Measuring whole-body vibration at surface and underground mines

Robin Burgess-Limerick

Robin Burgess-Limerick & Danellie Lynas
Minerals Industry Safety and Health Centre, Sustainable Minerals Institute, The University of Queensland
e. r.burgess-limerick@uq.edu.au

Abstract

Long term exposure to high amplitude whole-body vibration is strongly associated with the development of back injury. Mobile plant used at mines are likely to be a source of high vibration amplitudes and management of the hazard requires systematic measurement of vibration levels. This paper describes measurements of whole-body vibration taken during projects funded by the Coal Services Health and Safety Trust (20624 & 20638), and the Australian Coal Association Research Program (C23022).

Collectively, the aims of the projects were to develop, validate and demonstrate the use of an iOS application (WBV) to enable simple and inexpensive measurement of whole-body vibration at surface and underground coal mines. After developing the application and assessing it's accuracy, iPOD Touch devices were used to collect 135 long duration measurements from earth-moving equipment in operation at a surface coal mine. Operators of dozers and off-road haul trucks, in particular, are exposed to vertical whole-body vibration levels which lie within, or above, the Health Guidance Caution Zone defined by ISO2631.1. The devices were subsequently used to collect 62 long duration measurements from a range of mobile plant in operation at three underground coal mines.

Introduction

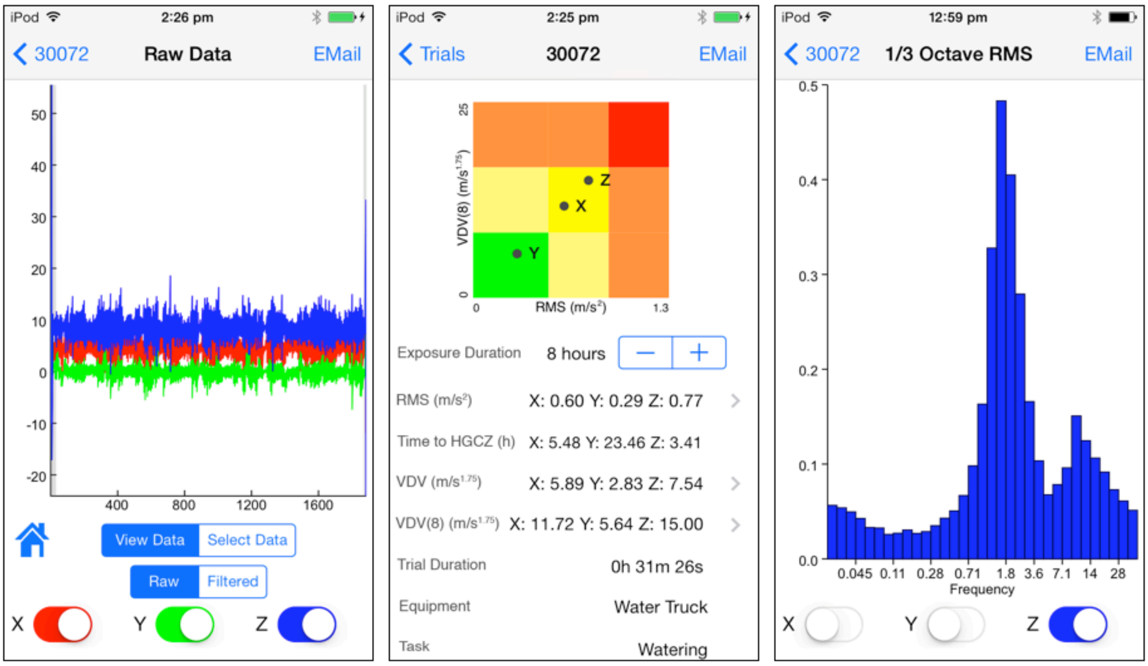
Long term exposure to high amplitude whole-body vibration is associated with a range of adverse health effects (Griffin, 1990), particularly back pain (Bernard, 1997; Bovenzi, 2010; Bovenzi & Hulshof, 1998; Pope etal., 1998; Sandover, 1983). Adverse consequences for cardiovascular, respiratory, digestive, reproductive, endocrine and metabolic systems are also possible. Operators of vehicles and mobile plant such as earth-moving equipment are exposed to significant whole-body vibration amplitudes (eg., Burgess-Limerick, 2012; Smets et al., 2010; Wolfgang & Burgess-Limerick, 2014a). Twelve hour shifts are commonplace in industries such as mining and hence considerable potential for harm exists (Burdof & Hulshof, 2006). The 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 being undertaken; and driver behaviour. Many of these variables are dynamic, varying over time scales ranging from hours (eg., activity), days (roadway conditions, seat adjustment), months (vehicle maintenance) or years (equipment design). Workplace management of the risks associated with this hazard requires assessment of vibration amplitudes and evaluation of the consequential risks before devising and implementing appropriate risk control measures.

The International Standards Organisation has published standard 2631.1 titled “Evaluation of Human Exposure to Whole-body Vibration: Part 1- General Requirements” (ISO 1997; 2010) which describes procedures for the measurement of whole-body vibration. Two principal methods of describing frequency-weighted acceleration amplitudes are defined in the standard: (i) the root mean square (r.m.s.); and (ii) the Vibration Dose Value (VDV). The VDV is a cumulative fourth root measure which is more sensitive to high amplitude jolts and jars. ISO2631-1 provides guidance regarding the evaluation of health effects, defining a “Health Guidance Caution Zone”. For exposures below the Health Guidance Caution Zone it is suggested that 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 accelerations greater than the Health Guidance Caution Zone, it is suggested that “health risks are likely”. For an eight hour daily exposure, the upper and lower bounds of the Health Guidance Caution Zone illustrated in Figure B.1 of ISO2631.1 Annex B are approximately 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 eight-hour equivalent [VDV(8)] are 8.5 $m/s^{1.75}$ and 17 $m/s^{1.75}$.

Measurement of whole-body vibration currently requires expensive ($4,500 to $10,000) equipment consisting of triaxial accelerometer mounted within a seat pad and connected by cable to an acquisition and analysis module. As well as being expensive and relatively fragile, the interfaces are complex and considerable training is required to enable data to be collected and interpreted. Mining operations consequently undertake measurement of whole-body vibration infrequently. Such ad hoc measurements are unlikely to provide a reliable indication of the vibration exposures of equipment operators and do not provide the information required by mine sites to effectively manage whole-body vibration exposures. This paper reports a series of three projects which: (i) developed and validated an iOS application (WBV) running on an iPod Touch device as an inexpensive whole-body vibration tool; and (ii) demonstrated the utility of the devices to efficiently gather large amounts of whole-body vibration data from surface and underground coal mining equipment.

WBV application development and accuracy assessment

Following extensive laboratory and field testing of the iPod Touch devices in comparison with commercially available whole-body vibration measurement devices (Wolfgang & Burgess-Limerick, 2014b; Wolfgang et al., 2014) an iOS application (WBV) was developed in conjunction with Byteworks (www.byteworks.us). The application allows the collection of three-dimensional accelerometer data while an iPod Touch is placed on the seat of a vehicle or mobile plant in operation. The battery life allows collection periods up to approximately 8 hours. 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 data which have been collected can then be inspected as a time series to identify any potential artefacts, and if necessary, data from the start and/or end of the trial may be non-destructively excluded from subsequent calculations (Figure 1). The application calculates r.m.s, Vibration Dose Value (VDV), and VDV(h) measures, (where h is the hours of exposure to the task each shift nominated by the user). These measures are presented numerically, and graphically with respect to the ISO2631.1 health guidance caution zone (HGCZ) appropriate for the nominated shift duration. The frequency spectrum of the accelerometer data may also be calculated and displayed. The results and raw and frequency weighted data may be subsequently emailed or downloaded for reporting or further analysis. The application, user manual and training materials are available for free download via the project website (ergonomics.uq.edu.au/wbv).



(a) (b) (c)

Figure 1: WBV application screens (a) time series data for visual inspection; (b) numerical and graphical presentation of summary statistics relative to the ISO2631.1 health guidance caution zone for the nominated exposure duration; and (c) frequency spectrum of collected acceleration data.

The accuracy of the iOS application was assessed by obtaining simultaneous pairs of measurements from iPod Touch and commercially available measurement device (SV106) during the operation of a range of surface coal mining equipment (Burgess-Limerick & Lynas, 2015). Figure 2 illustrates 96 pairs of vertical acceleration measurements (r.m.s) obtained from the WBV application and iPod Touch. The average absolute error between SV106 and iPod measurements of vertical accelerations was 0.033 m/s^2 and the average constant error for these iPod measurements was 0.013 m/s2. The standard deviation of the constant error was 0.039 m/s^2, suggesting that the WBV application installed on a 5th generation iPod Touch provides a 95% confidence of +/- 0.077 m/s^2 r.m.s. for the vertical direction (1.96 x Standard Deviation of the Constant Error) which is consistent with the previous assessment based on raw accelerometer data gathered via iPod Touch from a different set of trials at three difference mines (+/- 0.06 ms^{-2}).

Thirty-eight pairs of measurements were obtained from situations which the SV106 measurement suggested exceeded the lower limit of the ISO2631.1 health guidance caution zone for an 8 hour exposure. All of these situations were correctly identified by the iPod Touch application. The remaining 58 pairs of measurements were obtained from situations which fell below the HGCZ according to the SV106 device. However, in three instances the data obtained from the iPod Touch suggested that the HGCZ threshold was marginally exceeded.

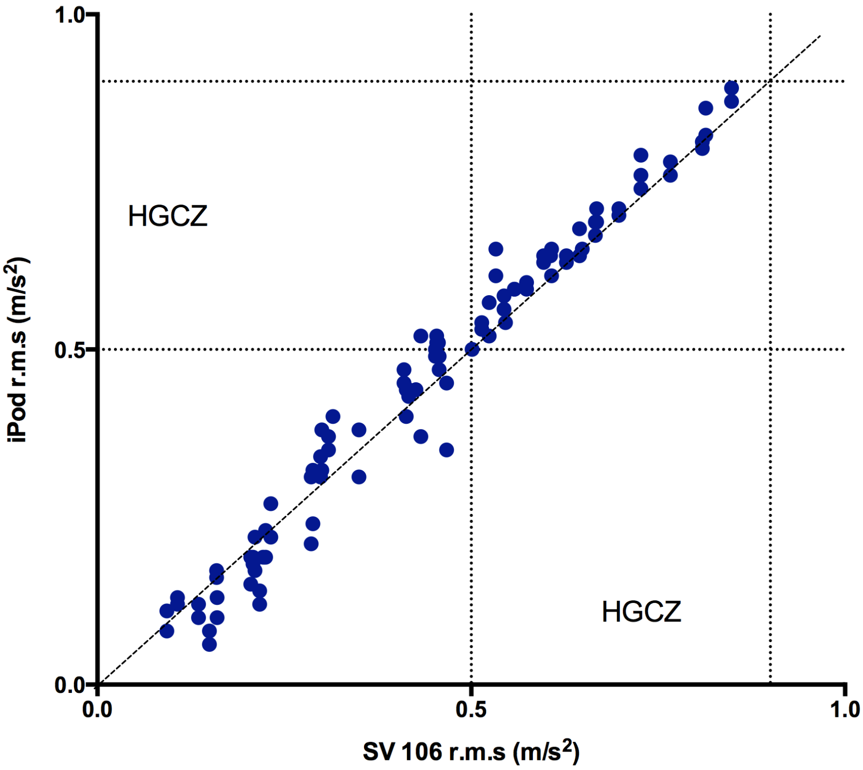


Figure 2: Ninety-six vertical whole-body vibration (r.m.s) measurements obtained at a surface coal mine using the iOS application compared with simultaneous SV106 measurements.

Surface coal mining whole-body vibration measurements

A survey of whole-body vibration exposure was subsequently undertaken at a surface coal mine. Measurements were taken with 30 iPod Touch devices using version 2.2 of the WBV iOS application (Burgess-Limerick & Lynas, 2016). The aim was to undertake multiple long duration measurements to provide a comprehensive assessment of the likely exposure of operators to this hazard. The simultaneous use of multiple iPod Touch devices allowed the efficient collection of multiple relatively long duration measurements from each equipment type. The devices were placed in a pouch sewn onto a neoprene square which was placed on an equipment operator's seat during normal operations. The WBV application was set to collect and analyse consecutive 20 minute samples of three-dimensional accelerometer data. Data collection was initiated on the iPod Touch devices and then they were distributed to the equipment operators who took them to their equipment and placed them on their seat. The devices were collected again from the operators at the end of each shift.

Sixty-five measurements were obtained from a range of equipment types during normal operations. The measurements were spread equally over day and night shifts across the two visits. Trial durations ranged from 60 to 460 minutes (average = 317 minutes). The measurement trials were distributed across equipment types as follows: Excavators (N=7), Dozers (N=15), Graders (N=3); Haul Trucks (N=29), Light vehicles (N=3); Loader (N=2); Semi-trailer truck (N=1) and Water trucks (N=5). Haul trucks and dozers were of particular interest. Twenty-nine measurements were obtained from sixteen haul trucks, and fifteen measurements were obtained from seven dozers. The haul truck models were Caterpillar 789B, 789C, 793F and 795F ranging in nominal payload from 177 tonnes to 313 tonnes. The dozer models were Caterpillar D11R, D10T and D11T.

The raw accelerometer data gathered in each 20 minute sample were visually inspected and samples corresponding to the period prior to equipment operation commencing were discarded. Samples in which negligible acceleration levels (less than 0.1 m/s2 peak to peak) corresponding to no equipment movement were recorded for greater than ten minutes were also discarded.

Figure 3 illustrate horizontal (X & Y) and vertical (Z) whole-body vibration amplitudes expressed as r.m.s for each of the 65 measurements. The data indicate that vertical accelerations were greater than horizontal accelerations for most equipment measured, with the exception of excavators. The majority of vertical whole-body vibration measurements lay within the Health Guidance Caution Zone (HGCZ) defined by ISO2631.1. The ISO standard suggests that while no health effects have been clearly documented for exposures below the HGCZ, for exposures within the HGCZ “caution with respect to potential health risks is indicated” and for exposures greater than the HGCZ it is suggested that “health risks are likely”. Seven of the 65 measurements were clearly above the HGCZ for both RMS and VDV(10) measures and five of these measurements were obtained from dozers (one third of the dozer measurements). Three measurements from dump trucks, and one from an excavator, lay above the HGCZ for the VDV measure only. Figure 4 illustrate the range of measurements obtained from dozers and dump trucks as a function of the specific dozer or truck involved. The variability within piece of equipment was similar to that across equipment, indicating that the sources of the variability in vibration amplitudes (and hence the opportunities for intervention) are elsewhere.

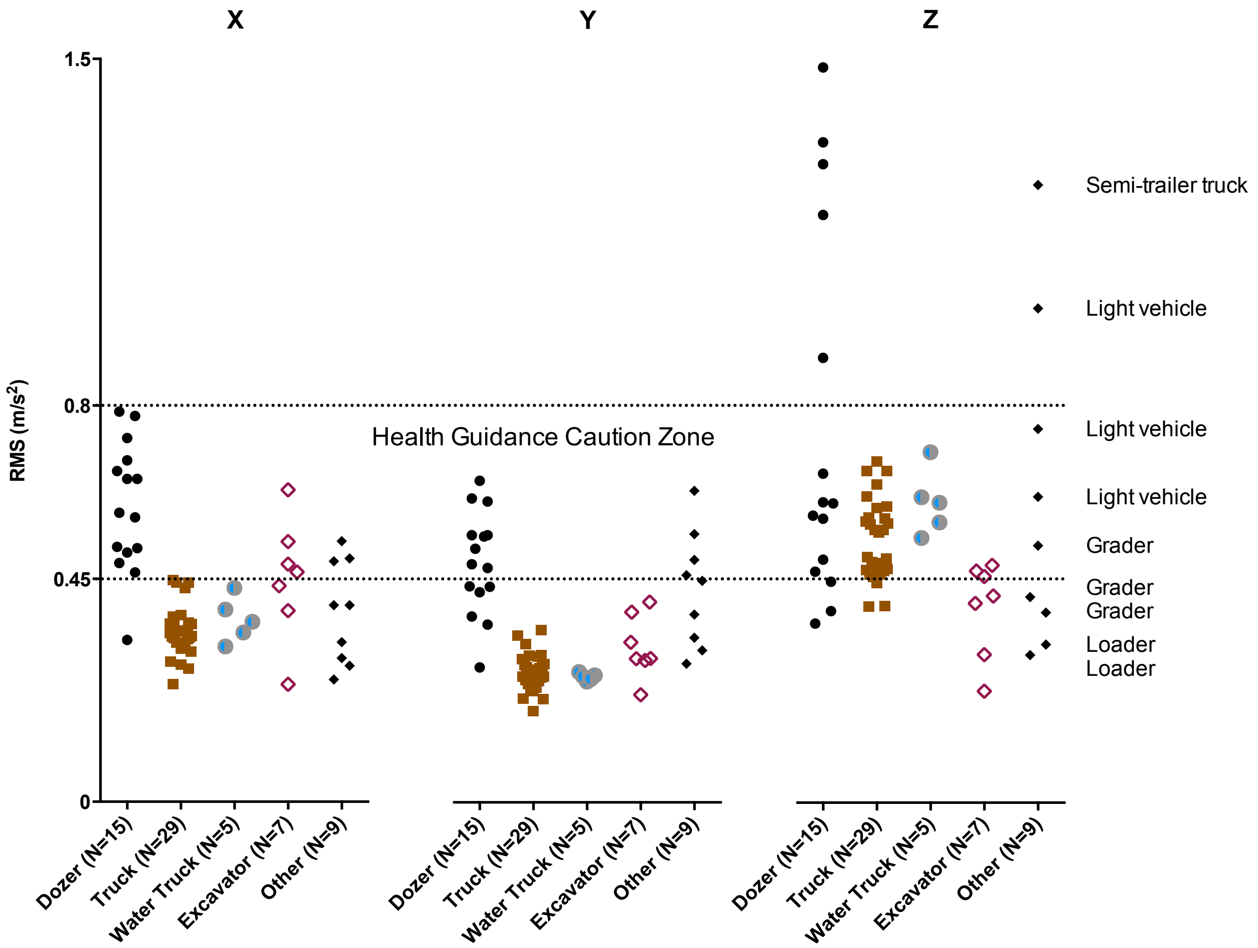
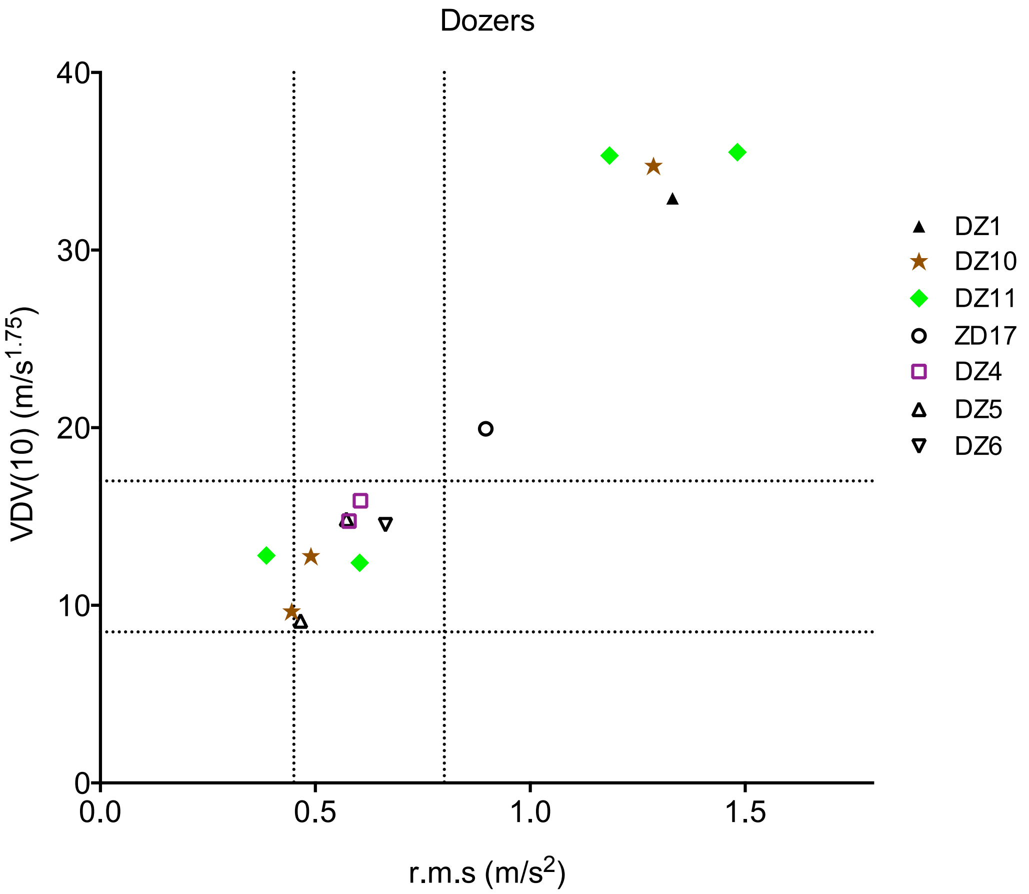


Figure 3: RMS values for each of 65 long duration whole-body vibration measurements taken from mobile plant and equipment during normal operations at a surface coal mine.



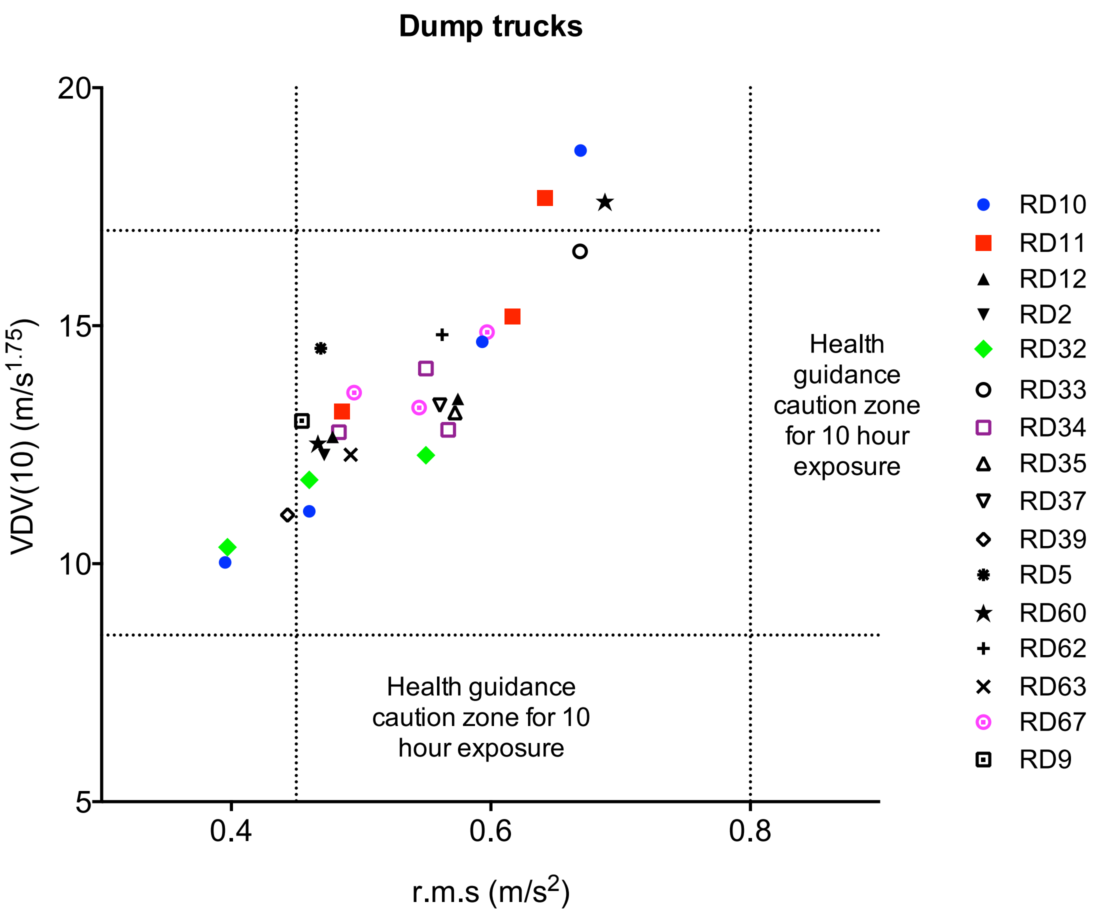


Figure 4: VDV(10) vs RMS for 15 dozer and 29 dump truck vertical whole-body vibration measurements.

The high measurements obtained from dozers prompted further investigations. A further 70 measurements were undertaken during normal dozer operations. Figure 5 presents the vertical VDV(10) vibration amplitudes as a function of the r.m.s. amplitude with respect to the 10 hour Health Guidance Caution Zone. The results of the investigation of dozer vibration exposures revealed that the four extreme measurements obtained from dozers in the site survey were not anomalous. Twenty-five of the 70 measurements exceeded the HGCZ for VDV(10), and 20 of the 70 measurements exceeded the HGCZ for both VDV(10) and r.m.s. Although data were gathered from operators following each shift regarding the tasks undertaken, the location and ground conditions; and operator identify and experience was also obtained; no consistent relationships between these variables and the vibration levels could be discerned. It is also apparent from Figure 13 that the data gathered from individual dozers during different shifts demonstrated considerable variability.

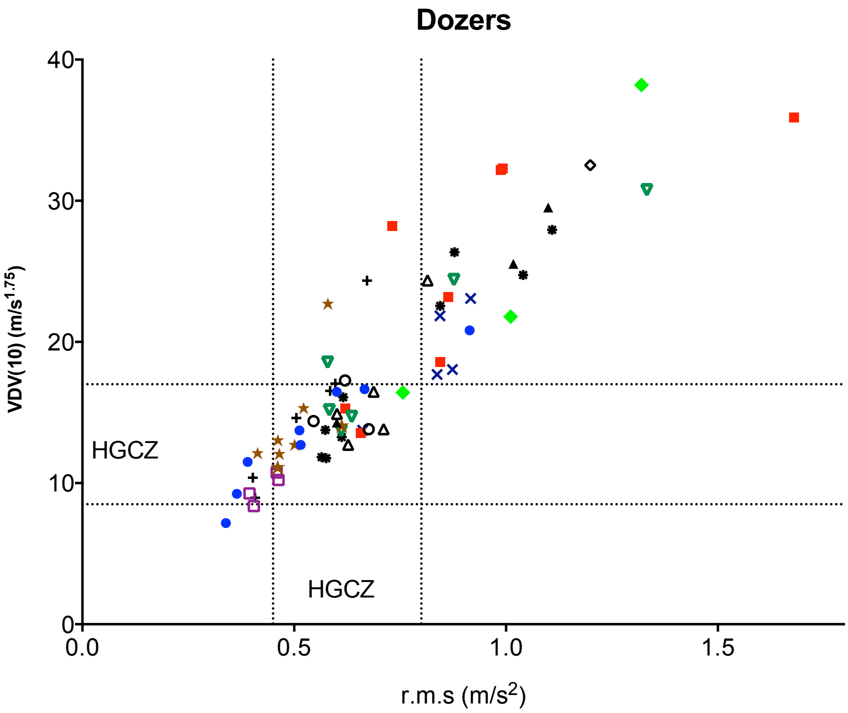


Figure 5: VDV(10) vs RMS values for each of 70 long duration vertical whole-body vibration measurements taken from dozers during normal operations.

Underground coal mining whole-body vibration measurements

Sixty-two measurements of whole-body vibration data were obtained from a range of underground equipment (Shuttle cars, N=22; PJB/SMV, N=26; LHD etc N=13, CM platform, N=1) at three NSW underground coal mines using the WBV iOS application installed on multiple iPOD touch devices. Measurement durations ranged from 15 to 268 minutes (mean=71 minutes). Figure 6 illustrates the vertical vibration levels expressed with respect to the Health Guidance Caution Zone for an eight hour exposure defined by ISO2631.1. The majority of measurements exceeded the Health Guidance Caution Zone. The highest values were measurements obtained from Shuttle cars, and LHD, Brumby, PET and Coal Tram equipment, as well as some rear seat transport measurements.

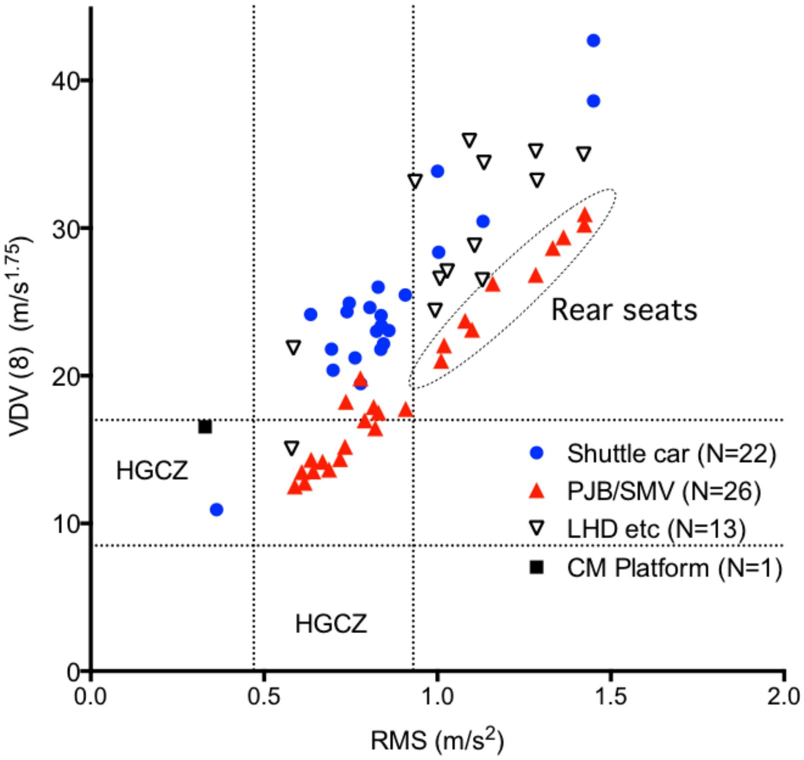


Figure 6: VDV(8) and RMS values for vertical vibration measurements from a range of underground coal mining equipment in use at three underground coal mines.

The large range of values obtained from shuttle cars, and the high values obtained during some measurement periods, highlights these equipment as deserving of further investigation to identify and evaluate potential control measures. Interest was expressed by the sites in gaining a better understanding of the consequences of different tyre choices (solid vs air) and determining whether improved shuttle car seating or suspension may reduce vibration exposures associated with shuttle cars. Planning for future work is underway.

It was also notable that measurements from personnel transport which exceeded the HGCZ were all taken from the rear seats of the transport vehicles. Although the duration of exposure is typically relatively short, attention to these exposures is also justified. Improved roadway standards are a potential means of achieving this. As well as reducing cumulative injuries associated with long term vibration exposure, improved roadway standards are also 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.

Figure 7 illustrates measurements from two personnel transport vehicles taken at five minute intervals during a trip into two of the mines. The data indicate that, in each case, the vibration levels varied, and were higher during one of the five minute segments of travel than any other. The implication is that the data could be used to identify portions of the roadway requiring maintenance. The data illustrate the potential for timely evaluations of proposed vibration control measures, and for the provision of information about roadway condition though regularly undertaking a standardised measurement of vibration correlated with location. TARPS could then be developed to indicate when roadway maintenance is indicated at any given location.

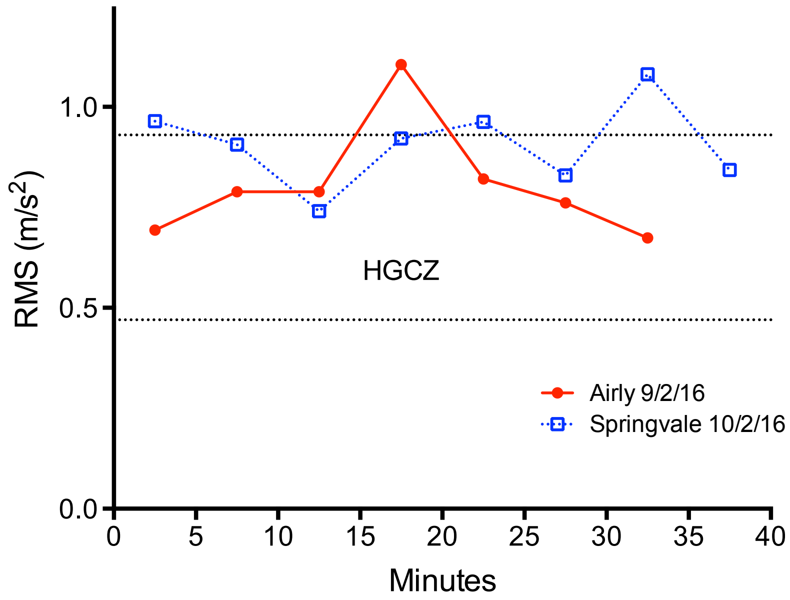


Figure 7: Vertical vibration RMS at five minute intervals taken from personnel transport.

Conclusion

The relatively low cost of the iPod Touch hardware, and the accuracy and simplicity of the WBV application, has the potential to facilitate routine collection of whole-body vibration exposure by site-based workplace safety and health staff as part of a systematic whole-body vibration risk management program. The ability to respond rapidly to operator feedback or complaints may also allow early identification of developing problems with roadways or equipment. The availability of the WBV application facilitates collection of adequate data to allow the identification and understanding of the sources of uncertainty in the evaluation of occupational exposure to whole-body vibration. In sum, the iOS application provides a means of efficiently evaluating whole-body vibration exposure within a workplace risk management process.

Considerable variability in measurement amplitudes, even within the same equipment type operated at the same site, was noted. Operators of surface mining equipment are relatively frequently exposed to vertical whole-body vibration levels which lie within, or above, the Health Guidance Caution Zone defined by ISO2631.1. Dozers, in particular, are sometimes associated with extreme whole-body vibration levels. Data gathered regarding operator experience, task and geological conditions did not allow the determination of the causes of these extreme exposure. Feedback, training and supervision may be effective strategies to reduce dozer vibration exposures.

High whole-body vibration levels are also 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, rear seat passengers in personnel transport, as well as materials transport equipment. The variability in measurements obtained from shuttle cars, and the high values obtained during some measurement periods, highlights these equipment as deserving of further investigation to identify and evaluate potential design control measures such as modifications to seating or suspension. Although the duration of exposure for rear seat passengers in personnel transport vehicles is typically relatively short, attention to these exposures is also justified. The potential use of the WBV iOS application within a Trigger Action Response Plan regime to manage roadway standards was also highlighted.

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