CONTINUOUS MONITORING OF WHOLE-BODY VIBRATION ASSOCIATED WITH SURFACE MINING EQUIPMENT

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Abstract

Long term exposure to high-amplitude whole-body vibration is associated with adverse health effects, especially back pain. Operators of surface mining equipment are known to be exposed to whole-body vibration. Vibration amplitudes experienced by operators are dynamic, a function of equipment design; seat design, condition and adjustment; roadway or ground conditions; vehicle maintenance; activity being undertaken; and operator behaviour. Ad hoc measurements are consequently of limited utility in assisting mines to manage exposures to the hazard. This paper describes the background to the design and implementation of hardware and software which enable continuous monitoring of floor and seat accelerometer installed in earth-moving equipment at a Queensland coal mine. The data have potential to enable evidence-based decisions regarding the implementation of control measures

Introduction

Operators of mobile plant used at surface coal mines are exposed to high amplitude whole-body vibration. The level of exposure is determined by a number of factors including the equipment (design, suspension and maintenance); the seat (design, adjustment and maintenance); the tyres; the roadway surface condition; the task and operator behaviour. Many of these factors are dynamic and vary over different time scales ranging from minutes (eg speed of driving) to hours (task), days (roadway maintenance), months (equipment maintenance) and to years (equipment design). To manage these changing conditions systematic and frequent evaluation of whole-body vibration exposures is required to ensure risk situations are identified and effective risk management strategies implemented.

International Standards Organisation standard 2631.1 “Evaluation of Human Exposure to Whole-body Vibration: Part 1-

General Requirements” describes procedures for the measurement of whole-body vibration. Two principle methods of describing frequency-weighted acceleration amplitudes are defined: (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 Z one (HGCZ) it is suggested that no health effects have been clearly documented. For exposures within the HGCZ “caution with respect to potential health risks is indicated” and for accelerations greater than the HGCZ, it is suggested that “health risks are likely.” For an 8-hr daily exposure, the upper and lower bounds of the HGCZ as indicated in 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 are 8.5 $m/s^{1.75}$ and 17 $m/s^{1.75}$.

While ISO2631.1 provides guidance regarding the measurement and evaluation of the health effects of whole-body vibration, obtaining such measurements typically involves the 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.

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 utilized as input to the operating system and applications such as games. An opportunity existed 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.

The 5th generation iPod Touch (Apple Inc., Cupertino, CA) (Figure 1) has a factory calibrated accelerometer (Microelectronics, Geneva, Switzerland) providing three dimensional 16 bit data output configured to a range of +/- 2g. An iOS application (WBV) was developed in conjunction with Byteworks (www.byteworks.us) and validated against commercially available whole-body vibration testing devices (Wolfgang & Burgess-Limerick 2014a; Wolfgang et al., 2014). Measurements made with the iPod Touch devices have been demonstrated to correspond well to measurements obtained via specialised whole-body vibration measurement systems (Wolfgang & Burgess-Limerick, 2014).

The accuracy of the iOS application was assessed by obtaining 96 simultaneous pairs of measurements from the iPod Touch and a commercially available measurement device (SV106) during the operation of a range of surface coal mining equipment during normal mining operations (Burgess-Limerick & Lynas, 2015). The results suggested that the iPod accelerometer data were accurate with a 95% confidence of +/- 0.06ms $^{-2}$ r.m.s for the vertical direction. The results prompted the development and subsequent public release of a free iOS application (WBV).

The application was installed on multiple iPod devices allowing site based simultaneous collection of long duration measurements. A range of mobile plant and equipment such as dozers, haul trucks, water trucks, excavators and graders are used at surface coal mines. Shuttle cars and other coal transport vehicles, personnel transport vehicles and Load-Haul-Dump (LHD) vehicles are used extensively in underground coal mines. Collecting occupational whole-body vibration data is challenging whether in surface mining, construction quarrying or underground mining operations, with only a few researchers having collected long duration whole-body vibration measurements. Scarlett and Stayer (2005) collected a single long duration measurement (3-4 hrs) from each of 13 different machines used in mining, quarrying and construction. Eger et al (2006) collected short duration measurements (10-26 min) from fifteen types of underground and surface mining equipment, with reported values for a grader falling within the HGCZ and for a bulldozer exceeding the HGCZ. Smets et al (2010) collected 60 minute duration whole-body vibration measurements from 8 haul trucks operating on surface metalliferous mines in Canada. All 8 VDB(8) measurements were within the HGCZ. In 2012 Burgess- Limerick reported 26 short duration measurements (16-70 min) from dozers working on a range of tasks on an Australian surface coal mine, with only one of the r.m.s measurements lying within the HGCZ and one of the VDV(8) exceeding the HGCZ. Wolfgang and Burgess-Limerick (2014b) collected 18-54 minute measurements of haul trucks operating on an Australian surface coal mine, with 20 of the 32 r.m.s measurements falling within the HGCZ. More recently Burgess-Limerick and Lynas (2016) collected 59 long duration measurements (100–460 minutes) from a range of surface coal mining equipment on an Australian mine site. Results indicated that operators of dozers in particular are frequently exposed to vertical whole-body vibration levels that lie within or above the HGCZ. Subsequently, long duration measurements were collected from 60 dozers during normal operation on an Australian mine site (Lynas & Burgess-Limerick, 2019).

Similarly, whole-body vibration exposures were measured at three low methane Australian underground coal mines, with measurements obtained from shuttle cars, personnel and equipment transport vehicles, a continuous miner and a coal tram. The majority of measurements taken exceeded the ISO2631.1 HGCZ (Burgess-Limerick & Lynas, 2016).

This research has demonstrated the that relatively low cost of the iPod Touch hardware, 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.

In 2017 an industry funded project commenced with the objectives of (i) developing, demonstrating and evaluating iOS and server software to allow continuous monitoring and analysis of each moving equipment operator vibration exposures using off-the-shelf hardware; (ii) to utilise this system to obtain an enhanced understanding of the sources of elevated whole-body vibration and impact loads associated with haul truck and dozer operation at a surface coal mine; and (iii) to make the software freely available for adoption by other sites.

Method

The WBV application was modified and installed on 5 iPhones. Initially it was planned to utilise the iPhone capability of GPS location in conjunction with the accelerometer data received via the WBV application and transmit the data via the mining company wireless network to a University of Queensland server. Five replacement truck seats were modified to allow the iPhones and associated adapters and cabling to be installed in the haul truck seats. The iPhones successfully sent GPS and accelerometer data however regular breaks in transmission were observed. The transmission breaks were consistent with the phones overheating, shutting down and restarting once cooled sufficiently. A number of options were considered, and it was decided to develop new hardware based on a Raspberry Pi (RPi) single board computer incorporating a GPS module and remote accelerometer, and located outside the seat. The iOS operating system imposed a 100Hz sampling limit which does not not exist with the RPi which enabled sampling at 250 Hz to allow higher frequency vibrations to be faithfully captured.

A challenge arose at this stage of the project with the mining company decision to close the site at which the data collection was being undertaken. Fortunately, the opportunity arose to continue the project at a similar open cut site under the same mining company ownership. Installation continued as planned with installation of the RPi in five haul truck seats (Figure 1).

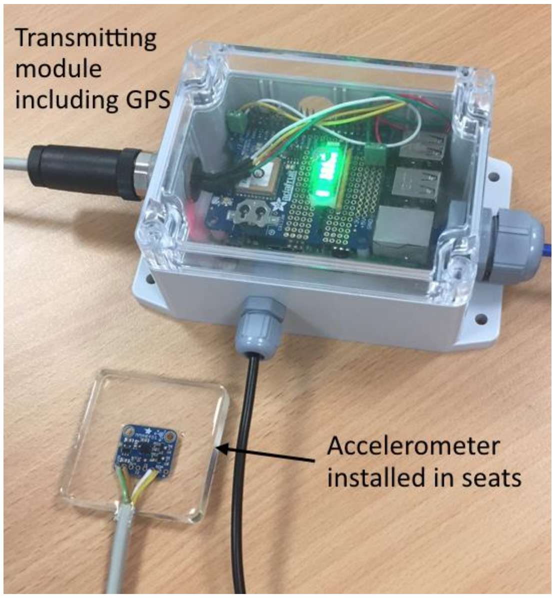


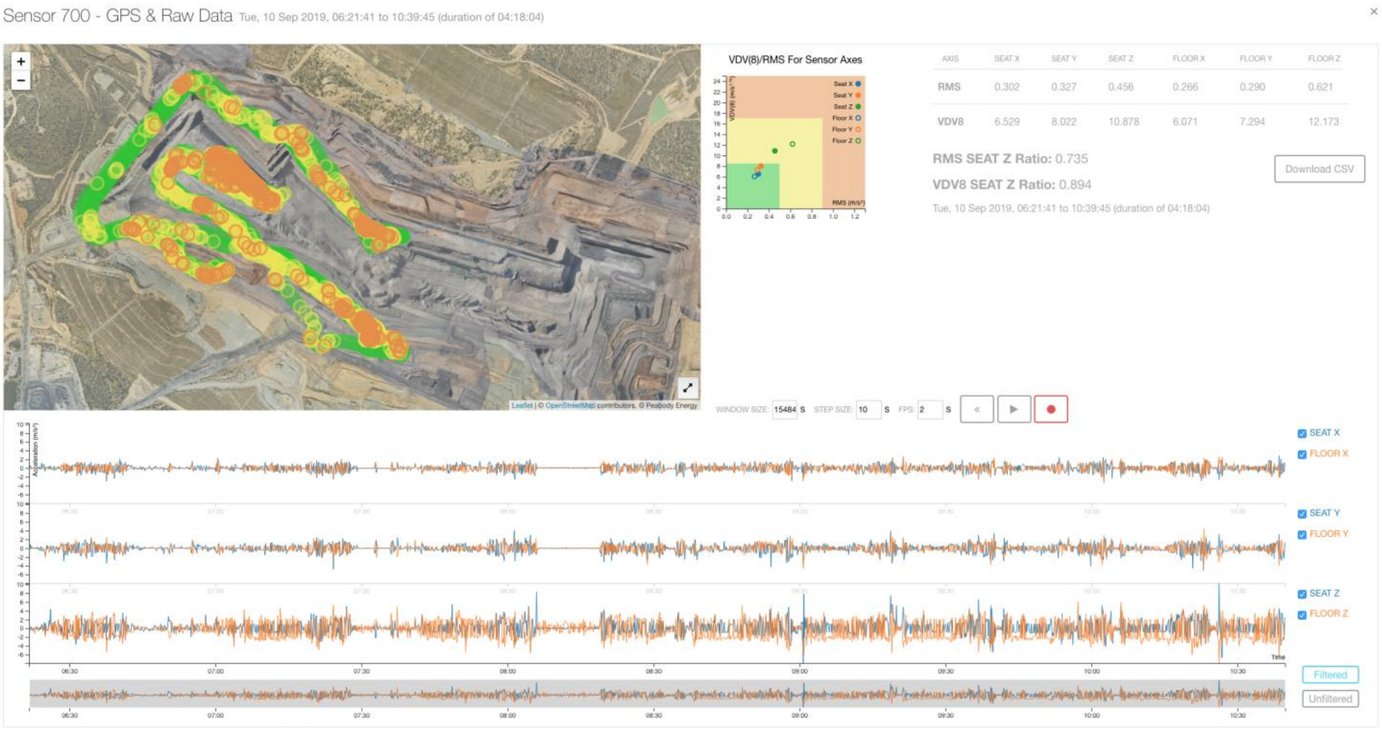
Figure 1: RPi Module and accelerometer. A second accelerometer is installed under the truck seat and connected to the RPi module. Simultaneous recordings from both accelerometers allow for a more detailed examination of the attenuation capabilities of the vehicle seats to be achieved.

Results and Discussion

Figure 2 illustrates floor and seat accelerometer data, along with GPS location, for a 4 hour, 18 minute sample from a haul truck in operation at a central Queensland coal mine. 128 samples varying in duration from 1 to 4 hours were obtained from this truck over a one month period. Figure 3 illustrates the distribution of the frequency weighted floor and seat accelerometers in the Z (vertical) direction expressed as r.m.s and VDV(8), as well as the distribution of the Seat Effective Amplitude Transmissibility for r.m.s and VDV. The long tail of the VDV distribution indicates that for some of the samples observed, the seat was not effectively attenuating vertical whole-body vibration, and indeed, was amplifying the vibrations.

A potential explanation for these differences is illustrated in Figure 4. Two samples are illustrated in which the floor and seat accelerations were measured from the same truck driving over the same roadway on the same day, while effectiveness of the seat varied considerably. During the first sample the seat was amplifying the accelerations at the floor (VDV SEAT = 1.26) while in the second sample the seat was effective in attenuating the vibrations (VDV SEAT = 0.894). The break between the two samples corresponded to a shift change. It is likely that the difference in seat performance observed over the month of measurements is related to variation in operator mass, and either the drivers' inability, or failure, to adjust the suspension of the seat to match the driver's mass.

Figure 5 provides an example of the use of the continuous data gathered to identify a event with potential acute injury risk potential such as a excavator bucket striking the truck tray.



Sensor 700 - GPS & Raw Data Tue, 10 Sep 2019, 06:21:41 to 10:39:45 (duration of 04:18:04)

AXIS	SEAT X	SEAT Y	SEAT Z	FLOOR X	FLOOR Y	FLOOR Z
RMS	0.302	0.327	0.456	0.266	0.290	0.621
VDV8	6.529	8.022	10.878	6.071	7.294	12.173

RMS SEAT Z Ratio: 0.735

VDV8 SEAT Z Ratio: 0.894

Tue, 10 Sep 2019, 06:21:41 to 10:39:45 (duration of 04:18:04)

WINDOW SIZE: 15484 S STEP SIZE: 10 S FPS: 2 S

Figure 2: Example seat and floor frequency weighted accelerations measured from a haul truck during normal operation at a central Queensland coal mine.

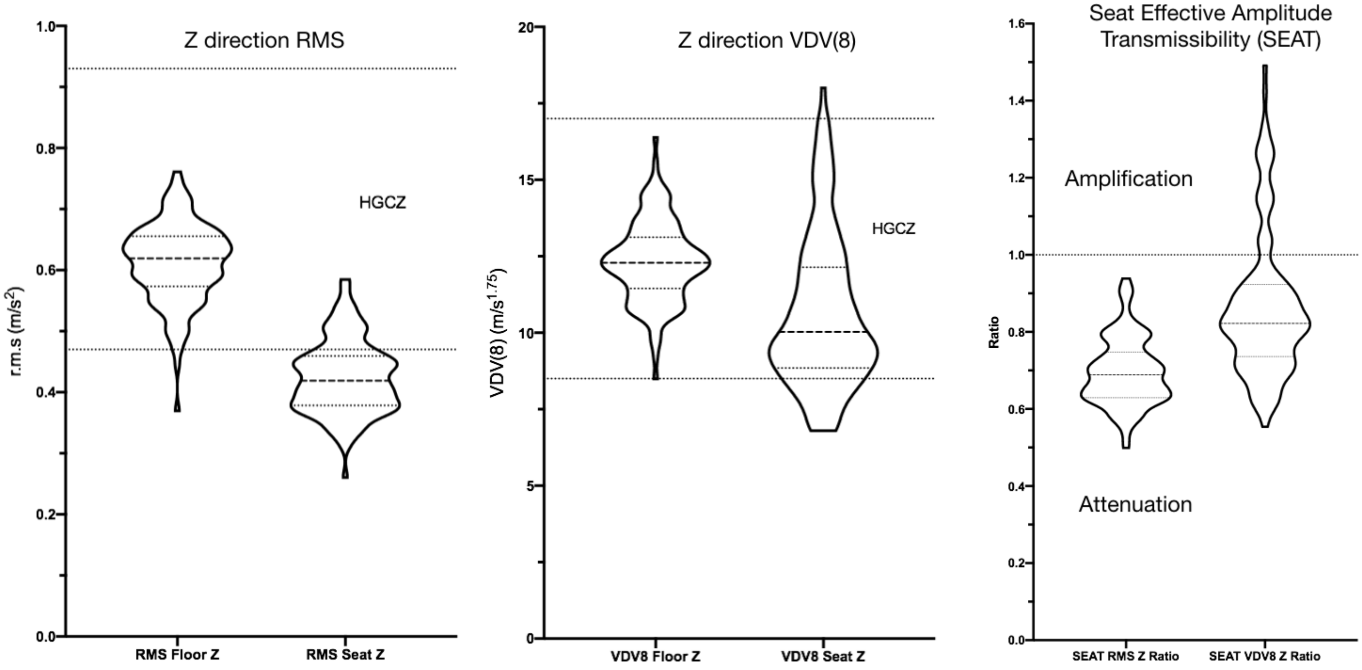
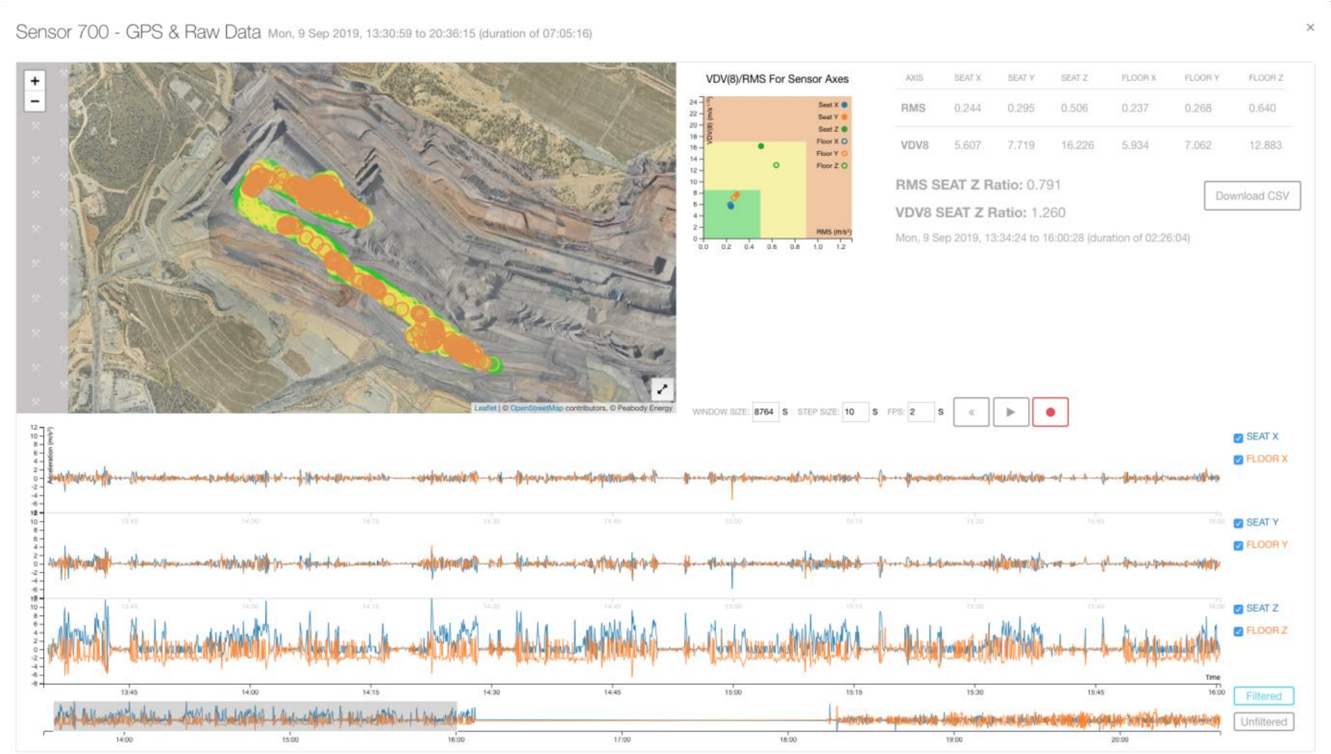


Figure 3: Frequency distribution of 128 1-4 hour samples of Z direction frequency-weighted accelerations measured at floor and seat of a haul truck over a one month period.



Sensor 700 - GPS & Raw Data Mon, 9 Sep 2019, 13:30:59 to 20:36:15 (duration of 07:05:16)

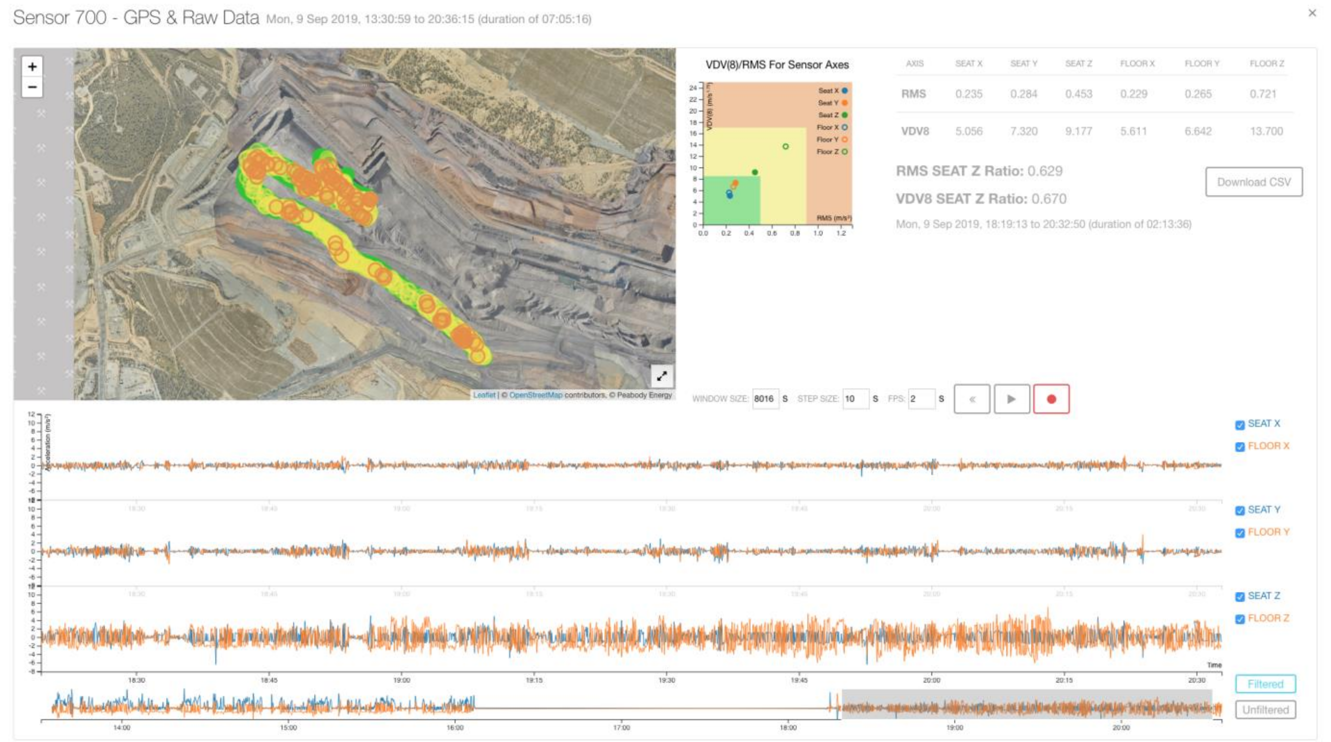
AXIS	SEAT X	SEAT Y	SEAT Z	FLOOR X	FLOOR Y	FLOOR Z
RMS	0.244	0.295	0.506	0.237	0.268	0.640
VDV8	5.607	7.719	16.226	5.934	7.062	12.883

RMS SEAT Z Ratio: 0.791

VDV8 SEAT Z Ratio: 1.260

Mon, 9 Sep 2019, 13:34:24 to 16:00:28 (duration of 02:26:04)

WINDOW SIZE: 8764 S STEP SIZE: 10 S FPS: 2 S



Sensor 700 - GPS & Raw Data Mon, 9 Sep 2019, 13:30:59 to 20:36:15 (duration of 07:05:16)

AXIS	SEAT X	SEAT Y	SEAT Z	FLOOR X	FLOOR Y	FLOOR Z
RMS	0.235	0.284	0.453	0.229	0.265	0.721
VDV8	5.056	7.320	9.177	5.611	6.642	13.700

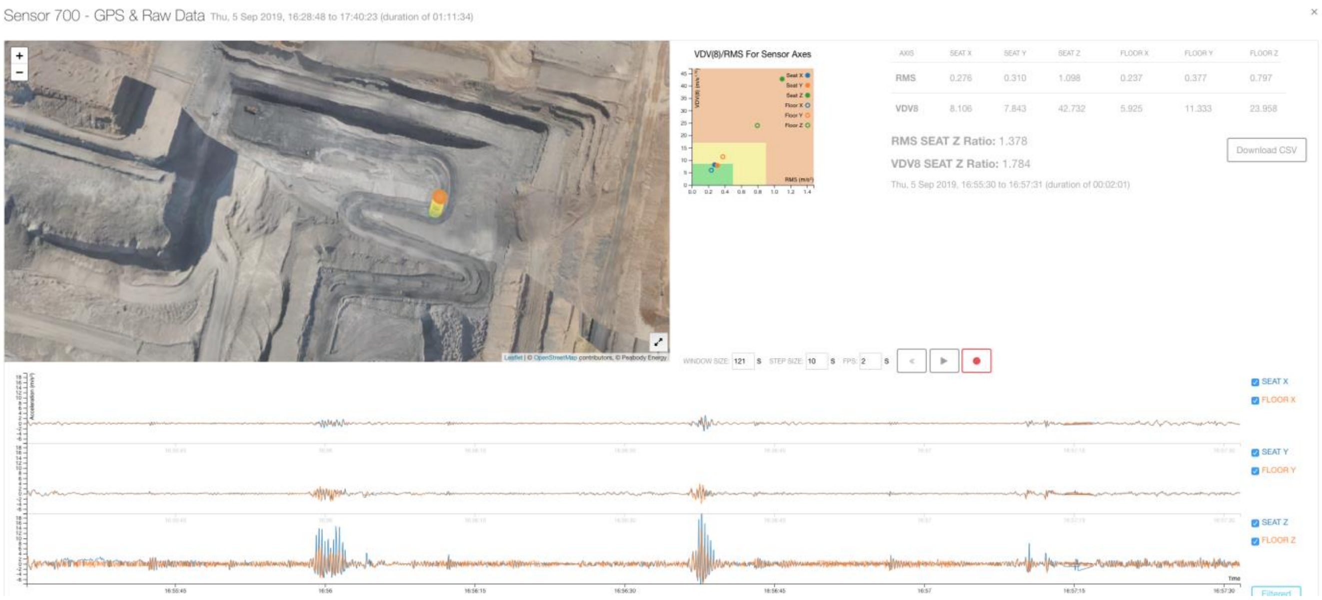
RMS SEAT Z Ratio: 0.629

VDV8 SEAT Z Ratio: 0.670

Mon, 9 Sep 2019, 18:19:13 to 20:32:50 (duration of 02:13:36)

WINDOW SIZE: 8016 S STEP SIZE: 10 S FPS: 2 S

Figure 4: Two sequential samples of whole-body vibrations illustrating variability in the effectiveness of the seat in attenuating accelerations.


Sensor 700 - GPS & Raw Data Thu, 5 Sep 2019, 16:28:48 to 17:40:23 (duration of 01:11:34)

AXIS	SEAT X	SEAT Y	SEAT Z	FLOOR X	FLOOR Y	FLOOR Z
RMS	0.276	0.310	1.098	0.237	0.377	0.797
VDV8	8.106	7.843	42.732	5.925	11.333	23.958

RMS SEAT Z Ratio: 1.378

VDV8 SEAT Z Ratio: 1.784

Thu, 5 Sep 2019, 16:55:30 to 16:57:31 (duration of 00:02:01)

WINDOW SIZE: 121 s STEP SIZE: 10 s FPS: 2 s

Figure 5. An example of an event with high acute injury potential captured by the continuous monitoring system.

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