., *A framework for the concurrent consideration of occupational hazards and obesity.* Ann Occup Hyg, 2008. **52**(7): p. 555-66.
25. American Coal Fundation. *Coal Mining in America*. 2014 [cited 2017 March 11]; Available from: http://teachcoal.org/coal-mining-in-america.
26. National Institute for Occupational Safety and Health. *Rate of Nonfatal Lost-time Injuries at Underground Work Locations by Commodity, 2006-2015:* . 2015 [cited 2017 March 11]; Available from: https://www.cdc.gov/niosh/mining/UserFiles/statistics/15g01uaa.svg.
27. Arias, O., et al., *Equivalent daily vibration exposure amont heavy equipment vehicles operators in an open pit coal mine.* , in *Fifth International Conference on Whole Body Vibration Injuries.*2013: Amsterdam, The Netherlands.
28. Johnson, P.W., J. Ibbotson-Brown, and O. Thamsuwan, *Evaluation of Seating Alternatives to Reduce Whole Body Vibration in Bus Vehicle Drivers.* , in *5th International Conference on Whole Body Vibration Injuries*2013: Amsterdam, The Netherlands.
29. Paddan, G.S. and M.J. Griffin, *Effect of seating on exposures to whole-body vibration in vehicles.* . J Sound Vib, 2002. **253**: p. 215-241.
30. Thamsuwana, O., Blood R., Ching, R. Boyle, L., Johnson, P. *Whole body vibration exposures in bus drivers: A comparison between. 2013. 43 (1); 9-17.* http://doi.org/10.1016/j.ergon.2012.10.003
31. Hong Zhao, Li-Lu Guo, and Xiang-Yan Zeng, “Evaluation of Bus Vibration Comfort Based on Passenger Crowdsourcing Mode,” Mathematical Problems in Engineering, vol. 2016, Article ID 2132454, 10 pages, 2016. doi:10.1155/2016/2132454