Minerals Industry Safety and Health Centre
Sustainable Minerals Institute

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA
CREATE CHANGE

Managing whole-body vibration associated with underground coal mining equipment

Coal Services Health and Safety Trust project 20643
Final report

Danellie Lynas
Robin Burgess-Limerick

Executive Summary

Prolonged exposure to high amplitude whole-body vibration is strongly associated with the subsequent development of back pain. The outcome of a previous CSHST project (20624) was the development of an iOS application (WBV) that allows an iPod Touch to be used to estimate whole-body vibration exposures. The devices were subsequently validated at surface coal mines. A subsequent CSHST project (20638) demonstrated that the iPod devices could be effectively utilised in underground coal mines and confirmed that high amplitude whole-body vibrations are experienced by operators of underground mobile plant. The objectives of the current project are to investigate elevated whole-body vibration exposure levels associated with underground coal in normal operation, and to evaluate a range of potential control measures to reduce exposure to this health hazard.

Investigations were undertaken at Centennial Coal's Clarence, Airly and Springvale mine sites from February, 2017 to March, 2019. Long duration measurements were collected using the WBV application installed on multiple iPod devices across a range of mobile equipment including shuttle cars, personnel and utility vehicles. A total of 188 long duration measurements were obtained from a range of underground equipment types, as well as numerous short duration measurements obtained from personnel transport vehicles to investigate the effects of vehicle speed and roadway surface condition on whole-body vibration exposure levels.

High whole−body vibration amplitudes were consistently shown to associated with a range of underground coal mining equipment. Vibration levels which exceed the ISO2631.1 Health Guidance Caution Zone were measured from shuttle cars, driver and rear seat passengers in personnel transport, as well as utility equipment primarily employed to transport materials. Shuttle cars, in particular, were associated with VDV(8) measurements which well exceeded the Health Guidance Caution Zone for an 8 hour exposure, suggesting that adverse health effects are a likely consequence of long term exposure. In the absence of other control measures, underground coal sites should consider restricting the daily exposure of operators to these vehicles. Replacing worn shuttle car seats was demonstrated to have potential to provide a meaningful benefit in reducing vertical vibration amplitudes by 0.12 m/s^2 r.m.s. and 6.3 $m/s^{1.75}$ VDV(8).

Another area of particular concern noted was the exposure of rear seat passengers in personnel transport vehicles. Vehicle speed was demonstrated to have a large influence on whole-body vibration amplitudes at both driver and rear passenger seats, however the effect was magnified considerably for rear seat passengers. The influence of improving roadway standards on whole-body vibration amplitudes was demonstrated through a finding of clear differences between vertical vibration measurements taken before and after roadway maintenance. The use of the WBV application to undertake regular surveys of roadway standards provides an opportunity for underground coal sites to ensure appropriate roadway maintenance is undertaken when required. In general, the WBV application offers sites the opportunity to assess the effectiveness of whole-body vibration control measures

The above scenario demonstrates that the WBV application installed on an iPod touch device allows collection of whole-body vibration measurements and provides the potential to evaluate the effectiveness of suggested control measures as part of sites' health management systems. The research has provided greater understanding of the causes of the elevated measurements and allowed the sites to measure the effectiveness of potential control measures in reducing whole-body vibration exposures associated with underground mining equipment.

Introduction

Prolonged exposure to high amplitude whole-body vibration is strongly associated with the subsequent development of back pain. The outcome of Coal Services Health and Safety Trust (CSHST) project 20624 was the development of an iOS application (WBV) that allows an iPod Touch to be used to estimate whole-body vibration exposures (Wolfgang & Burgess−Limerick, 2014; Wolfgang et al., 2014). The devices were subsequently validated and used at a central Queensland surface coal mine to describe the exposures associated with surface coal mining equipment (Burgess-Limerick & Lynas, 2015, 2016a; 2016b). CSHST project 20638 (Burgess-Limerick & Lynas 2016c) demonstrated that the iPod devices may be effectively utilised in underground coal mines, and confirmed that high amplitude whole-body vibrations are experienced by operators of mobile plant in underground coal mines. However, the causes of these elevated vibration levels are not fully understood and the relative effectiveness of the range potential control measures is not known. The objectives of the current project are to investigate elevated whole-body vibration exposure levels associated with underground coal in normal operation, and to evaluate a range of potential control measures to reduce exposure to this health hazard.

Drivers and passengers of mobile plant, equipment, or vehicles are exposed to vibration transmitted through the seat, with frequencies between 1 and 20 Hz corresponding with the resonant frequencies of body tissues in the trunk. Long term exposure to high amplitude accelerations at these frequencies have been identified as a significant contributor to the subsequent development of back pain (Bernard 1997; Bovenzi and Hulshof, 1998; Sandover, 1983; Wilder and Pope, 1996). Such exposures have also been directly or indirectly linked as a contributor to adverse health consequences for the cardiovascular, nervous, digestive, metabolic, endocrine and reproductive systems (Griffin, 1990; Thalheimer, 1996). The effects of whole−body vibration are cumulative, often taking a number of years for associated health changes to occur.

Exposure to hazardous levels of whole−body vibration has been recognised by the mining industry as a significant issue. Both ACARP and the CSHST have identified management of whole−body vibration exposure as a priority area for research, and the topic has been the subject of previous CSHST funded research (McPhee et al, 2009). The NSW Department of Industry, Mining Design Guideline 1009 "*Managing road and vehicle operating areas in underground coal mines"* makes specific mention of operator exposure to whole−body vibration. Guidance has also been provided to mining companies and mining equipment manufacturers by the NSW mine safety regulator in MDG15 "*Guidelines for Mobile and Transportable Equipment for Use in Mines*" which stipulates in clause 3.6.3 that:

> *Adequate preventative measures shall be taken to prevent excessive vibration being transmitted to the Operator during the operation of any equipment. The transmitted vibration during operations shall not exceed the levels specified by AS2670.1. 'Evaluation of human exposure to whole−body vibration − General requirements'.*

The NSW Department of Industry, Division of Resources and Energy requires all mines sites to have in place a Health Management System, and the management of whole−body vibration exposure is a priority areas that requires a site specific management plan.

ISO 2631−1 / AS2670.1 (ISO, 1997; 2010) describes procedures for the evaluation of whole-body vibration. The standard identifies acceleration as the primary quantity by which to measure vibration and provides direction regarding measurement calculations. The basic evaluation method is the calculation of the weighted root−mean−square (r.m.s) acceleration in units m/s^2. The

Vibration Dose Value (VDV) is an alternative fourth root measure which is more sensitive to high amplitude jolts and jars and provides a better indicator of health risks of vibrations containing transient high acceleration values. No measurement durations are specified, however, the standard indicates measurement should be “sufficient to ensure reasonable statistical precision and to ensure that the vibration is typical of the exposures that are being assessed”. Similarly, the standard does not specify exposure limits, instead providing guidance regarding the evaluation of health effects, in the form of a “Health Guidance Caution Zone” (HGCZ). For exposures below this zone it is suggested no health effects have been clearly documented. For exposures within the Health Guidance Caution Zone “caution with respect to potential health risks is indicated”, and for acceleration values greater than the Health Guidance Caution Zone it is suggested that “health risks are likely”. For an 8 hour daily exposure, the upper and lower bounds of the Health Guidance Caution Zone are 0.47 m/s^2 and 0.93 m/s^2 r.m.s., respectively. The corresponding values for the VDV measure expressed as an 8 hour equivalent [VDV(8)] are 8.5 $m/s^{1.75}$ and 17 $m/s^{1.75}$.

A range of mobile plant and equipment are used at underground mining operations including shuttle cars, load-haul-dump, and personnel transport vehicles. Whole−body vibration exposures experienced by mining equipment operators are a function of many variables including equipment design; seat design, condition and adjustment; roadway conditions; vehicle maintenance; activity undertaken; and driver behaviour. Many of these variables are dynamic in nature, varying over time periods ranging from hours (activity undertaken), days (roadway conditions, seat adjustment), months (vehicle maintenance), or years (equipment design). Managing such a dynamic hazard is currently challenging for underground mine sites because frequent and systematic measurement of whole−body vibration has not been feasible with existing technology.

Conventional measurement of whole−body vibration involves a three−dimensional accelerometer mounted in a seat pad connected by a cable to a data analysis and storage module. Obtaining sufficient whole−body vibration measurements at underground coal mines to manage exposure to the hazard has previously been difficult because of the complexity, expense, and relative fragility of the measurement equipment. Consequently, relatively few measurements of whole−body vibration are routinely undertaken at underground coal mines. Such *ad hoc* measurements are unlikely to reliably capture the varying degrees of whole-body vibration exposure experienced by equipment operators or provide the information required to effectively manage operator whole−body vibration exposures. CSHST project 20638 (Burgess-Limerick & Lynas 2016c) demonstrated that the iPod devices provided accurate measurements confirming high amplitude whole-body vibrations are experienced by operators of underground mobile plant. This project seeks to better understand the operational conditions in which these high amplitude vibrations are experienced. The first part of this report describes exposure levels measured from a range of mobile underground mining equipment used in underground coal operations at Clarence, Airly and Springvale sites. The second part of the report describes the outcomes of investigations to assess the magnitude of improvements associated with potential control measures.

Part 1: Whole-body vibration measurements at underground coal mines

Data collection

Site visits were undertaken from February 2017 to March 2019. During this time measurements were obtained at the three participating sites (Clarence, Airly and Springvale collieries). The visits yielded 186 long duration whole-body vibration measurements from a range of underground equipment (Shuttle Cars, N=140; PJB/SMV, N=61; LHD etc, N=22), and 128 short duration measurements from transport vehicles to measure the effects of speed and roadway condition on whole-body vibration exposure levels. CSHST project 20638 highlighted operator exposures to whole-body vibration exceeding the ISO2631.1 Health Guidance Caution Zone measured from shuttle cars, driver and rear seats of personnel transport vehicles, and equipment transport vehicles. To investigate this further, measurements were obtained from a number of scenarios during normal mine site operations. Across the three sites, recorded measurements are summarised in Table 1. A visit to Androck Engineering and Mining (Rutherford) was also undertaken in May 2018 to inspect an new shuttle car being built for Centennial Coal.

Table 1: Summary of measurements taken during site visits 2017-2019 across the three sites.

Site	Shuttle cars	Utility vehicles / Equipment Transport	SMV/PJB	Short Duration Measurements
Clarence	91	16	19	Roadway maintenance 14 Speed 91 Dollycar 1
Airly	38	6	3	24 Speed
Springvale	13			
Median measurement duration (hrs)	3.2	2.4	1.8	

Method

The development and validation of an iOS application (WBV) has made it possible to use consumer hardware to gather long duration whole-body vibration exposure estimates across many pieces of equipment simultaneously (Wolfgang & Burgess-Limerick, 2014a; Wolfgang et al. 2014b; Burgess-Limerick & Westerfield, 2014; Burgess-Limerick & Lynas, 2015).

A 5th generation iPod Touch (Apple Inc., Cupertino, CA) (123 x 59 x 6 mm, 88g) incorporates a factory calibrated LIS331DLH accelerometer (STMicroelectronics, Geneva, Switzerland) providing three dimensional 16 bit data output configured to a range of +/- 2g. The maximum sampling rate is restricted by the operating system to a nominal 100 Hz, although in practice the sampling rate achieved is closer to 90Hz (Wolfgang and Burgess-Limerick, 2014a). Site data collection and analysis by Wolfgang and Burgess-Limerick (2014b) and Wolfgang et.al (2014) demonstrated the potential for such devices to gather accelerometer data of suitable accuracy to estimate whole-body vibration amplitudes in conventional vehicles and off-road mining equipment respectively.

The iOS application (WBV) (Burgess-Limerick & Westerfield, 2014) allows the collection of three-dimensional accelerometer data from an iPod Touch placed on the seat of a vehicle or mobile plant in operation. At the conclusion of a trial the Wd and Wk frequency weightings are applied to the raw accelerometer data as specified by ISO2631.1. The iPod sampling rate limitations and variability in inter-sample interval reported by Wolfgang and Burgess- Limerick (2014b) are likely to be the principal source of any inaccuracies in the estimation of whole-body vibration. However, in addition to the accuracy assessments undertaken during development of the application, Burgess-Limerick & Lynas (2015) subsequently collected 96 simultaneous pairs of whole-body vibration measurements from the WBV application installed on an iPod Touch and a commercially available whole-body vibration device during the normal operation of a variety of vehicles and mobile plant at a surface coal mine. The iOS application was shown to provide a 95% confidence of +/− 0.077 m/s^2 r.m.s. constant error for the vertical direction when compared to the gold standard device. Situations in which vibration levels lay outside the ISO2631.1 Health Guidance Caution Zone were accurately identified, and the qualitative features of the frequency spectra were reproduced.

Each iPod Touch was secured in a pocket sewn onto a neoprene square (350 mm). A reflective label was attached to one corner of each neoprene square which allowed iPod trial identifying information to be attached. Prior to each shift commencement, operators received individual instruction on how and where to place the neoprene square so that the iPod was located lengthways under the ischial tuberosities of the operator once seated (Figure 1) . The device was returned at the end of each shift for data retrieval. Whilst there is potential for operator error in iPod placement, subsequent data inspection indicated data patterns recorded to be consistent with that expected during respective equipment operation.

Figure 1: iPod placement on the seat of transport vehicle.

Analysis

Analysis of the data collected requires visual inspection and editing and this process was undertaken following each site visit. The WBV application was configured to record consecutive 20 minute samples of three-dimensional accelerometer data for the total shift duration for the long duration trials, and to record 5 minute samples where short duration measurements were obtained (e.g. for analysis of the effect of vehicle speed on whole-body vibration exposure levels). The application applied Wd and Wk frequency weightings specified by ISO2631.1 to horizontal (X, Y) and vertical (Z) accelerations respectively. The filtered accelerometer data gathered in each sample were subsequently downloaded and visually inspected. Samples in which minimal acceleration levels (less than 0.1 m/s^2 peak to peak) indicating that the equipment was not in operation were recorded for greater than ten minutes were discarded. r.m.s values and VDV values were calculated for total measurement. The VDV measures were extrapolated to an eight-hour exposure VDV(8).

Results and Discussion

Figure 2 illustrates typical frequency weighted vertical whole-body vibration recordings obtained from a range of underground coal mine mobile plant. The corresponding frequency spectra are illustrated in Figure 3.

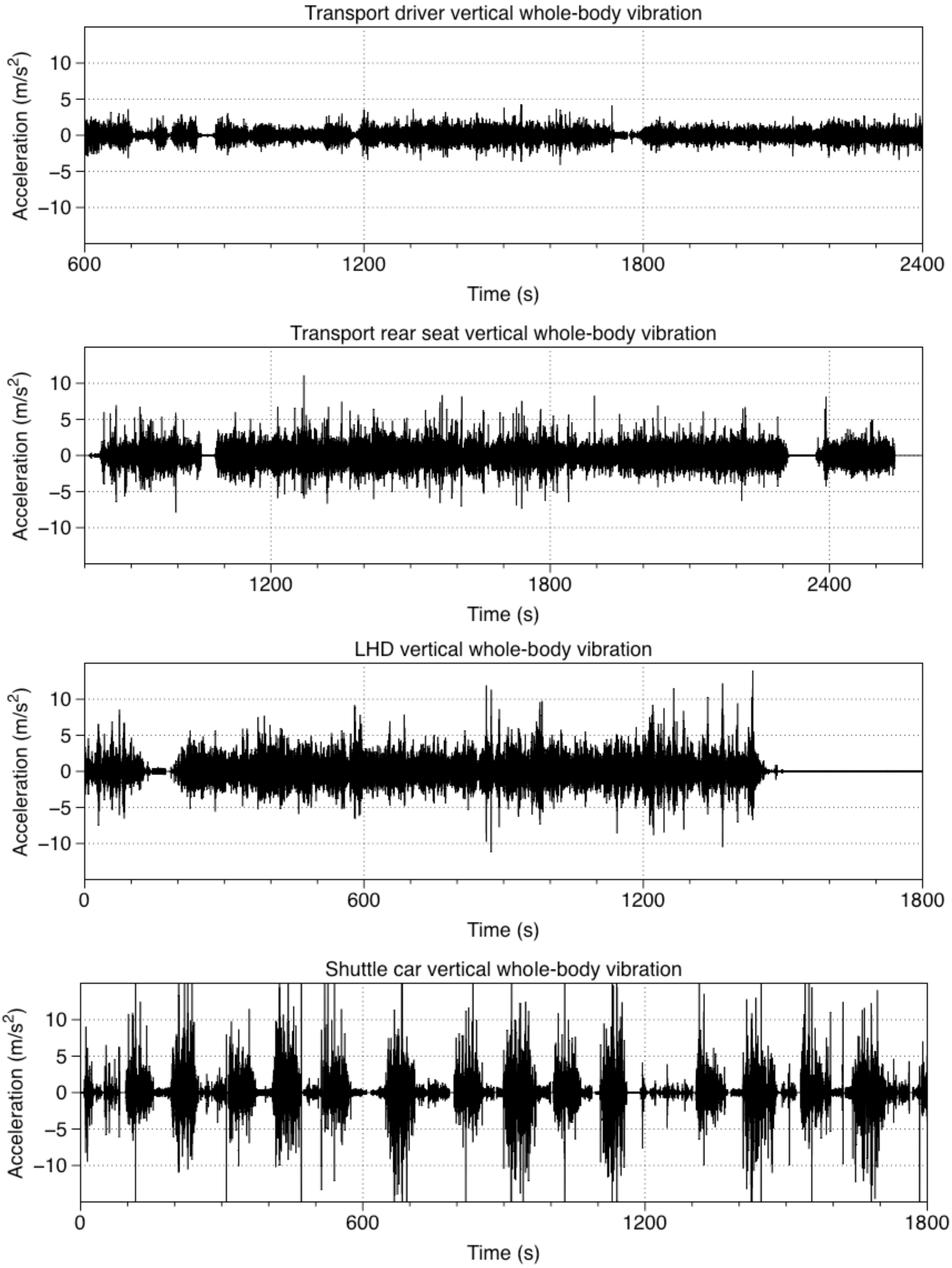

Figure 2: Frequency weighted vertical whole−body vibration samples taken from a range of underground coal mining equipment.

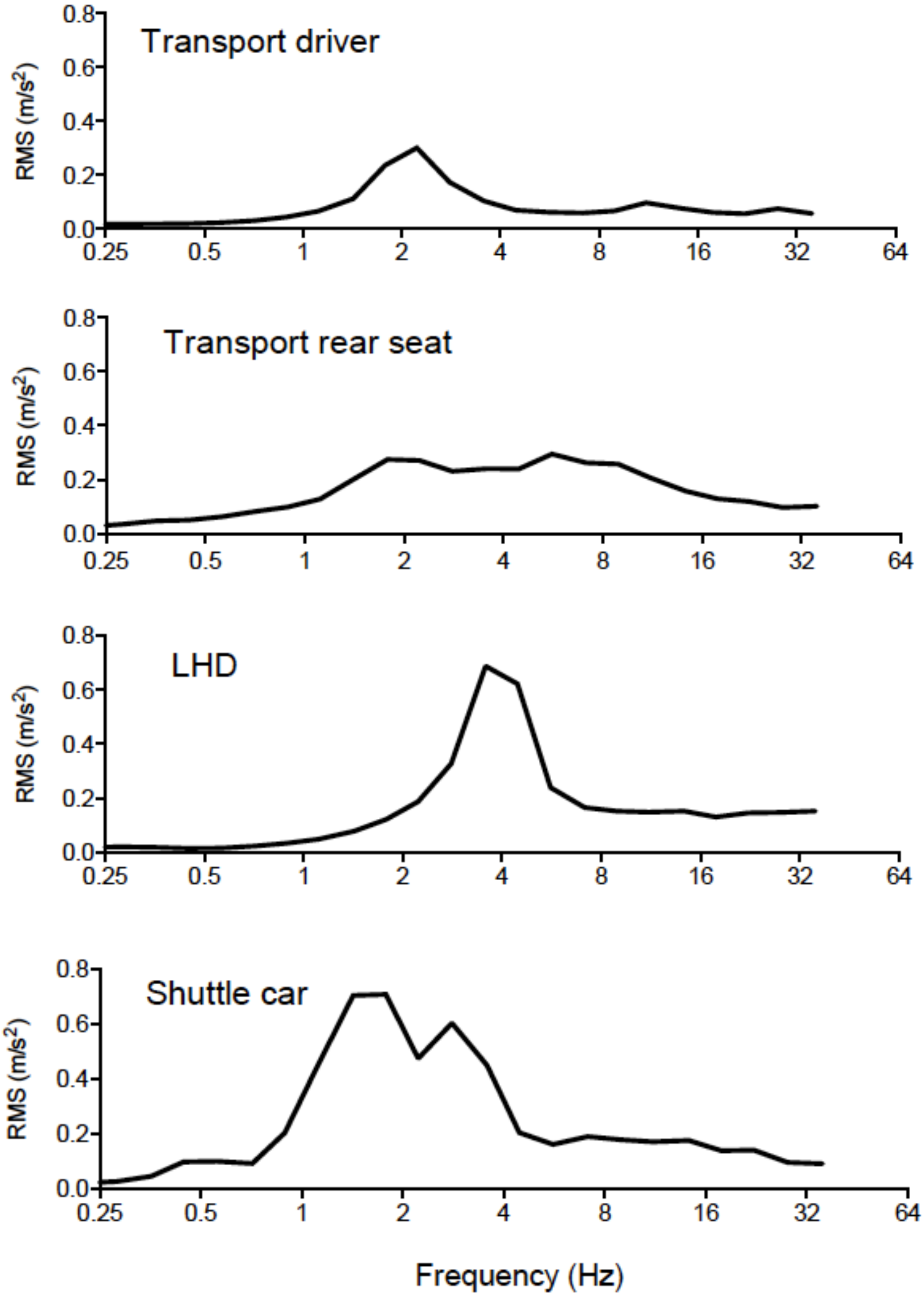

Figure 3: Frequency spectra for vertical whole-body acceleration measurements taken from a range of underground coal mining equipment.

Shuttle cars were identified as requiring more detailed examination. Figure 4 illustrates the vertical whole-body vibration measurements obtained from shuttle cars operating at each site during 2017-2019 visits. Considerable variability was evident, however the measurements indicated high amplitudes of whole-body vibration with all except two measurements exceeding the ISO 2631.1 Health Guidance Caution Zone for both VDV(8) and r.m.s. The average r.m.s and VDV(8) shuttle car measurements obtained for each site were 0.90 m/s^2, 0.83 m/s^2, 0.55 m/s^2 and 31.44 m/s$^{1.75}$, 31.55 m/s$^{1.75}$, 23.78 m/s$^{1.75}$, for Airly, Clarence and Springvale site respectively.

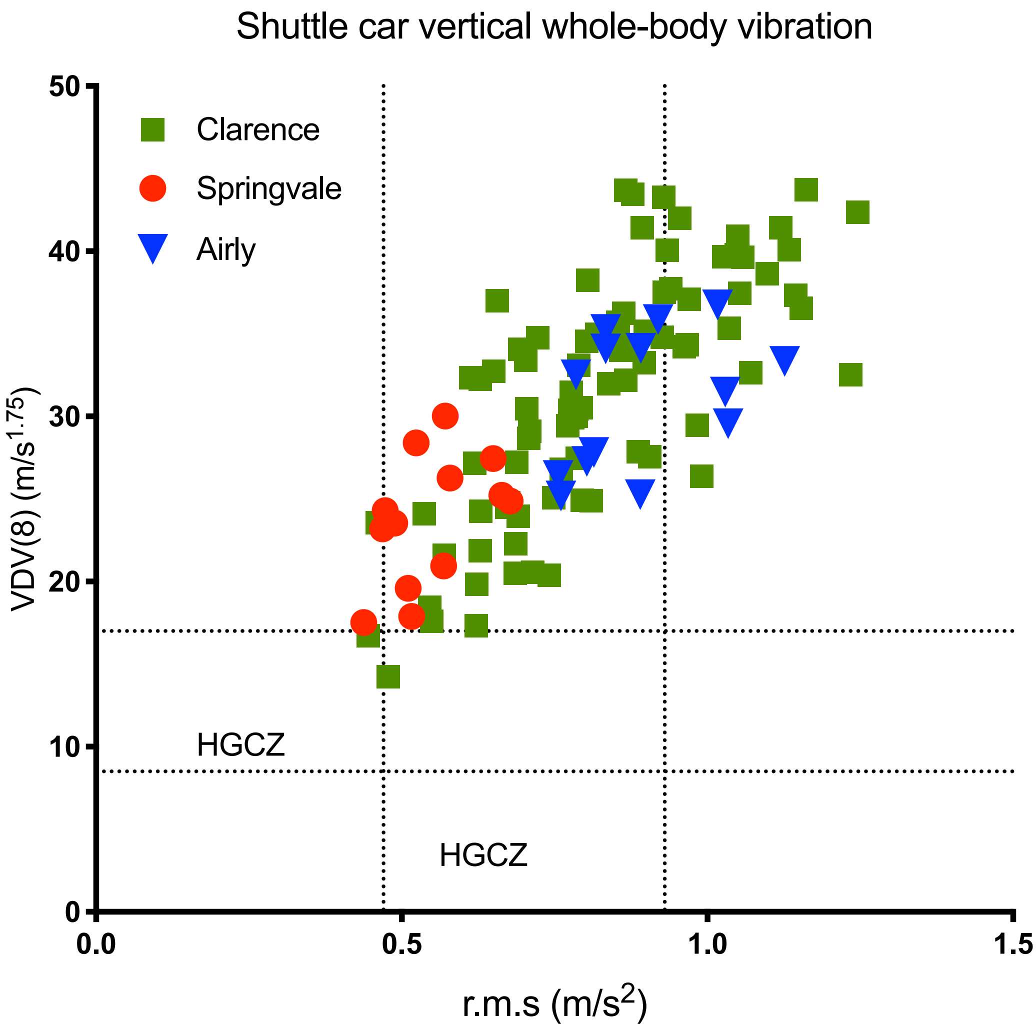

Figure 4: Vertical whole-body vibration measurements taken from shuttle cars at three underground coal mines. The data are expressed as VDV(8) and r.m.s. with respect to the ISO2631.1 Health Guidance Caution Zone (HGCZ) for an 8 hour daily exposure.

Figure 5 illustrates shuttle car data from each site by individual cars. The range of values recorded from individual shuttle cars appears to be large. The differences observed between sites are likely to be a consequence of different mining methods (longwall vs place change) which in turn influences roadway conditions, wheeling distances, wait time, and the number of trips each car makes per shift. Other influencing factors accounting for the variability of measurements from a single car include the condition and adjustability of the seat mechanism (including driver knowledge of appropriate adjustment); tyre composition/suspension of each car; roadway conditions over which the cars are operating; and the behaviour of the operator.

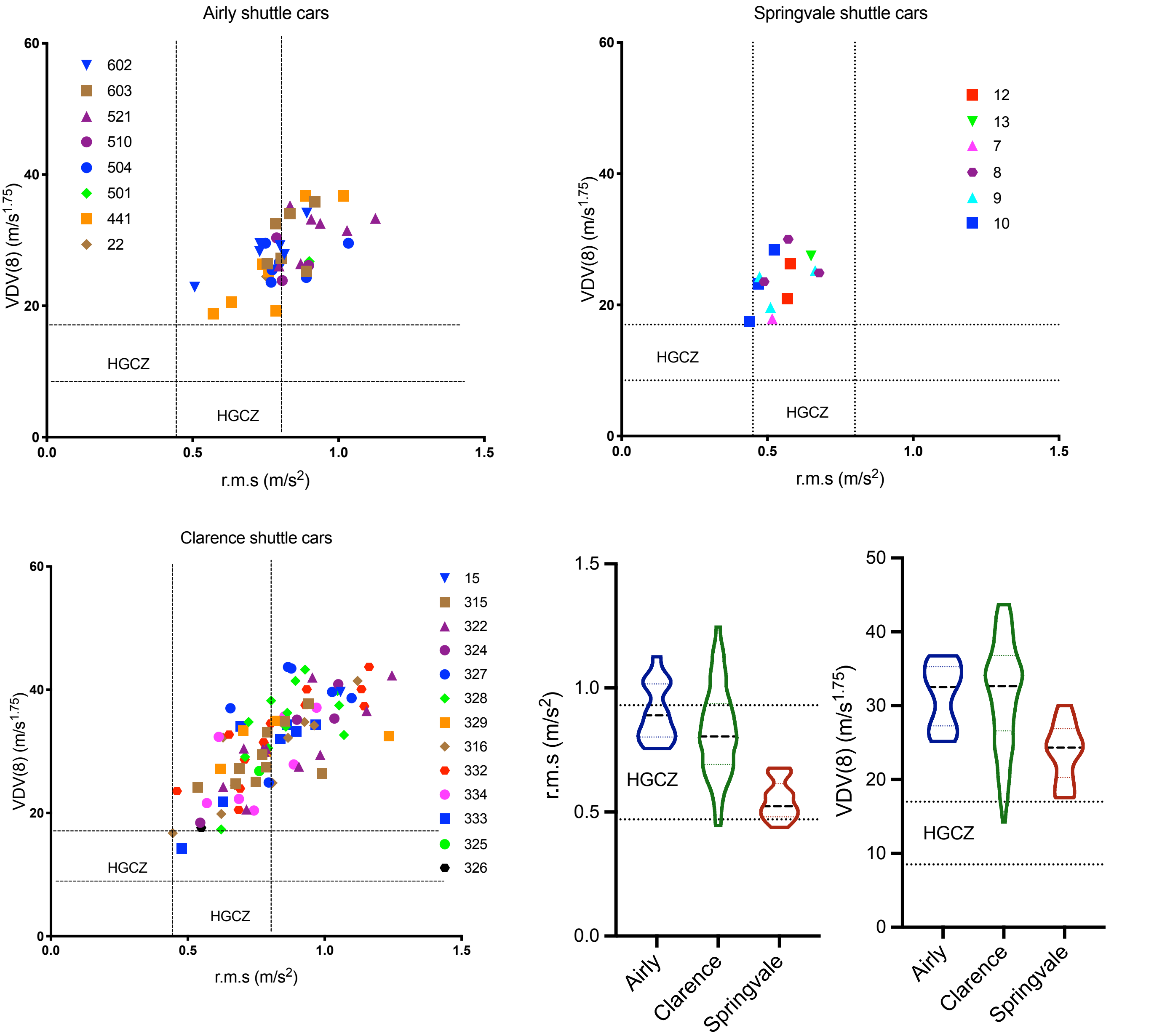

Figure 5: Vertical whole-body vibration measurements taken from shuttle cars at three underground coal mines for individual shuttle cars. The data are expressed as VDV(8) and r.m.s. with respect to the ISO2631.1 Health Guidance Caution Zone (HGCZ) for an 8 hour daily exposure.

Figure 6 illustrates personnel transport vehicle data obtained during Clarence site visits in 2017-2018 from driver and rear seat passenger travelling the main access road. Whilst travel time is relatively short, all measurements fall either within the Health Guidance Caution Zone (HGCZ) or above for both VDV(8) and r.m.s. values, suggesting that attention to these exposures is justified. To investigate this further, a number of measurements were subsequently taken from both from and rear seat positions in SMV and PJB vehicles. For example, during 2019 two site visits to Clarence mine yielded 34 paired driver and passenger measurements for travel into and out of the mine, aligning the vehicle measurements with roadway maintenance activity. These, and other measurements taken at both Clarence and Airly sites to investigate the effects of vehicle speed and roadway conditions on whole-body vibration exposures are discussed in further detail in the second section of this report.

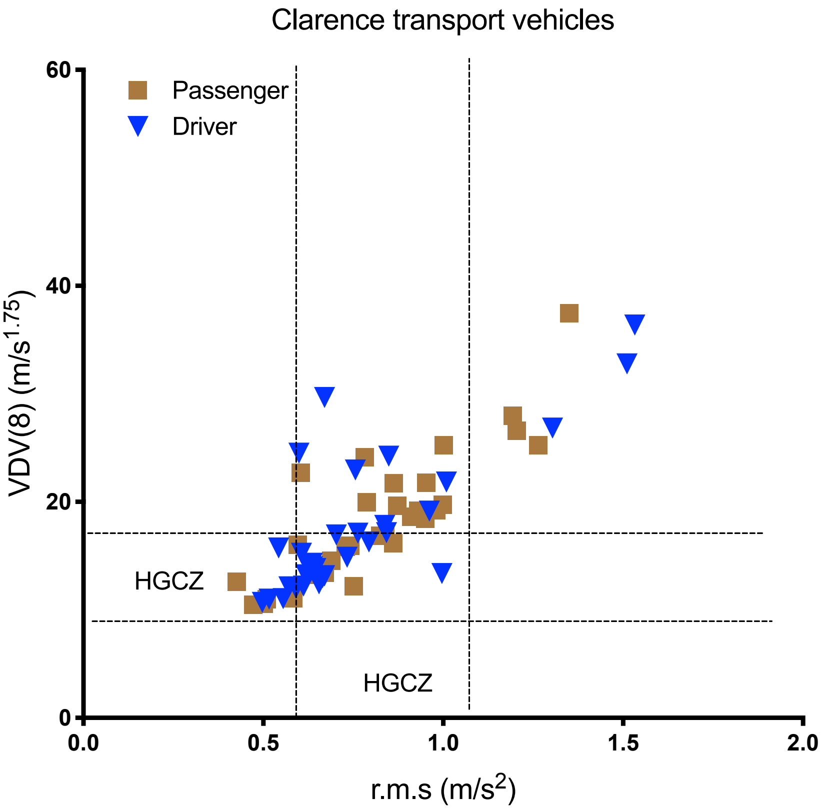

Figure 6: Vertical whole-body vibration measurements taken from personnel transport vehicles (SMV/PJB) at Clarence underground coal mine. The data are provided for driver and passenger and expressed as VDV(8) and r.m.s. with respect to the ISO2631.1 Health Guidance Caution Zone (HGCZ) for an 8 hour daily exposure.

Figure 7 illustrates utility vehicle (primarily materials transport) data obtained from Clarence and Airly sites. The majority of measurements recorded from both sites, for both VDV(8) and r.m.s. lie above the upper limits of the Health Guidance Caution Zone. Utility vehicles undertake a number of tasks during a shift and may be operated with different attachments depending on task requirements (e.g. duck bill, bolt pods, road leveller, cable reel, gravel trailer) and may be travelling with a full or empty bucket. While collecting measurements from these vehicles (EIMCO, LHD, coal tram) at Clarence site additional data collection relating to the tasks undertaken during the shift was sought (e.g. information on roadway condition; seat condition and adjustability; travel distances), unfortunately not all operators provided this information which prevented further analysis. Figure 8 provides a comparison between personnel and supply vehicle VDV(8) and r.m.s. from data obtained during visits to Clarence mine site in 2018. All vehicles demonstrated measurements exceeding the HGCZ for both VDV(8) and r.m.s., confirming both personnel and utility vehicles are sources of operator exposures in excess of the HGCZ and deserving of the implementation of control measures to reduce these exposure levels.

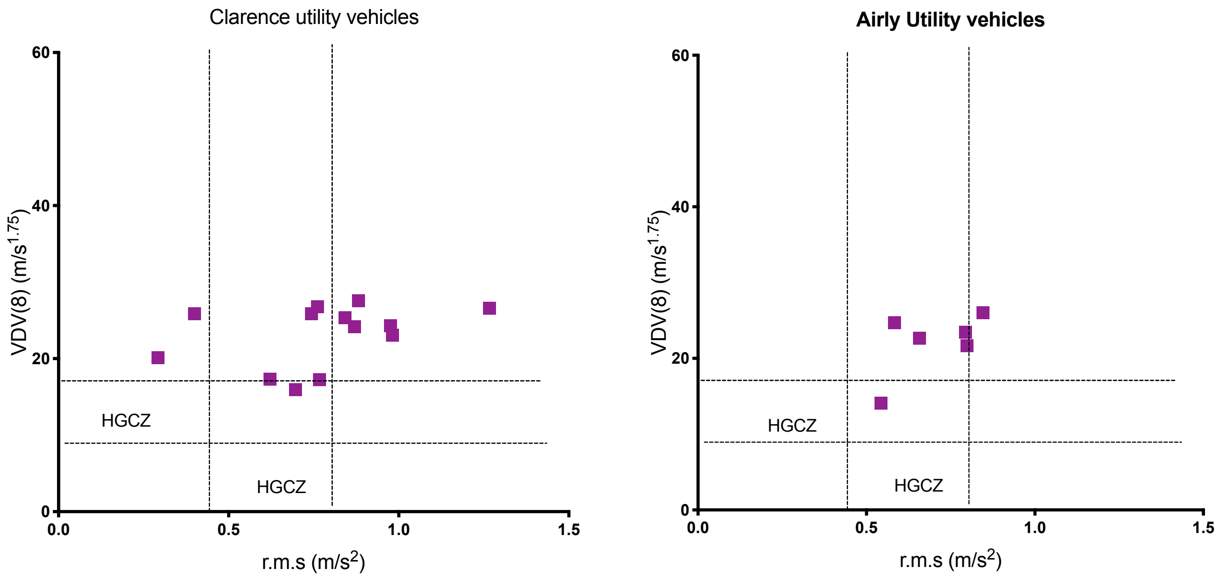

Figure 7: Vertical whole-body vibration measurements taken from utility vehicles (LHD's) at Clarence and Airly mines. The data are expressed as VDV(8) and r.m.s. with respect to the ISO2631.1 Health Guidance Caution Zone (HGCZ) for an 8 hour daily exposure.

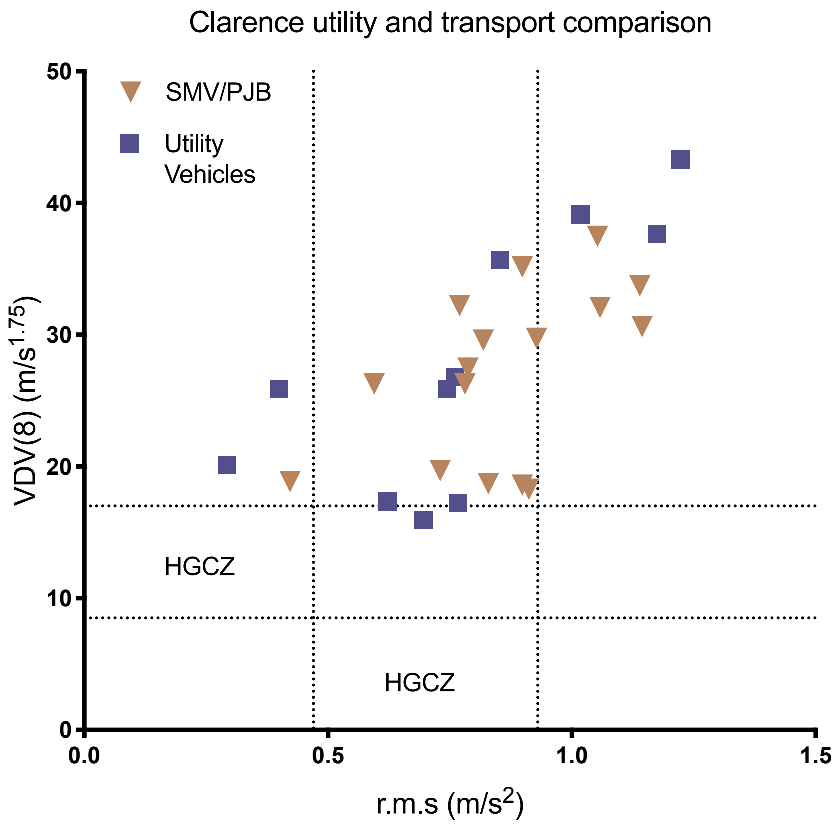

Figure 8: Comparison vertical whole-body vibration measurements taken from personnel and supply vehicles at Clarence mine. The data are expressed as VDV(8) and r.m.s. with respect to ISO2632.1 Health Guidance Caution Zone (HGCZ) for an 8hour daily exposure.

Part 2: Intervention strategies to reduce operator whole-body vibration exposures

Whole-body vibration measurements across a range of equipment used in underground coal operations were collected during CSHST project 20638. This data, combined with data collected during the first stage of this project, provides a comprehensive database of operator exposure measurements. The measurements confirm that the large range of values and the high values obtained from shuttle cars, personnel and equipment transport vehicles during some measurement periods are deserving of further investigation to identify and evaluate potential control measures. Interim project meetings were held with the three participating sites, where interest was expressed in gaining a better understanding the effects of vehicle travel speed and the effect of regular roadway maintenance on the measurements obtained from personnel transport vehicles, and in particular, the differences in exposure levels measured between driver and rear seat passengers. Interest was expressed in determining whether improved shuttle car seating or suspension may reduce vibration exposures associated with this equipment. Sites agreed that additional shuttle car data combined with more detailed information regarding the characteristics of the shuttle cars (model, tyres, seating, maintenance history) may be helpful in understanding which control measures could be most effectively implemented on site to target reductions in operator whole-body vibration exposure levels.

Data collection was undertaken in the following scenarios:

- New seats in two shuttle cars during major refurbishment. Measurements were taken from before and after seat replacement.
- Personnel transport vehicles were driven at different speeds over the same roadway with data collected from driver and rear passengers.
- Personnel vehicles travelling into and out of the mine site over the same roadway pre and post roadway maintenance (including paired data from driver and rear passenger travelling into and out of the mine site) was undertaken at one site.

Seat replacement

The effect of replacing worn shuttle car seats with new seats was evaluated at Clarence. Two of shuttle cars were fitted with new seats (one KAB the other Sears). Seat design, condition and adjustment is known to influence operator whole-body vibration exposure levels (Blood et.al, 2010; Paddan & Griffin, 2002). However, seat installation needs to suit both the vehicle and its operating environment, and performance differences across seats may have significant health implications for drivers and equipment operators (Blood et.at, 2010). Weight adjustability is often incorporated in seat design and manufacture, which implies a manual adjustment that is often overlooked in practice on site, or confused with height adjustment. Appropriate seat adjustment requires operator understanding of, and training in, how to correctly adjust the seat, and automatic weight sensing and adjustment is more likely to be effective in vibration attenuation.

In late 2017, the worn seats in shuttle car 324 were replaced with new Sears seats. (Figure 9 shows seat condition before and new replacement seats). In 2018, a second shuttle car (SC 325) was refurbished and the seats were replaced with KAB seats. Whole-body vibration measurements were recorded before and after seat replacement. Floor and seat measurements were also obtained during two shifts from shuttle car 325 prior to seat replacement. The vertical r.m.s. SEAT measurements obtained were 1.08 and 0.97, indicating that the worn seat was providing little, if any, attenuation of vertical whole-body vibration.

Figure 9: Seat condition before replacement and new seats awaiting installation.

Figure 10 illustrates VDV(8) and r.m.s. vertical whole-body vibration values obtained from the two shuttle cars following new seat installation (N=9) compared to values observed with the old seats (N=7). While the small number of measurements precluded meaningful statistical comparison, the vertical whole-body vibration amplitudes measured after the change were lower for both shuttle cars. The average reduction in r.m.s. and VDV(8) amplitudes across both cars was 0.12 m/s² r.m.s. and 6.34 $m/s^{1.75}$ VDV(8) which represents a meaningful improvement.

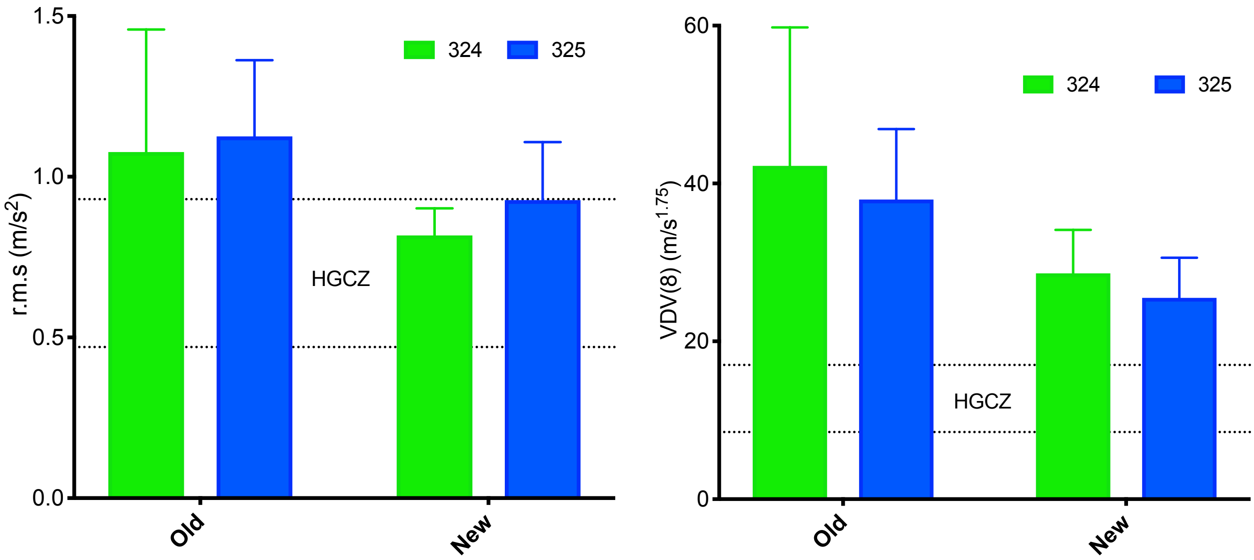

Figure 10: r.m.s. (left panel) and VDV(8) (right panel) vertical whole-body vibration measurements from two shuttle cars before and after seat replacement (mean and SD).

Driving Speed

Vehicle speed has a direct impact of whole-body vibration amplitude (Smets et.al, 2010; Wolfgang & Burgess-Limerick, 2014b). Measurements undertaken as part of CSHST project 20638 demonstrated higher vertical vibration levels for rear seat passengers than the driver of the vehicle. This prompted further investigation of the effects of speed on whole-body vibration exposures during this project.

To investigate further the effect of vehicle speed on whole-body vibration exposure levels, the iPod touch devices were used to gather measurements from the driver and front seat passenger of an SMV personnel transport vehicle traversing the same section of the main access road at 2 different speeds (Figure 11). The vehicle's speedometer was not functioning and the experienced driver estimated the speed of vehicle, driving the vehicle either: (i) "flat out" at a speed reflecting the vehicle driven as fast as it would normally be driven or (ii) at a slowest speed (approximately 5 km/h). Slightly higher r.m.s and VDV(8) amplitudes were recorded for the passenger than for the driver at the slowest speed, however the difference was greatly magnified at the higher speed indicating the difference in seating provided for driver and front passenger.

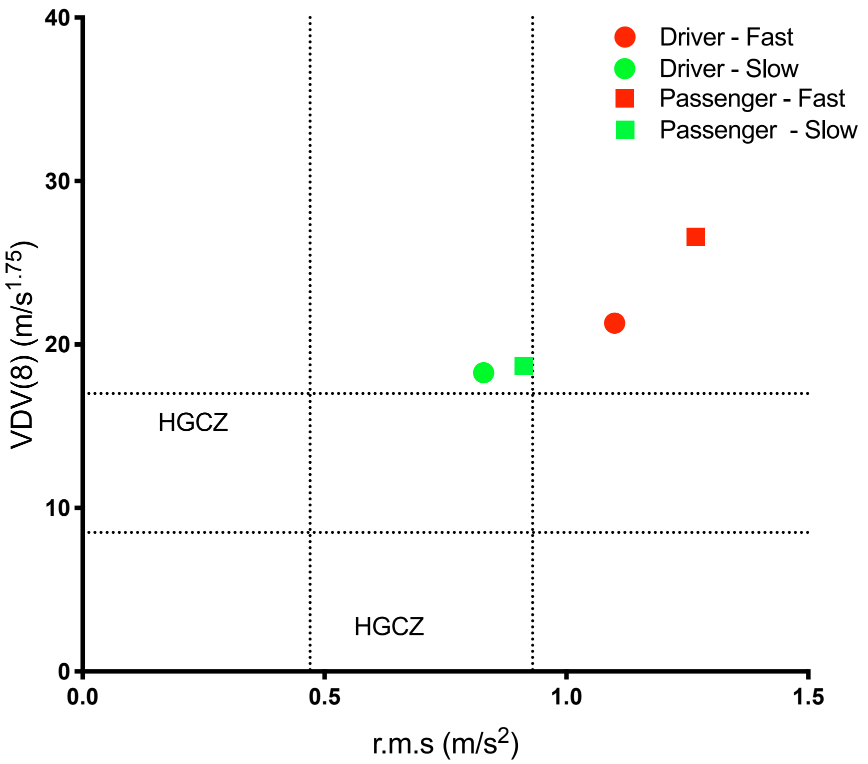

Figure 11: Vertical whole-body vibration amplitude for SMV driver and front passenger at slow and fast vehicle speeds.

Measurements were subsequently taken from two different personnel transport vehicles (PJB R510 and SMV502) driven by the same driver over the same stretch of roadway at Airly, a round trip distance of 1.1km each way, at three different speeds as follows:

SMV 502: Average Speed 1: 10 km/hr
Average Speed 2: 16km/hr
Average Speed 3: 22km/hr

PJB 510: Average Speed 1: 9 km/hr
Average Speed 2: 13km/hr
Average Speed 3: 19km/hr

iPods were placed under the driver of the vehicle and a passenger seated in the rearmost seat. This position, located behind the rear suspension of the vehicle, is known to offer the roughest ride in both types of personnel transport vehicles. Figure 12 illustrates vertical VDV(8) and r.m.s. values for both the driver and rear passenger in PJB R510 and SMV 502 vehicles for the three different speeds.

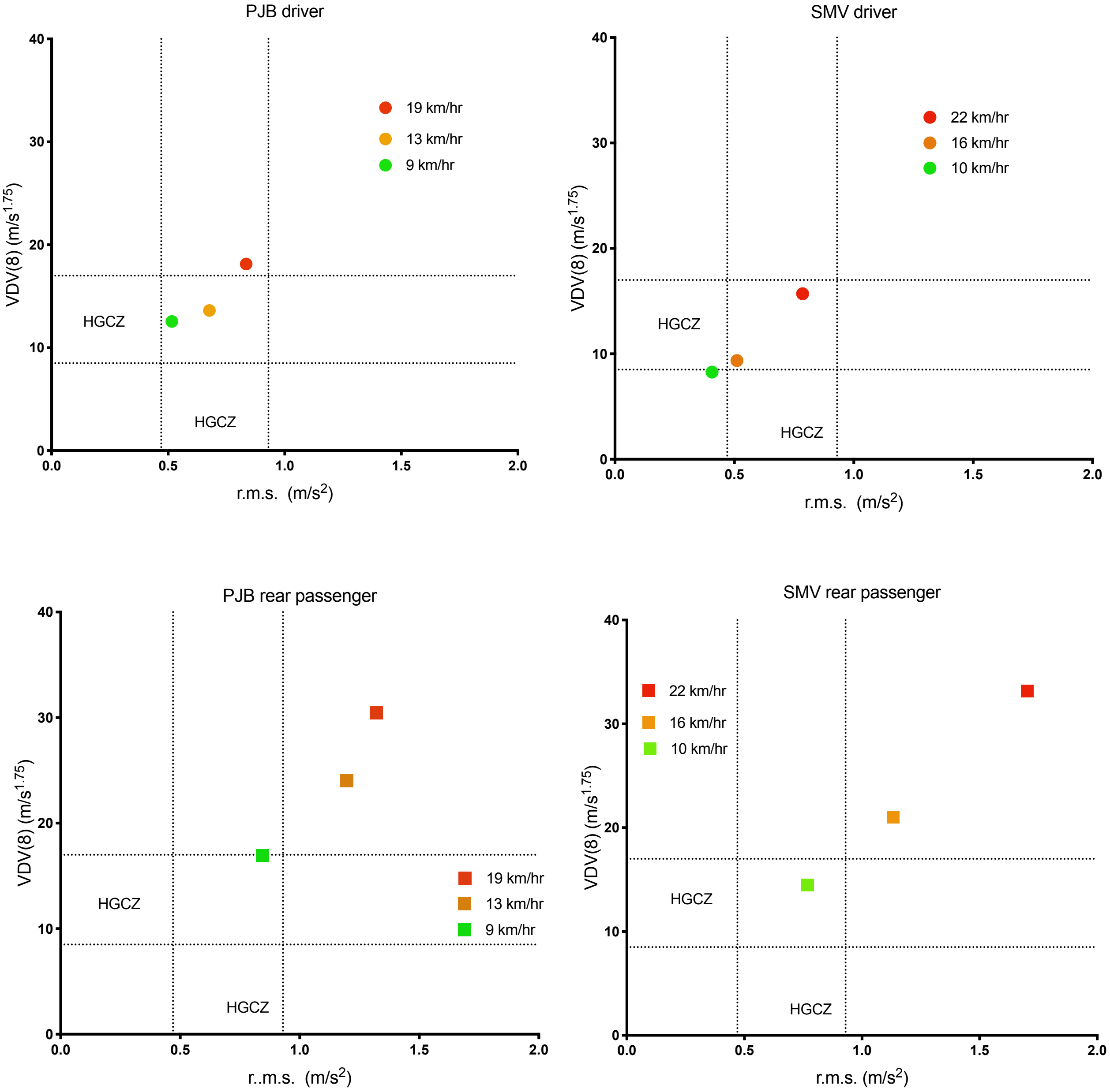

Figure 12: Vertical whole-body vibration amplitude for SMV and PJB driver and rear passenger at slow and fast transport vehicle speeds.

The effect of increasing vehicle speed on increasing vertical vibration amplitudes was consistent regardless of seating position, however while the values measured at the driver's seat for both vehicles was largely within the ISO2631.1 health guidance caution zone regardless of speed, the effect on the rear passenger was much greater, and the vertical vibration measurements well exceeded the HGCZ for speeds greater than 10 km/hr, and were extremely high for the highest speeds.

Although the duration of exposure whilst travelling in the personnel vehicles is typically relatively short, attention to these exposures is justified. Improved roadway standards are a potential means of achieving this. As well as reducing cumulative injuries associated with long term vibration exposure, improving roadway standards are important to avoid instantaneous injuries which occur as a consequence of rear passengers being thrown into the roof when transport vehicles travel into pot-holes at speed.

Roadway maintenance

In general, vibration amplitudes during equipment operation are known to be influenced by a number of factors including the the roadway or surface condition (Lewis & Johnson, 2012). Data collection to investigate the effectiveness of regular roadway maintenance was undertaken on two separate visits to Clarence mine site.

A series of whole-body vibration measurements was obtained in March 2017 using the iPod Touch device placed on the seat of personnel transport vehicle (SMV09). Measurements were also obtained from a passenger seated behind the driver as the vehicle travelled out-bye and panel travel roads. Measurements were taken prior to roadway maintenance and repeated following maintenance to parts of the affected roadways. On both occasions the vehicle was driven by the same driver and the vehicle remained the same. The vehicle was driven in low gear during much of the travel due to the poor roadway conditions. The iPod WBV application was set to record at 5-minute intervals, and a stopwatch was used to assist with documenting location within the mine site corresponding to each 5-minute interval. The rear seat passenger documented the roadway conditions as described by the driver and recorded in 5-minute intervals. Following the initial measurements, roadway maintenance was carried out on parts of the affected roadway. Whole-body vibration measurements and data analysis was repeated using the WBV application in the same manner as described previously.

Measurements were obtained at 5-minute intervals from driver and passenger seat positions as the vehicle travelled from the diesel bay pit bottom to an operating panel via the main travel road. The VDV(8) measurements for the first 30 minutes of the journey lie largely towards the higher end of the HGCZ as defined in ISO 2631.1 with measurements taken towards the end of travel significantly exceeding the HGCZ limits. VDV(8) measurements are higher for the rear seat passenger than the driver. Figure 13 illustrates the vertical vibration amplitude expressed as VDV(8) for the vehicle journey leaving pit bottom to turning onto the main travel road. The recorded values of the measurements corresponded with the description of roadway conditions on the main travel road as outlined in a previously prepared workplace inspection report. The report indicated severe pothole damage requiring immediate attention.

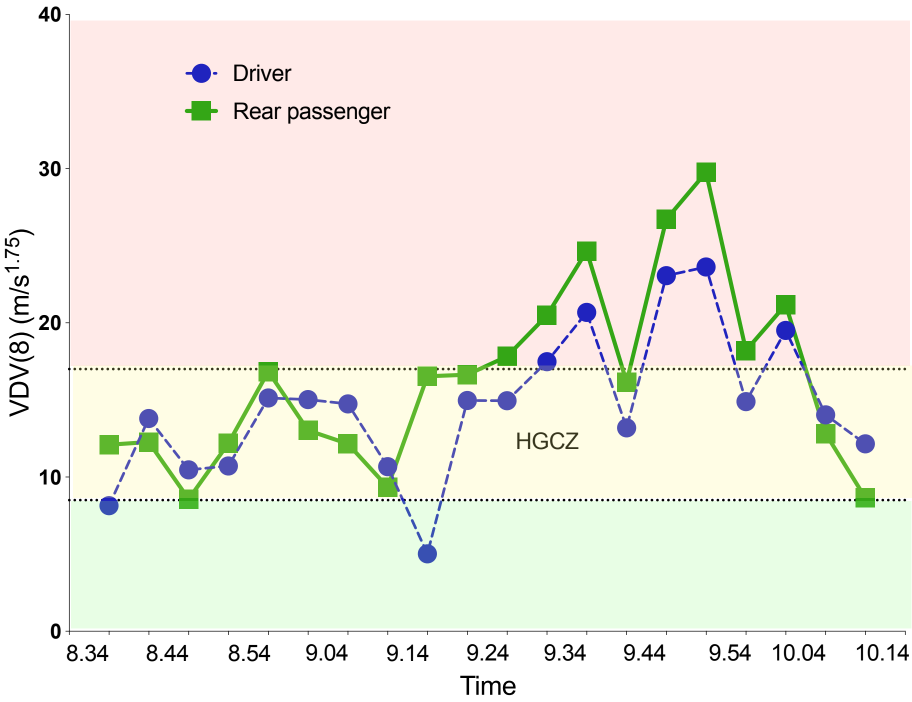

Figure 13: Vertical whole-body vibration amplitude for SMV driver and front passenger at 5 minute intervals during for driver and rear passenger while navigating the main travel road.

The whole-body vibration measurements were repeated following maintenance of the roadway section identified as requiring attention. The driver, vehicle and travel route remained the same. Figure 14 illustrates r.m.s. values for the driver for a 30 minute section of the trip from leaving end of one of the panels and to returning to diesel bay at the pit bottom. The average decrease in vertical whole body vibration amplitude for the driver was 0.195 m/s² r.m.s which is a substantial improvement.

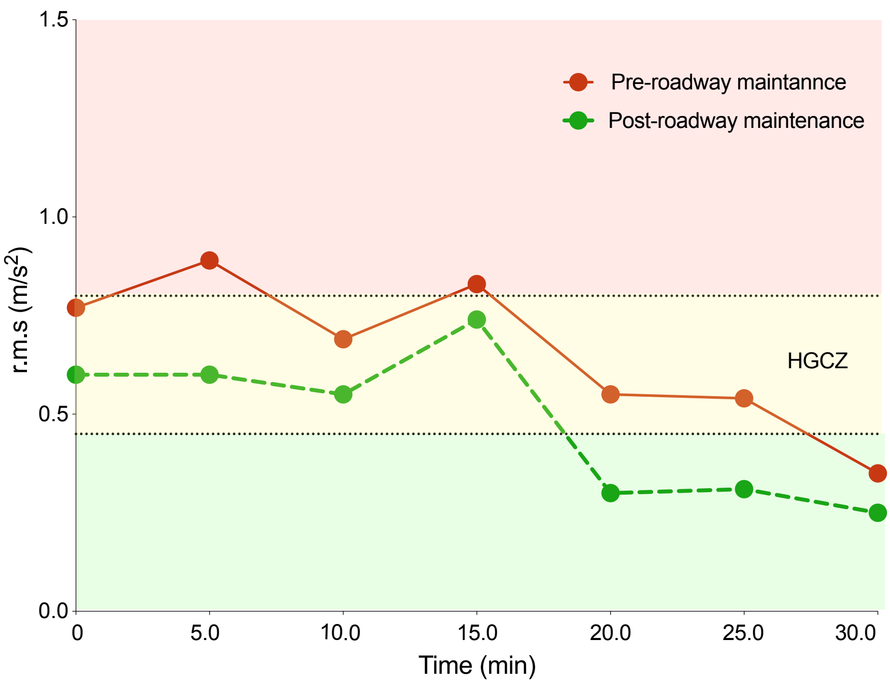

Figure 14: Vertical whole-body vibration amplitude for SMV driver at 5 minute intervals for the same section of roadway before and after maintenance.

Further measurements of transport driver and passenger whole-body vibration before and after roadway maintenance were obtained from the main travel road at Clarence in 2019. Twenty-six measurements were obtained from the driver's seat, and 16 measurements were obtained from rear passenger seats during normal operations over a six day period prior to roadway maintenance being undertaken by the site. A further 18 measurements were obtained from the driver's seat, and 12 from rear passenger seats, over a five day period following roadway maintenance. Figure 16 illustrates the impact of roadway maintenance on vertical whole-body vibration amplitude expressed as r.m.s and VDV(9) for driver (front) and rear seat passengers. The average reduction in vertical whole-body vibration amplitude measured for the driver's seats was 0.093 m/s^2 r.m.s, and 3.6 $m/s^{1.75}$ VDV(8). The average reduction in measured for the rear passenger seats was 0.059 m/s^2 r.m.s, and 2.6 $m/s^{1.75}$ VDV(8).

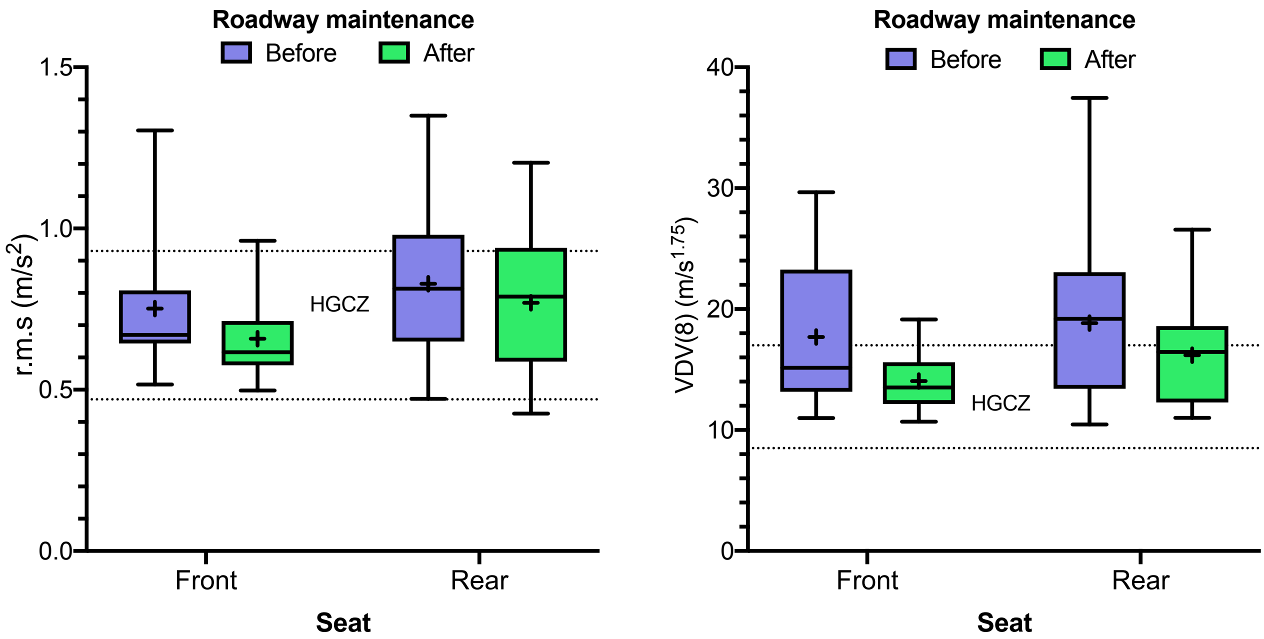

Figure 15: Vertical whole-body vibration amplitude for SMV driver at 5 minute intervals for the same section of roadway before and after maintenance.

Conclusion

High whole−body vibration amplitudes were consistently shown to associated with a range of underground coal mining equipment. Vibration levels which exceed the ISO2631.1 Health Guidance Caution Zone were measured from shuttle cars, driver and rear seat passengers in personnel transport, as well as utility equipment primarily employed to transport materials. Shuttle cars, in particular, were associated with extremely VDV(8) measurements which well exceeded the Health Guidance Caution Zone for an 8 hour exposure. This finding suggest that adverse health effects are a likely consequence of long term exposure. In the absence of other control measures, underground coal sites should consider restricting the daily exposure of operators to these vehicles. Replacing worn shuttle car seats was demonstrated to have potential to provide a meaningful benefit of the order of 0.12 m/s^2 r.m.s. and 6.3 $m/s^{1.75}$ VDV(8).

Another area of particular concern noted was the exposure of rear seat passengers in personnel transport vehicles. Vehicle speed was demonstrated to have a large impact on whole-body vibration amplitudes at both driver and rear passenger seats, however the effect was magnified considerably for rear seat passengers.

The influence of improving roadway standards on whole-body vibration amplitudes was demonstrated through a finding of clear differences between vertical vibration measurements taken before and after roadway maintenance. The use of the WBV application to undertake regular surveys of roadway standards provides an opportunity for underground coal sites to ensure appropriate roadway maintenance is undertaken when required. In general, the WBV application offers sites the opportunity to assess the effectiveness of whole-body vibration control measures

The above scenario demonstrates that the WBV application installed on an iPod touch device allows collection of whole-body vibration measurements and provides the potential to evaluate the effectiveness of suggested control measures as part of sites' health management systems.

Acknowledgements

We thank Peter Smith, Jacques Le Roux, Barry Riley, Adam Stait, Brian Nichols, Dennis Wallace, Greg Guest, Frank Paxton, Paul Irwin and Bob Miller sincerely for their enthusiastic support of the project.

References

Bernard, B.P. (Ed.) (1997). *Musculoskeletal Disorders and Workplace Factors: A Critical Review of Epidemiologic Evidence for Work−related Disorders of the Neck, Upper Extremities, and Low Back.* US Department of Health and Human Services, National Institute of Occupational Safety and Health. DHHS (NIOSH) Publication No. 97−141.

Blood, R.P., Ploger, J.D., Yost, M.G., Chang, R.P. & Johnson, P.W.(2010). Whole-body vibration exposures in metropolitan bus drivers: A comparison of three seats. *Journal of Sound and Vibration.* 329,109-120.

Bovinzi, M., Hulshof C.T.J. (1998). An updated review of epidemiological studies on the relationship between exposure to whole−body vibration and low back pain. *Journal of Sound and Vibration, 215,* 595−611.

Burgess-Limerick, R. & Lynas, D. (2015). An iOS application for evaluating whole−body vibration within a workplace risk management process. *Journal of Occupational and Environmental Hygiene*, *12*, D137−D142.

Burgess−Limerick, R. & Lynas, D. (2016a). Long duration measurements of whole−body vibration exposures associated with surface coal mining equipment compared to previous short−duration measurements. *Journal of Occupational and Environmental Hygiene, 13, 339−345.*

Burgess-Limerick, R. & Lynas, D. (2016b). *Managing Whole-Body Vibration at Surface Coal Mines.* ACARP project C23022 Final Report.

Burgess-Limerick, R. & Lynas, D. (2016c). *Assessing Whole−Body Vibration Exposures of Underground Coal Miners. CSHST* project C20638 Final Report.

Burgess-Limerick, R. & Westerfield, M. (2014). Whole-body vibration. http://w.w.w.byteworks.us/Byte_Works/WBV.html. Accessed 18 March 2018.

Griffin, MJ. (1990). *Handbook of human vibration.* Amsterdam, the Netherlands: Elsevier.

International Standards Organisation (1997). *Evaluation of Human Exposure to Whole−body* Vibration. Part 1 – General Requirements. ISO2631.1. ISO, Geneva, Switzerland.

International Standards Organisation (2010). *Evaluation of Human Exposure to Whole−body Vibration. Part 1 – General Requirements. ISO2631.1. Amendment 1. ISO,* Geneva, Switzerland.

Kim, J.H, Marin, L.S. & Dennerlein, J.T. (2018). Evaluation of commercially available seat suspensions to reduce whole-body vibration exposures in mining heavy equipment vehicle operators. *Applied Ergonomics, 71,78-86.*

Lewis, C.A. & Johnson, P.W. (2012). Whole-body vibration exposure in metropolitan bus drivers. *Occupational Medicine, 62*, 519-24.

McPhee, B., Foster, G., Long, A. (2009). *Bad Vibrations*, second Ed. Coal Services Health &Safety Trust, Sydney.

MDG15 "*Guidelines for Mobile and Transportable Equipment for use in Mines",* New South Wales Department of Planning and Environment, NSW Resources Regulator, revised 2018. resourcesandgeoscience.nsw.gov.au. Accessed 1 April 2019.

Sandover, J. (1983). Dynamic loading as a possible source of low−back disorders. *Spine,* 8: 652−8.

Smets, M.P., Eger, T.R., & Griener, S.G. (2010). Whole-body vibration experienced by haulage truck operators in surface mining operations: A comparison of various analysis methods utilized in the prediction of health risks. *Applied Ergonomics,* 41: 763-70.

Thalheimer, E. (1996). Practical approach to measurement and evaluation of exposure to whole−body vibration in the workplace*. Seminars in Perinatology 20* (1), 77−89.

Wilder, D.G., & Pope, M.H. (1996). Epidemiological and aetiological aspects of low back pain in vibration environment – an update. *Clinical Biomechanics 1, 6*1−73.

Wolfgang, R. & Burgess−Limerick, R. (2014a). Using consumer electronic devices to estimate whole−body vibration exposure*. Journal of Occupational Environmental Hygiene, 11*:D77−81.

Wolfgang, R., DiCorletto, L. & Burgess−Limerick R. (2014b). Can an iPod Touch be used to assess whole−body vibration associated with mining equipment? *The Annals of Occupational Hygiene, 55,* 1200−1204.