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Managing Whole-Body Vibration at Surface Coal Mines


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Executive Summary

Operators of earth moving equipment are exposed to vibration through the seat. Prolonged exposure to high amplitude whole body vibration causes serious long term health effects, particularly back disorders. Management of this hazard is difficult, in part because measurement of vibration exposure requires expensive equipment and expertise, and measurements are consequently undertaken infrequently. More frequent measurements undertaken as part of a comprehensive vibration management plan will enable the identification of effective control measures to reduce vibration exposures. This project has validated, implemented, and evaluated the use of an iOS application (WBV) installed on iPod Touch devices as an inexpensive whole body vibration measurement device.

Workplace management of whole-body vibration exposure requires systematic collection of whole-body vibration data in conjunction with the numerous variables which influence vibration amplitudes. The cost and complexity of commercially available measurement devices is an impediment to the routine collection of such data by workplaces. An iOS application has been developed which allows an iPod Touch to be used to measure whole-body vibration exposures. The accuracy of the application was demonstrated by simultaneously obtaining 98 pairs of whole-body vibration measurements from both the iPod Touch application and a commercially available whole-body vibration measurement device during the operation of a variety of vehicles and mobile plant in operation at a surface coal mine. Situations in which vibration levels lay within the ISO2631.1 health guidance caution zone were accurately identified, and the qualitatively features of the frequency spectra were reproduced. The low cost and relative simplicity of the application has potential to facilitate its use as a screening tool to identify situations in which musculoskeletal disorders may arise as a consequence of exposure to whole-body vibration.

Considerable variability in measurement amplitudes, even within the same equipment type operated at the same site, has been noted. However, the measurements have previously been undertaken for relatively short durations. Fifty-nine measurements were collected from a range of earth-moving equipment in operation at a surface coal mine. Measurement durations ranged from 100 minutes to 460 minutes (median = 340 minutes). The results indicate that the measurements previously observed are not an artifact of the relatively short durations and confirm that 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 causes of these extreme exposure to be determined. Subsequent measurements which included simultaneous video recording of the dozer operation failed to capture the same extreme vibration levels. It may be that the operator’s knowledge that they were being video recorded influenced their behaviour. This, in turn, suggests that systematic observation, feedback, training and supervision may be an effective strategy to reduce the prevalence of extreme dozer vibration exposures.

Interest has been expressed in extending the functionality of the iOS application to allow real-time continuous measurement and monitoring of whole-body vibration and this possibility will be the subject of a subsequent project proposal.
**Whole-body vibration**

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 et al., 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, 2014). Twelve hour shifts are commonplace in industries such as mining and hence considerable potential for harm exists (Burdof & Hulshof, 2006). 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/s² and 0.93 m/s² r.m.s. respectively. The corresponding values for the VDV measure expressed as an eight-hour equivalent [VDV(8)] are 8.5 m/s¹.⁷⁵ and 17 m/s¹.⁷⁵.

**Previous measurements of surface mining equipment**

A range of mobile plant and equipment such as dozers, haul trucks, water trucks, excavators and graders are used at surface coal mines. Data previously collected from such equipment suggests that the vibration amplitudes to which operators are exposed may lie within or above the ISO2631.1 Health Guidance Caution Zone. Dozers in particular have been identified as sometimes being associated with very high whole-body vibration levels. Off-road haul trucks have also been identified as being a source of elevated vibration levels.

For example, Scarlett & Stayner (2005) collected a single long duration measurement (3-4 hours) from each of 13 different types of machines used in mining, construction and quarrying. Vertical r.m.s acceleration values and VDV(8) values reported included: 0.22 m/s² and 11.7 m/s¹.⁷⁵ for an excavator and 0.37 m/s² and 14.8 m/s¹.⁷⁵ for an 80 Tonne Rigid Dump Truck (below the Health Guidance Caution Zone for the r.m.s measure and within the Health Guidance Caution Zone for the VDV(8) measure for both equipment types); 0.61 m/s² and 15.4 m/s¹.⁷⁵ for a face shovel loading trucks (within the Health Guidance Caution Zone for both measures); and 1.45 m/s² and 26 m/s¹.⁷⁵ for a Bulldozer undertaking civil-construction
activities (exceed the Health Guidance Caution Zone for both measures). These are the only published long duration measurements (greater than 90 minutes) of whole-body acceleration during mining equipment operation able to be located, however only one measurement was taken from each equipment type.

Eger et al., (2006) collected short duration measurements (10 to 36 minutes) from fifteen types of surface and underground mining equipment. Vertical r.m.s acceleration values reported included 0.37 m/s² for a 150 tonne surface haul truck (below the Health Guidance Caution Zone), 0.79 m/s² for a grader (within the Health Guidance Caution Zone) and 1.64 m/s² from a bulldozer (exceeds the Health Guidance Caution Zone).

Smets et al (2010) collected 60 minute duration whole-body vibration measurements from eight haul trucks of varying capacities during normal operation at metalliferous surface mines in Canada. The vertical accelerations measured as r.m.s. ranged from 0.44 m/s² to 0.82 m/s² r.m.s. The VDV(8) measurements ranged from 8.8 m/s¹.⁷⁵ to 16.4 m/s¹.⁷⁵. Seven of the eight r.m.s. measurements were within the ISO2631.1 Health Guidance Caution Zone. All eight VDV(8) measurements were within the Health Guidance Caution Zone.

An investigation of whole-body vibration amplitudes recorded during 18 to 54 minute measurements of haul trucks in operation at an Australian surface coal mine (Wolfgang & Burgess-Limerick, 2014) concluded that 20 of 32 r.m.s. measurements were within Health Guidance Caution Zone while 30 of 32 VDV(8) measurements were within the Health Guidance Caution Zone. The vertical whole-body vibration amplitude measurements ranged from 0.27 m/s² to 0.74 m/s² and the VDV(8) measurements ranged from 7.9 m/s¹.⁷⁵ to 15.3 m/s¹.⁷⁵.

Burgess-Limerick (2012) reported 26 short duration measurements (16 to 70 minutes) from dozers performing a range of tasks at a surface coal mine in Australia. The vertical acceleration values ranged from 0.37 to 0.82 m/s² r.m.s. and from 7.6 to 19.1 m/s¹.⁷⁵ VDV(8). Only one of the r.m.s. measurements lay within the Health Guidance Caution Zone. None of the VDV(8) measurements was below the Health Guidance Caution Zone, and one VDV(8) measurement exceeded the Health Guidance Caution Zone.

The vibration exposures experienced by operators of mobile equipment are a function of the characteristics of the task being undertaken (Newell et al., 2006); the supporting environment (roadway or surface condition)(Lewis & Johnson, 2012); the equipment (such as suspension design and maintenance)(Donati, 2002; Pinto & Stacchini); seat design, condition and adjustment (Blood et al., 2010; Paddon & Griffin, 2002); tyre design and maintenance (Li & Schindler, 2014); and driver behaviour (eg., speed)(Tiemessen et al., 2007). Many of these characteristics are dynamic, varying over time scales ranging from minutes (eg., speed) to hours (task), days (roadway conditions, seat adjustment), months (vehicle or seat maintenance) or years (equipment design). Managing such a dynamic hazard requires systematic and relatively frequent evaluation of whole-body vibration exposures to ensure that high risk situations are identified and opportunities for effective risk treatments are identified.

While ISO2631.1 provides guidance regarding the measurement and evaluation of the health effects of whole-body vibration, obtaining such measurements requires use of a seat-pad mounted accelerometer connected by relatively fragile cable to an analysis module. As well as the equipment being expensive, the interfaces are complex and considerable training is
required to enable data to be collected and interpreted. As a consequence, workplaces such as mines undertake measurement of whole-body vibration only infrequently. Such ad hoc measurements are unlikely to provide a reliable indication of the vibration exposures of equipment operators in such dynamic environments and do not provide the information required to effectively identify the sources of elevated vibration levels, and hence, the opportunities for implementing control measures.

A new way to measure whole-body vibration

Miniature personal electronic computing devices have become ubiquitous. Their popularity has resulted in rapid advances in processor power, data storage, and battery life at a relatively low cost. The typical device is equipped with a range of sensors including an accelerometer which provides data that are utilised as input to the operating system and applications such as games. However these data have also been utilised for other purposes such as measurements of human movement (Mohan et al., 2008; He, 2012; Nolan et al., 2013; Sieling & Moon, 2011; Tapia, 2004) as well as pot-hole detection and road surface monitoring (Mednis et al., 2011). An opportunity exists to utilise personal electronic devices to provide a simple and inexpensive method of estimating whole-body vibration for use within a workplace risk management process.

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. Consistent sensitivity of the accelerometers across multiple devices has been demonstrated (Amick et al., 2013). The maximum sampling rate is restricted by the operating system to a nominal 100 Hz.

Preliminary investigations comparing the iPod Touch accelerometer data with an accelerometer calibrator, and with data gathered from light vehicles and heavy mining equipment, provided promising results (Wolfgang & Burgess-Limerick, 2014; Wolfgang et al., 2014). Sampling rate limitations were highlighted as the primary potential source of potential inaccuracies. In particular, limitations of the 5th generation iPod Touch restricted the actual sampling rate achieved to approximately 89 Hz, and some variability in the inter-sample intervals was noted. However, the frequency weightings employed by ISO2631.1 place greatest emphasis on much lower frequency accelerations, with the consequence that the sampling rate limitations do not appear to markedly influence the accuracy of the amplitudes measured. While an iPod Touch device certainly does not meet the requirements of ISO8041 for vibration measurement instrumentation, when accelerometer data gathered from an iPod Touch were processed off-line using the ISO2631.1 frequency weightings and compared with simultaneous measurements from 58 trials from a range of mining equipment under field conditions made via a commercially available devices, the results suggested that the iPod accelerometer data was accurate with a 95% confidence of +/- 0.06 m/s² r.m.s. for the vertical direction (1.96 x Standard Deviation of the Constant Error). These results prompted the development and subsequent public release of a free iOS application (WBV) (Burgess-Limerick & Westerfield, 2014) with the aim of providing an inexpensive and simple means of evaluating whole-body vibration exposure suitable for use within a workplace risk management process at surface coal mines.
Project objective and stages

The objective of the project was to evaluate the suitability of the iOS application for this purpose. The first stage of this evaluation was to assess the accuracy of data obtained using the iOS application through a comparison with data simultaneously obtained from a commercially available whole-body vibration device during the operation of a variety of vehicles and mobile plant in operation at a surface coal mine. The usability of the application was also assessed during this stage of the project. The second stage of the project was to utilise the iOS application to undertake a comprehensive site wide survey of the whole-body vibration exposures to which operators of surface coal mining equipment are exposed. The third stage of the project was to undertake a more detailed investigation of the vibration exposures associated with the use of dozers at a surface coal mine.

Stage 1: WBV application accuracy assessment

The WBV 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 artifacts, and if necessary, data from the start and/or end of the trial may be non-destructively excluded from subsequent calculations (Figure 1a). A global setting also allows a fixed period of up to 10s to be cropped from the start and end of each trial by default.

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 vertical acceleration data.
The WBV 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 (Figure 1b). The frequency spectrum of the accelerometer data may also be calculated and displayed (Figure 1c). The numerical and graphical results, and raw and frequency weighted data, may be subsequently emailed or downloaded for reporting or further analysis.

**Accuracy assessment methods**

Whole-body vibration measurements were obtained using the WBV application installed on two 5th generation iPod Touch devices placed under the seat-pad of an SV106 (Svantek Sp., Warsaw, Poland) measurement device which was in turn placed on the seat of a variety of mobile equipment undertaking normal operations at a surface coal mine (Figure 2). Fifty-one measurement trials were completed during two site visits in April and May 2014 from which 96 simultaneous pairs of measurements were obtained (6 iPod measurements were unavailable due to software errors). The measurement trials were distributed across equipment types as follows: Dozer (N=3), Dragline (N=5), Drill (N=6), Excavator (N=8), Grader (N=1), Light vehicle (N=9), Shovel (N=4), Haul truck (N=9), and Water truck (N=6). Measurement duration for each trial ranged from 10 to 50 minutes (median 27 minutes).

![Figure 2: Svantech (SV38V) seat pad accelerometer in place over two 5th generation iPod Touch for data recording (A) and removed to illustrate iPod Touch placement (B) during accuracy assessment trials.](image)

**Accuracy assessment results and discussion**

Figure 3 illustrates 96 vertical acceleration measurements (r.m.s) obtained from the WBV application and iPod Touch in comparison to simultaneous measurements obtained from a commercially available measurement device (SV106). The average absolute error between SV106 and iPod measurements of vertical accelerations was 0.033 m/s² 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/s², suggesting that the WBV application installed on a 5th generation iPod Touch provides a 95% confidence of +/- 0.077 m/s² 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). Table 1 provides a statistical summary for X, Y & Z directions.

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 3: 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.

Table 1: 95% limits of agreement for X, Y, and Z whole-body vibration measurements derived from 96 pairs of iPod Touch accelerometer measurements and simultaneous gold standard measurements.

<table>
<thead>
<tr>
<th></th>
<th>X r.m.s. (m/s²)</th>
<th>Y r.m.s. (m/s²)</th>
<th>Z r.m.s. (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean constant error</td>
<td>0.008</td>
<td>0.008</td>
<td>0.013</td>
</tr>
<tr>
<td>Standard deviation of constant error</td>
<td>0.051</td>
<td>0.036</td>
<td>0.039</td>
</tr>
<tr>
<td>Lower 95% limit of agreement</td>
<td>-0.091</td>
<td>-0.079</td>
<td>-0.065</td>
</tr>
<tr>
<td>Upper 95% limit of agreement</td>
<td>0.108</td>
<td>0.062</td>
<td>0.089</td>
</tr>
</tbody>
</table>
Information about the frequency spectra of whole body vibration may be beneficial in the determination of appropriate engineering control measures such as changes to seating or vehicle suspension. Although the limited sampling rate of the iPod Touch may be expected to introduce aliasing errors, the data illustrated in Figure 4 from four different equipment types suggest that the frequency spectra provided by the iPod Touch are qualitatively similar to those obtained from the SV106 device.

Figure 5 summarises the vertical whole-body vibration results obtained from the fifty-one gold-standard measurements taken from a range of equipment at the surface coal mine. The results indicate that the accelerations expressed as RMS lay below the Health Guidance Caution Zone (HGCZ) defined by ISO2631.1 for measures taken from dragline, drills, excavator and shovel; while some measurements taken from haul trucks and dozers lay within the HGCZ; and all measurements taken from light vehicles and water trucks lay within the HGCZ. The single measurement taken from a grader also lay within the HGCZ.

However, when the Vibration Dose Value (expressed as an 8 hour equivalent) was calculated, the majority of measurements from all equipment types other than the dragline lay within or above the HGCZ defined by ISO2631.1. Sixteen measurements (31%) were above the HGCZ for VDV(8) including five of the nine measurements obtained from haul trucks and two of the three measurements from dozers. Long term exposure to vibration levels above the HGCZ are likely to be associated with subsequent health effects.

The relatively small number of measurements and the short duration of the measurements precludes drawing any strong conclusions. However these results suggested that a more comprehensive and systematic examination of whole-body vibration exposures at the mine site was justified.

A range of usability improvements were also made to the iOS application on the basis of this experience and version 2.2 was published on-line in June 2014. Further improvements were made to the iOS application to improve battery life and enable new features including GPS data recording in version 2.3 (June 2015) and version 2.31. (December, 2015) allows data files to be transferred directly to computer via itunes. A separate Java application (WBVanalysis) has been developed and made freely available to assist with the offline inspection and analysis of multiple contiguous samples drawn from the same shift. Additional independent accuracy investigations are proceeding as part of a project being conducted at Laurentian University (Canada). All data collection in the current project has utilised iPods and no GPS data was available as a consequence. Discussions are underway with University of Washington (USA) researchers to undertake the accuracy testing of the WBV application installed on the iphone hardware. The iPhone SE may be particularly suitable for simultaneously gathering GPS and whole-body vibration data.
Figure 4: Frequency spectra of vertical whole-body vibration for four different equipment types derived from data simultaneously obtained by iOS application and a commercially available device (SV106). The frequency spectra calculated from the iPod data is truncated at 35 Hz because of the sampling rate limitations.
Figure 5: Box and whisker plots (Median, inter-quartile range, and range) for vertical whole-body vibration as RMS (Top) and VDV(8) (Bottom) for a range of equipment in operation at a surface coal mine.
Site survey methods

A more detailed survey of whole-body vibration exposure was subsequently undertaken during two further visits in August and October 2014. Measurements were taken with 30 iPod Touch devices using version 2.2 of the WBV iOS application. The aim of this phase of the project 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. Removing idle periods from the measurements means that the measurements may over-estimate the total vibration exposure over the course of a shift. However, one aim of the research was to determine whether the high values previously obtained were a consequence of the short measurement durations, which did not include idle times. If idle times, such as crib breaks for example, were included in the long duration measurements, and the long duration measurements had been found to be substantially lower, then this may have purely been because idle times were included. The resulting trial durations ranged from 100 minutes to 460 minutes (median = 340 minutes). The measurements were collected during two measurement periods of four consecutive 12 hour shifts. The two measurement periods were separated by 4 weeks.

The WBV application applied the Wd and Wk frequency weightings specified by ISO2631.1 to horizontal and vertical accelerations respectively, before calculating r.m.s and VDV amplitudes of the frequency-weighted accelerations for each period. Average r.m.s values were calculated for the whole duration of each of the measurements, while the VDV measure were expressed for each measurement were extrapolated to an ten-hour exposure as VDV(10). “k” weightings of 1.4 specified by ISO2631.1 for horizontal directions were not applied.
**Site survey results and discussion**

Figure 6 provides an illustration of 60 minute samples of vertical whole-body vibration measurements (filtered according to ISO2631.1) for a dozer, dump truck, water truck, and excavator. The data reveal considerable differences in the vibration amplitudes and patterns which correspond to the different equipment functions.

Figure 7 and Figure 8 illustrate horizontal (X & Y) and vertical (Z) whole-body vibration amplitudes expressed as r.m.s and VDV(10) 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 9 and 10 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) is elsewhere.

The measurements previously collected from dozers and haul trucks in previous projects has highlighted considerable variability in vibration levels, even within measurements taken from the same equipment types operating at the same site. This variability suggests that, if the sources of the variability (e.g., geological conditions, suspension design or condition, seat adjustment, speed) could be identified, it may be possible to put in place control measures to reduce the vibration amplitude experienced by operators.

However, it is also possible that the apparent variability arises as a consequence of the relatively short duration measurements which are more likely to capture non-representative samples of work. That is, it may be that the variability observed (and particularly the highest values measured) may be an artifact of the short sample durations, and that the real exposure levels of operators would be observed to be more consistent if averaged across a whole shift. Consequently, a comparison was made between the relatively long duration measurements made in the current project from a range of earth-moving equipment in operation at a surface coal mining site with short duration measurements previously published from bulldozers and haul trucks.
Figure 6: One hour samples of vertical whole-body vibration measurements (filtered according to ISO2631.1) for a dozer, dump truck, water truck, and excavator.
Figure 7: 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 8: VDV(10) 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 9: VDV(10) vs RMS values for each of 15 long duration vertical whole-body vibration measurements taken from dozers during normal operations at a surface coal mine.
Figure 10: VDV(10) vs RMS values for each of 29 long duration vertical whole-body vibration measurements taken from dump trucks during normal operations at a surface coal mine.

Figure 11 illustrates vertical direction whole-body vibration VDV(8) as a function of A(8) for the 29 long duration measurements gathered from haul trucks during this project, and 32 shorter duration measurements previously obtained from similar trucks at a different surface coal mine. Figure 12 illustrates vertical whole-body vibration VDV(8) as a function of A(8) for 15 long duration measurements obtained from dozers, and 26 shorter duration measurements previously reported from similar dozers at a different surface coal mine. Table 2 summarises each group of measurements.

The fourth-power nature of the VDV measure gives greater emphasis to high peak values (jolts and jars) than the root-mean-square measure. However, the consequence is that a single high peak value can greatly increase the magnitude of the resulting measurement. This, combined with the cumulative nature of the measure and the stochastic nature of whole-body vibration means that increasing the duration of a measurement sample increases the probability of a random high peak value (a statistical outlier) being included in the measurement, and thus longer duration measurements may be anticipated to lead to greater magnitude VDV(8) values than short duration measurements. And indeed, higher VDV(8) values were observed for the long duration measurements of both truck and dozers. However,
the average A(8) measurements from the long duration samples of dozer tasks was also substantially higher than the previous shorter duration measurements. While the dozers in operation at the sites were similar, it is likely that there were also differences in the mix of tasks involved and/or the geological conditions encountered, or other factors such as seat design or condition, as well as the sample duration.

The range of vertical A(8) measurements obtained from the long duration measurements of haul trucks was lower than the range obtained during the previous short duration measurements. However the range of the long duration VDV(8) measurements was slightly greater than the range of the short duration measurements and the standard deviations of the haul truck measurements were similar. In contrast, the variability of the long duration measurements obtained from a sample of dozers was considerably greater than that previously obtained.

Although the measurements were taken from equipment in operation at different surface coal mines, the variability of the long duration measurements reported here suggests that the variability previously observed is not an artifact of the relatively short duration measurements. While the exclusion of periods when the equipment was idle from the measurements may lead to an overestimate of the estimated total shift vibration exposure, the data also suggest that a substantial proportion of A(8) haul truck whole-body vibration exposures at the surface coal mine are within the Health Guidance Caution Zone and that almost all exposures are within, or above the Health Guidance Caution Zone when expressed as VDV(8). This is of concern given that 12 hour shifts are common in the industry, and haul truck drivers may spend 10 hours a day exposed to these vibration levels. The finding of similar results from haul trucks in operation at different mines in different states operated by different companies also suggests that the exposure to the hazard is likely not to be isolated to an individual mines, and may be common across Australian surface coal mines.
Figure 11: Vertical whole-body vibration VDV(8) plotted as a function of r.m.s for 29 long duration measurements obtained from haul trucks (this project) and 32 shorter duration measurements (Wolfgang & Burgess-Limerick, 2014) obtained from similar haul trucks (789B/785B/785C & 930E ranging from 136 tonne to 290 tonne payload) at a different surface coal mine. Lower and upper boundaries of the Health Guidance Caution Zone defined by ISO2631.1 for A(8) and VDV are indicated, along with the lines of best fit.
Figure 12: Vertical whole-body vibration $VDV(8)$ plotted as a function of r.m.s for 15 long duration measurements obtained from dozers in operation (this project) and 26 shorter duration measurements (Burgess-Limerick, 2012) obtained from similar dozers (D11R & D10) in operation at a different surface coal mine. The dotted lines indicate the lower and upper boundaries of the Health Guidance Caution Zone defined by ISO2631.1 for r.m.s and VDV measures.
Table 2: Summary variability measures for vertical whole-body vibration measurements obtained from haul trucks and dozers during operation at surface coal mines.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Haul Trucks</th>
<th>Dozers</th>
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<tbody>
<tr>
<td></td>
<td>29 long duration measurements</td>
<td>32 short duration measurements (Wolfgang &amp; Burgess-Limerick, 2014)</td>
</tr>
<tr>
<td></td>
<td>26 short duration measurements (Burgess-Limerick, 2012)</td>
<td></td>
</tr>
<tr>
<td>A(8)</td>
<td>Mean 0.53 m/s²</td>
<td>0.50 m/s²</td>
</tr>
<tr>
<td>range</td>
<td>0.29 m/s²</td>
<td>0.47 m/s²</td>
</tr>
<tr>
<td>SD</td>
<td>0.08 m/s²</td>
<td>0.10 m/s²</td>
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<tr>
<td>VDV(8)</td>
<td>Mean 12.8 m/s¹.75</td>
<td>11.9 m/s¹.75</td>
</tr>
<tr>
<td>range</td>
<td>8.2 m/s¹.75</td>
<td>7.4 m/s¹.75</td>
</tr>
<tr>
<td>SD</td>
<td>2.0 m/s¹.75</td>
<td>2.1 m/s¹.75</td>
</tr>
</tbody>
</table>

Stage 3: Dozer investigations

The results of the site survey were presented to the site senior leadership team at the participating mine site early in 2015. It was agreed that the project should next focus on determining how commonly the extreme dozer exposures occurred, and to identify the conditions associated with such extreme vibration exposures. During a site visit in May, 2015, 70 whole shift measurements were undertaken during normal dozer operations. Additional data were also collected from a range of other equipment types. Figure 13 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.
Three further site visits were undertaken from September 2015 to February 2016 to gather simultaneous video footage and vibration measurements from dozer operations in an attempt to determine the sources of the elevated vibration levels. Twenty-two simultaneous video and vibration recordings of dozer activity were undertaken during these visits. Figure 14 provides the vibration recordings obtained.

Of these 22 measurements, only two exceeded the health guidance caution zones and the attempt to define the circumstances leading to extreme dozer vibration values was consequently unsuccessful. One potential explanation for the failure to capture video of extreme situations is that the dozer operators’ behaviour was altered by the knowledge that the operation was being recorded. This points to dozer operator training and supervision as a potential means of reducing vibration exposures.
Conclusions

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.

It is feasible for multiple iPod Touch devices to efficiently collect vibration data for equipment on surface mine sites. 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, have previous been noted. This variability has been confirmed. 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. Subsequent measurements which included simultaneous video recording of the dozer operation failed to capture the same extreme vibration levels. It may be that the operator's knowledge that they were being recorded influenced their behaviour. This, in turn, suggests that observation, feedback, training and supervision may be effective strategies to reduce dozer vibration exposures.

**Dissemination/Uptake**

The project web page (ergonomics.uq.edu.au/wbv) provides information about the project including link to the free WBV application, the WBVanalysis java application, technical documentation and a user manual, as well as a procedure for the management of whole-body vibration and educational materials.

Results of the project have been published as follows:


An abstract has been accepted for a presentation to the 2016 Queensland Mine Safety and Health conference (Aug 14-16, 2016), and an abstract has been submitted to the 2016 NSW Mining Health, Safety, Environment & Community Conference (Aug 29 & 30, 2016).

The WBV application is in use at a range of surface coal mines in NSW and Queensland. Glendell (Glencore) in particular has been very active in collecting data from dozers which will be combined with the data gathered during this project for subsequent publication. Other sites to which iPODs have been distributed include Ravensworth & Clermont (Glencore); Millenium (Peabody); Commodore, Meandu & Blackwater (Downer); as well as the Northparkes underground metalliferous mine. The devices are also being evaluated in use at three Centennial underground coal mines as part of a separate NSW Coal Services Health and Safety Trust project.
Future opportunities

Interest has been expressed by multiple companies in extending the ability of the WBV application from the current “batch mode” data collection whereby contiguous vibration samples are collected during a shift and the vibration results downloaded subsequently, to continuous real-time recording and analysis of whole-body vibration levels conveyed to a control room via a wireless local area network. These data could be inspected in real-time, and synchronised with data retrieved from in vehicle monitoring systems and site video surveillance cameras to allow both retrospective investigation of elevated vibration levels and real-time management of operator exposures. A proposal for a project to develop and evaluate the software required for this development will be submitted for the 2016 ACARP funding round.

The finding that the prevalence of extreme dozer vibration levels appeared to be significantly reduced as a consequence of dozer operators being video recorded suggests that an intervention consisting of systematic observation, feedback, training and supervision may provide an opportunity to reduce dozer vibration exposures. Further investigation and evaluation is justified.

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References


