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Evaluation of operator whole-body vibration and shock exposure in a South African open cast mine

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by

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Abstract

This study quantifies whole-body vibration on a range of mine machinery typically used in a South African open cast mine. The ISO 2631-1 (1997) standard was used in the computation of weighted root mean square (WRMS) and vibration dose values (VDVs) whereas the ISO 2631-5 (2004) standard was used in the computation of daily static compressive stress (S_{ed}) and R factor values. Two methods have been used to evaluate the whole-body vibration on a wide range of equipment used in an open cast mine. There are two main parameters for each of the standards. The ISO 2631-1 (1997) standard utilises the daily exposure A(8) and VDV, whereas the new ISO 2631-5 (2004) standard methodology uses the parameters S_{ed} and R factor.

ISO 2631-1 (1997) is poor in taking account of transient shocks. This led to the development of ISO 2631-5 (2004). Signals were therefore generated in the laboratory to further explore the parameters of the two standards.

Vibration signals of more-or-less steady periodic processes can be approximated by superposition of sinusoids. To investigate the effect of shocks on the WBV response parameters used in the two standards, a series of investigations were conducted using very simplified simulations to capture the essential nature of various operational conditions, and qualitatively explain the trends in the response parameters. Pure sinusoidal data was first generated without shocks and investigated. Subsequently, sinusoidal signals with higher amplitudes were generated and investigated. Sinusoidal signals with increasing shock amplitude up to and exceeding the crest factor of 9 based on ISO 2631-1 (1997) were generated and analyzed. Finally, simulated data with different shock magnitude for five typical example cases were then generated and analyzed.

The pure sinusoidal data was artificially generated using the signal generator at different amplitudes and frequencies, which are similar to field observed frequencies to enable numerical investigation of parameters to be carried out. A subset of the data was selected based on frequencies and amplitudes obtained on the field so as to have a representative data set on which investigations were carried out.

The two parameters of the two standard methodologies were computed using simulated sinusoidal signal data. The trends in each of the parameters corresponding to each of the standards were monitored using various scenarios obtained by varying the signal parameters and compared against each other. There was approximate proportional correlation between the two parameters (VDV and S_{ed}) with varying degrees of slope for each scenario. The S_{ed} and VDV parameters are plotted on the x- and y-axes respectively. The graphs with slope greater than 1 corresponded to signals with low or no shock content; whereas the graphs with slope less than 1 corresponded to high shock content.

The shock parameters (VDV and S_{ed}) corresponding to the ISO 2631-1 (1997) and ISO 2631-5 (2004) standard methodologies were computed from field data and compared to see if the same trend obtained from the numerically obtained sinusoidal signals could be validated. It was found that the there was a gradual band correlation with slope less than 1 between the VDV and S_{ed} parameters corresponding to signals of high shock content thereby validating the numerical findings.

Since little or no extensive epidemiological studies have been carried out on the new methodology; it is recommended that more epidemiological studies be done to determine the exposure action and exposure limit values with respect to shocks in the S_{ed} parameter for the new ISO 2631-5 (2004) standard methodology.

It is advisable that caution is taking when using the new ISO 2631-5 (2004) standard methodology in evaluating whole-body vibration measurements until the limits are properly established. It is suggested that the new standard be used along with the established ISO 2631-1 (1997) standard methodology.

Keywords: Whole-body vibration, ISO 2631-1 (1997), ISO 2631-5 (2004), open cast mine, transient shock

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Table of contents

Acronyms

Acronym	Meaning
A(8) for WBV	The daily exposure (8-hour energy-equivalent continuous, frequency-weighted RMS acceleration)
$A(8)_n$	Normalised daily exposure (8-hour energy-equivalent continuous, frequency-weighted RMS acceleration)
ANN	Artificial Neural Network
ATD	Anglo Technical Division
ATVs	All-terrain vehicles
CF	Crest factor
D_k	The acceleration dose in the k direction
D_y	Group mean total (lifetime) exposure duration in years
EAV	Exposure action value
EAV_n	Normalised exposure action value
EFV	Expeditionary fighting vehicle
ELV	Exposure limit value
ELV_n	Normalised exposure limit value
EMG	Electromyography
EU	European Union
FEL	Front End Loader
HAV	Hand-arm vibration
HEMM	Heavy earth-moving machineries
HGCZ	Health Guidance Caution Zone
HHA	Health Hazard Assessment
HVM	Human Vibration Meter
ICP	Integrated Circuit Piezoelectric
LHD	Load haul dump
MARS	Multi-axis Ride Simulator
MR	Magneto-rheological
MSD	Musculoskeletal disorders
PC	Personal Computer
PCB	Printed Circuit Board
R	Risk factor

R_n	Normalized Risk factor
RMS	Root Mean Square
RNN	Recurrent Neural Network
S_e	Equivalent static compressive stress
SEAT	Seat Effective Amplitude Transmissibility
S_{ed}	Daily equivalent static compressive dose
S_{edn}	Normalized daily equivalent static compressive dose
S_{ui}	Ultimate strength of the lumbar spine
SVAN	Sound Vibration Analyzer
TGV	Tactical Ground Vehicles
USAARL	United States Army Aeromedical Research Laboratory
VDV	Vibration Dose Value
VDV_n	Normalized Vibration Dose Value
WBV	Whole-Body Vibration
WRMS	Weighted Root Mean Square

List of Figures

Figure 4.6	Relationship between health predicted by (a) VDV_n versus $A(8)_n$ values, (b) R_n factor versus S_{edn} values, (c) $A(8)_n$ versus S_{edn} values and (d) VDV_n versus S_{edn} values for simulated data with different amplitude and low shock magnitude for five typical example cases. The associated HGCZ are also indicated in the figures	69
Figure 4.7	Relationship between health predicted by (a) VDV_n versus $A(8)_n$ values, (b) R_n factor versus S_{edn} values, (c) $A(8)_n$ versus S_{edn} values and (d) VDV_n versus S_{edn} values for simulated data with different amplitude and shock magnitude for five typical example cases. The associated HGCZ are also indicated in the figures.	70
Figure 5.1	Weighted RMS acceleration magnitudes for LHDs	72
Figure 5.2	Weighted RMS acceleration magnitudes for excavators	73
Figure 5.3	Weighted RMS acceleration magnitudes for front end loaders	73
Figure 5.4	Weighted RMS acceleration magnitudes for dozers	74
Figure 5.5	Weighted RMS acceleration magnitudes for drills	74
Figure 5.6	Weighted RMS acceleration magnitudes for graders	74
Figure 5.7	Weighted RMS acceleration magnitudes for liquid conveyers	75
Figure 5.8	Weighted RMS acceleration magnitudes for 4x4	75
Figure 5.9	Weighted RMS acceleration magnitudes for compactor	75
Figure 5.10	VDV magnitudes for LHDs	77
Figure 5.11	VDV magnitudes for excavators	78
Figure 5.12	VDV magnitudes for front end loaders	78
Figure 5.13	VDV magnitudes for dozers	79
Figure 5.14	VDV magnitudes for drills	79
Figure 5.15	VDV magnitudes for graders	79
Figure 5.16	VDV magnitudes for liquid conveyers	80
Figure 5.17	VDV magnitudes for 4x4	80
Figure 5.18	VDV magnitudes for compactor	80
Figure 5.19	S_{ed} magnitudes for LHDs	82
Figure 5.20	S_{ed} magnitudes for excavators	83
Figure 5.21	S_{ed} magnitudes for front end loaders	83
Figure 5.22	S_{ed} magnitudes for dozers	84
Figure 5.23	S_{ed} magnitudes for drills	84
Figure 5.24	S_{ed} magnitudes for graders	84
Figure 5.25	S_{ed} magnitudes for liquid conveyers	85

List of Tables

1. Introduction and objectives

1.1 Background

Mining involves frequent and intensive usage of heavy machinery that often results in significant exposure of operators to shock and vibration, over prolonged periods. Such exposures may lead to discomfort, interference with activities and impaired health (Griffin, 1990).

To deal with the complexity and diversity of these effects on the human body, it is customary to consider human vibration as either a whole-body vibration problem or a hand arm vibration problem. Whole-body vibration refers to where the whole body is exposed to vibration through contact by the buttocks or feet whereas hand-arm vibration refers to where the hand are exposed to vibration through contact. Various international standards have been developed which govern the way in which human vibration should be measured and reported, as well as provide indications of the health risk involved. In this regard ISO 2631-1 (1997) and ISO 5349-1 (2001) are well known in industry. The complexity of the problem however still escapes final agreement and standardization.

European Parliament legislation (EU Directive 2002/44/EC, 2002) stipulates minimum standards for health and safety of workers exposed to either hand-arm or whole-body vibration. Unlike Europe, South Africa does not have legislation which governs maximum acceptable vibration levels. However, it might be expected that the EU initiative may gradually start to influence the situation in South Africa (Heyns, 2007). EU practice is therefore considered here in the evaluation of acceptable vibration levels.

The EU legislation specifies daily vibration exposure levels (exposure action value (EAV) and exposure limit value (ELV)), shown in Table 1.1, in addition to requiring employers to reduce worker vibration exposure levels wherever it is practically possible. Where an operator is likely to be exposed to vibration, an assessment of the likely daily vibration exposure is to be made. If the exposure level is above the EAV, a range of actions must be taken to reduce exposure and decrease risks. If the ELV is exceeded, immediate action must be taken to reduce vibration exposure below the ELV and procedures be implemented to prevent it being exceeded again. Prediction of whole-body vibration (WBV) health risks is based on ISO 2631-1 (1997) and ISO 2631-5 (2004) health guidance caution zone (HGCZ) limits as shown in Table 1.1.

Table 1.1 Table of exposure action and limit values and health guidance caution zone values for whole-body vibration

Exposure/HGCZ	ISO 2631-1 (1997)		ISO 2631-5 (2004)	
	WRMS	VDV	S_{ed}	R
EAV/ HGCZ lower limit	0.50 m/s^2	9.1 $m/s^{1.75}$	0.50 MPa	0.80
ELV/ HGCZ upper limit	1.15 m/s^2	21.0 $m/s^{1.75}$	0.80 MPa	1.20

Since vibration exposure is dependent on the magnitude of vibration and the duration of exposure, the duration of operation of such machines which cause high levels of vibration, could possibly be limited to reduce exposure. With reference to WBV the ELV stated by the EU directive should not be taken as a safe level of vibration exposure in the workplace, but rather as a high, undesirable level of vibration exposure to be complied to (Whole-body vibration guide to good practice). It is on this basis that the directive requires action to be taken, as far as is reasonably practicable, to reduce vibration exposure once levels are above the EAV.

Numerous epidemiological studies have been conducted all over the world, documenting the detrimental effects of high levels of vibration exposure on human beings.

A pilot study (Van Niekerk et al. 2000; MHSC, 2004) has shown that vibration levels in South African mines are very high. Subsequent work by Phillips et al. (2007) confirmed these conclusions.

Mdlazi (2008) conducted research to investigate the impact of whole-body vibration on the day to day activities at Anglo operations South Africa. It was concluded that there is enough evidence that a number of vehicles and equipment at Anglo operations expose a large number of employees to high vibration levels and that vibration exposure levels have to be managed to minimize the risk of injury.

The problem is very complex and needs to be very carefully managed. This is currently being understood and addressed at various levels. In South Africa the situation is still confused with a limited legal framework and diverse approaches to the problem (Heyns, 2007). While vibration measurements and analyses are usually conducted in accordance with ISO 2631-1 (1997), a unified approach to the problem requires the development of a system of commonly acceptable and practically executable best practice which addresses issues such as measuring procedures, measuring instruments, occupational exposure limits for whole-body vibration, exposure control measures and assessment and management of WBV related disease (Heyns, 2007).

It is against this background that a best practice document for South African conditions needs to be developed, based on experience all over the world. There have been a number of initiatives in South Africa, all based on ISO 2631-1 (1997). This work has shown high levels of vibration and occurrence of transient shocks. In situations where transient shocks are present, the ISO 2631-1 (1997) is however now understood to be insufficient to fully evaluate whole-body vibration (Nicol, 1996; Marjanen, 2005). Hence, there is the need for a separate evaluation methodology for such cases of whole-body vibration in the presence of transient shocks (Marjanen, 2005).

The International Organisation for Standardization released an updated whole-body vibration standard, ISO 2631-5 in 2004. For the new standard WBV levels are either below the daily equivalent static compressive stress (S_{ed}) value of 0.5 MPa or between the S_{ed} values of 0.5 MPa and 0.8 MPa or above the S_{ed} value of 0.8 MPa. According to ISO 2631-5 (2004), S_{ed} values below 0.5 MPa give an indication of low probability of an adverse health effect whereas S_{ed} values above 0.8 MPa give an indication of high probability of an adverse health effect. However, S_{ed} values between 0.5 MPa and 0.8 MPa give an indication of moderate probability of an adverse health effect. Alternatively, WBV levels are either below the R factor of 0.8 or between the R factors of 0.8 and 1.2 respectively or above the R factor of 1.2. The R factor takes into account increased age and reduced strength. According to ISO 2631-5 (2004); R factors below 0.8 give an indication of low probability of an adverse health effect whereas R factors above 1.2 give an indication of high probability of an adverse health effect. However, R factors between 0.8 and 1.2 give an indication of moderate probability of an adverse health effect.

North American railroad operators are exposed to vibration and shock. Twenty two US railroad locomotives had low WRMS vibration levels (Johanning et al., 2002). The highest WRMS value was 0.43 m/s^2 and a mean WRMS value of 0.32 m/s^2 which is below the EAV based on ISO 2631-1 (1997). Johanning et al. (2006) reported higher predicted risks based on ISO 2631-1 (1997) variables than ISO 2631-5 (2004) variables for 20 locomotive operators. According to their findings, frequency-weighted RMS acceleration values indicated several locomotive operators were exposed to vibration levels above HGCZ limits outlined in ISO 2631-1 (1997); however, fewer operators were found to be at risk according to ISO 2631-5 (2004). Since the impacts or shocks were not high enough as earlier explained; this led to low values of S_{ed} based on ISO 2631-5 (2004) which led to even lower risk predictions.

Cooperrider and Gordon (2008) also reported higher risks for locomotive operators, based on VDVs from an ISO 2631-1 (1997) analysis when compared to S_{ed} values from an ISO 2631-5 (2004) analysis. In their study, four locomotive operators had VDVs that placed them within the HGCZ (for an 8-h working shift); however, all the S_{ed} values were below the boundary for low probability of adverse health effects.

A recent study (Eger et al., 2008) explores the differences in health risk predictions in the operation of load haul dump mining vehicles, and concludes that more dialogue is needed to identify the appropriate application of ISO 2631-1 (1997) and ISO 2631-5 (2004). Eger et al. found that the risk indicated by values obtained by using ISO 2631-1 (1997) was higher than that based on ISO 2631-5 (2004). They had WRMS values ranging from 0.06 m/s^2 to 1.06 m/s^2 and a mean WRMS value of 0.76 m/s^2. However, they had crest factors above nine which indicted the presence of shocks. This was because the impacts were high relative to the lower values of WRMS obtained from the data since crest factor is a ratio of the highest impact magnitude to the WRMS. When the shocks are low this could still lead to lower values of S_{ed} which leads to the prediction of lower risk to health based on ISO 2631-5 (2004).

Another study (Alem, 2005) found that the risk based on values obtained by using ISO 2631-1 (1997) was less than that based on ISO 2631-5 (2004) in the presence of high transient shocks on US army vehicle on cross country rough terrain. Yet another study (Chen et al., 2009) carried out on riders of twelve motorcycles on rough roads with high shock content, suggested that health risk predicted based on the daily dose of equivalent static compression stress of ISO 2631-5 (2004) is more stringent than that based on the vibration dose value of ISO 2631-1 (1997). The findings from these studies contradict each other.

There is a need for further research studies on the ISO 2631-5 (2004) standard, and for South Africa, especially its application in the mining industry.

1.2 Dissertation overview

The dissertation is divided into chapters dealing with introduction and objectives; measurement and analysis; results; numerical investigation of parameters; evaluation of results of investigation; and conclusions and recommendations.

The first chapter deals mainly with the literature pertaining to comprehensive investigations done using the ISO 2631-1 (1997) methodology and the much smaller body of pioneering work done on the ISO 2631-5 (2004) standard methodology.

The second chapter deals with the measuring and analysis methodologies. The chapter lists the equipment used in measurement and shows how the computations of the various parameters in the standards are done.

The third chapter reports on the analysis of vibration data obtained from field measurements on the various machines on the open cast mine using the two standard methodologies under consideration.

The fourth chapter deals with the laboratory simulation of data which is used to compute the various parameters in the standard methodologies under investigation. The characteristics of the data are varied to see the trend in the results obtained. The numerical results of simulation so obtained are used to see trends and differences in results between ISO 2631-1 (1997) and ISO 2631-5 (2004).

The fifth chapter evaluates the results obtained from the field based on the ISO 2631-1 (1997) and ISO 2631-5 (2004) standard methodologies in comparison to each other. Also results obtained on the field are compared to numerical results.

The sixth and final chapter concludes the dissertation and discusses the accomplishments, shortcomings and recommendations for further study.

1.3 Literature survey

1.3.1 Various whole-body vibration standards

There were about 150 human vibration national standards about two decades ago (Mansfield, 2005). Since, then some of the standards have been updated and several new ones have been written. Some of the standards used globally for whole-body vibration are tabulated below in Table 1.2. Many of these standards are based on ISO 2631-1 (1997) and give similar results. As such ISO 2631-1 (1997) is used most often.

Table 1.2 Major whole-body vibration standards

ISO 2631-1(1997) ISO 2631-2(1989) ISO 2631-4(2001) ISO 2631-5(2004)	Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration. Part 1: General Requirements. Evaluation of human exposure to whole-body vibration – Part 2: Continuous and shock induced vibration in buildings (1 to 80 Hz) Part 4: Guidelines for the evaluation of the effects of vibration and rotational motion on passenger and crew comfort in fixed-guideway transport systems Part 5: Method for evaluation of vibration containing multiple shocks
ISO 8041(1990)	Human response to vibration – Measuring instrumentation
BS 6841(1987)	Measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock
SAE J1013(1992)	Measurement of whole-body vibration of the seated operator of off-highway work machines
SAE J1384(1993)	Vibration performance evaluation of operator seats
ANSI S2.72/Part 1-2002 (R 2007)	American National Standard Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration – Part 1: General requirements
AS 2670.1-1990	Evaluation of human exposure to whole-body vibration - General requirements

The standard instructs doing a risk assessment also for the repeated shocks. Partly for this reason ISO 2631-5 (2004) was produced. The purpose of ISO 2631-5 is to define a method for analyzing the effect of multiple shocks in relation to human health. The standard has a method on how to analyze the effect of transient shocks based on an experimental model of the lumbar spine response. Using the method one can calculate the pressure that a shock or multiple shocks will create to the spine and thus analyze if it will be damaged or not. It is the only current standard that can be used to analyze shocks properly.

To evaluate the health effects, the standard introduces a static compressive stress value (S_{ed}). S_{ed} is calculated from the sixth power sum of acceleration dose values multiplied with dose coefficients. There are separate procedures for horizontal and vertical directions in the standard. Horizontal directions are assumed to have a linear response. The acceleration data is filtered using a single-degree-of-freedom lumped-parameter model. The vertical direction model is based on a recurrent neural network model, which is non-linear. There are several variables to be chosen when calculating the health risk. One of them is the age of the worker. Starting age defines the total years of exposure until retirement, which contributes to the likeliness of the health risk. Other factors are the exposure time on a given day, which defines the acceleration daily dose value, and exposure days in a year, which also affects the final value.

The differences between ISO 2631-1 (1997) and ISO 2631-5 (2004) are tabulated below**.**

Table 1.3 Differences between ISO 2631-1 (1997) and ISO 2631-5 (2004)

ISO 2631-1 (1997)	**ISO 2631-5 (2004)**
Crest factors higher than 9 indicate the presence of shock	Examples of conditions resulting in vibration containing multiple shocks are given to include, but not limited to, machinery travelling over rough surfaces, small boats in rough sea, aircrafts in buffeting, presses and mechanical hammers
Shock is evaluated by using the Vibration dose value (VDV) parameter	Shock is evaluated by using the equivalent static stress (S_{ed}) parameter
The basicentric axis with the highest magnitude is arbitrarily picked	S_{ed} values computed based on input from the three basicentric axes
Does not handle transient shocks well	Handles transient shocks well
VDV is 4th power based method	S_{ed} is 6th power based method
Weighting along the three basicentric axes similar	Response in x- and y-axes is linear and based on single degree of freedom model while z-axis is non linear and based on a RNN model
Does not model response to whole-body vibration response	Models lumbar spine response to vibration
Procedure simpler to understand	Procedure more complicated

1.3.2 Discussion of whole-body vibration field studies

Occupational health and safety issues have been investigated in several countries including British Columbia (Teschke et al., 2008), China (Zeng et al., 2007), Croatia (Goglia and Grbac, 2005), Finland (Yränheikki and Savolainen, 2000), Malaysia (Rampal et al., 2006), Spain (Sese´ et al., 2002), amongst others.

Griffin (1998) compared guidance on measuring, evaluating and assessing the health effects of whole-body vibration and repeated shock given in ISO 2631 (1974, 1985), BS 6841 (1987), and ISO 2631 (1997) standards. International Standard 2631 (1974, 1985) offers a set of exposure limits. British Standard 6841 (1987) defines a measurement and evaluation procedure (based on frequency weightings and the vibration dose value, VDV), and gives an action level that can be used to assess vibration severity. It also mentions some appropriate actions (consideration of the fitness of exposed persons, design of safety precautions, regular health checks). International Standard 2631 (1997) is unclear in several important areas: which body postures and axes are to be assessed; whether evaluations of multi-axis vibration should be based on the “worst axis” or a combination of the frequency-weighted acceleration in all axes. He concluded that the recently revised ISO 2631-1 (1997) for measuring, evaluating and assessing human exposures to vibration and shock will cause unnecessary confusion.

Salmoni et al. (2008) presented three case studies in transportation to highlight difficulties experienced when assessing whole-body vibration (WBV) exposure within an industrial occupational health setting. Across the three cases and various vehicles, the z-axis was always dominant with acceleration values collected at the seat–operator interface ranging from 0.10–1.08 m/s^2. Some of the main challenges discussed include the use and interpretation of safety standards, time and event sampling, effective access to equipment and operators, and lack of control when testing.

Fritz et al. (2005) found that long-term vibration stress can contribute to degenerative changes in the joints of the human body, especially in the lumbar spine. An important factor in the development of these diseases is given by the forces transmitted in the joints. Because the forces can hardly be measured, a biomechanical model was developed which simulates the human body in the standing and the sitting postures. The vibration properties of the model were adapted to the transmissibility transfer function provided in the standards and the literature. With the model the compressive forces at the driving point of the body, in the leg joints, and in two motion segments of the spine were simulated under a vertical pseudo random vibration. Transfer functions between the accelerations of the ground or of the seat and the forces were computed. The consideration of the forces resulted in a stronger weighting of low-frequency vibrations compared to the weighted acceleration as suggested by ISO 2631-1 (1997). In order to enable an assessment of the health risk a force-related guidance value was derived which amounted to 0.81 m/s^2 (RMS).

Scarlett et al. (2007) conducted a study to quantify whole-body vibration (WBV) emission and estimated exposure levels found upon a range of modern, state-of-the-art agricultural tractors, when operated in controlled conditions (traversing ISO ride vibration test tracks and performing selected agricultural operations) and whilst performing identical tasks during ‘on-farm’ use. Tractor WBV emission levels were found to be very dependent upon the nature of field operation performed, but largely independent of vehicle suspension system capability (due to the dominance of horizontal vibration). However, this trend was reversed during on-road transport. They concluded that further ‘on-farm’ WBV data collection is required to enable creation of a robust, generic WBV emission database for agricultural tractor operations, to enable estimation of likely WBV exposure by employers.

Hoy et al. (2005) conducted a cross-sectional study to investigate the risks from whole-body vibration and posture demands for low back pain (LBP) among forklift truck (forklift) drivers using ISO 2631-1 (1997). They found that whole-body vibration acted associatively with other factors (not independently) to precipitate LBP.

Bovenzi and Hulshof (1998) updated the information on the epidemiologic evidence of the adverse health effects of whole-body vibration (WBV) on the spinal system by means of a review of the epidemiologic studies published between 1986 and 1996. In a systematic search of epidemiologic studies of low back pain (LBP) disorders and occupations with exposure to WBV, 37 articles were retrieved. The findings of the selected studies and the results of the meta-analysis of both cross-sectional and cohort studies showed that occupational exposure to WBV is associated with an increased risk of LBP, sciatic pain, and degenerative changes in the spinal system, including lumbar intervertebral disc disorders. Upon comparing the epidemiologic studies included in their review with those conducted before 1986, they concluded that research design and the quality of exposure and health effect data in the field of WBV had improved in the last decade.

Rehn (2005) characterized whole-body vibration (WBV) exposure from various all-terrain vehicles (ATVs) like snowgroomers, snowmobiles and forwarders, and investigated how frequently the drivers' cervical spine is positioned in a non-neutral rotational position during operation. They obtained field measurements of WBV according to the international standard ISO 2631-1 (1997) in 19 ATVs. The sum of the vectors of frequency-weighted RMS acceleration varied between 0.5 and 3.5 m/s^2, which meant that for most vehicles they exceeded the action value stated by the European Union (0.5 m/s^2 WRMS). In general, snowmobiles achieved the highest vibration total value. The dominant vibration direction for the snowmobile was the x-axis but the z-axis also had relatively high vibration dose values and maximal transient vibration values. The z-axis was the dominant vibration direction for the snow groomer and the y-axis for the forwarder. Frequency and duration of non-neutral rotational neck postures were relatively low for all driver categories. They concluded vibration magnitudes in ATVs are considerably higher than the EU's action value and the health guidance caution zones in ISO 2631-1 (1997). The dominant vibration direction varies depending on the machine type.

1.3.3 Duration of measurement of whole-body vibration

Mansfield and Atkinson (2003) discovered that when searching the literature, one is hard pressed to find reports of whole-body vibration measurements with duration longer than a few minutes. When making a risk assessment according to standards and directives, the vibration exposure must be assessed and often measured. It has previously been assumed that a measurement of a few minutes will suffice as being representative of the full working day, although there is little evidence to back-up this assumption. They measured vibration exposure for drivers for a full working day. The exposures were analysed to investigate the potential errors from making measurements from 10 seconds to 60 minutes when compared with the full working day exposure. They recommended that measurements of vertical whole-body vibration in vehicles should last at least 10 minutes.

1.3.4 Attenuation of whole-body vibration

Rodean and Arghir (2007) investigated the biodynamic response of the human body subjected to vertical vibrations in an auto vehicle, in two different situations: the driver sitting on a rigid seat and the driver sitting on a vehicle seat with seat cushion and additional seat suspension respectively. In doing so, a seat suspension model with a detailed lumped parameter model of the human body, was developed. The human body can be considered as a mechanical system and it may be roughly approximated by a linear lumped parameter at low frequencies and low vibration levels. The lumped parameter model of the human body consists of four parts: pelvis, upper torso, viscera and head. The seat suspension is formed by a spring and dashpot. They concluded that adding the seat cushion with the mechanical characteristics (mass, stiffness, damper) and the additional seat suspension resulted in the modification of the eigenvalues of the given mechanical system (the human body) close to the natural frequencies. This means the seat with an additional mechanical system changes the human body's natural frequencies and can protect the human body inside an auto vehicle.

Newell and Mansfield (2008) investigated the influence of sitting in different working postures on the reaction time and perceived workload of subjects exposed to whole-body vibration. Twenty-one subjects were exposed to 1–20 Hz random vibration in the vertical and fore-and-aft directions. A task was completed while seated in four posture conditions: upright or twisted, with and without armrests. Posture combined with whole-body vibration exposure had a significant influence on the ability to perform the task. The combined environmental stressors significantly degraded the performance; not only did their reaction times become compromised, the participants' workload demand also increased. The most severe decrement in performance and workload was experienced while seated in a twisted posture with no armrest support. They concluded the inclusion of armrests significantly improved the participants' ability to complete the task with a lower workload demand.

Tiemessen et al. (2007) found that musculoskeletal disorders (MSD) at the workplace cost a lot. These MSD, low back pain in particular, could be caused by exposure to whole-body vibration (WBV). They suggested preventive strategies to reduce vibration exposure may contribute to a decrease in MSD. They explored evidence-based preventive strategies to reduce vibration exposure on drivers by using 15 laboratory studies, 17 field studies, 4 laboratory/field studies and 1 intervention study. The intervention study, described an intervention strategy to reduce WBV exposure in the workplace. The other studies only identified factors that have effects on vibration exposure. They categorized the factors into two: (1) design considerations and (2) skills and behaviour. Most studies focused on factors within category (1) while factors within category (2) may be promising as well, as these factors are often less expensive and easier to implement. They suggested factors from both categories should be combined in preventive strategies, as there is a lack of evidence of effective preventive strategies to reduce vibration exposure on drivers. This might lead to a decrease in the incidence of low back pain due to exposure to whole-body vibration.

1.3.5 Whole-body vibration in the mining industry

Mandal et al. (2006) measured frequency weighted root mean square (WRMS) acceleration of 18 (eighteen) heavy earth-moving machineries (HEMM) comprising dumper, dozer and shovels in three opencast mines using a human vibration monitoring system. Analysis of the data showed that 13 of the 18 pieces of equipment had vibration levels beyond safe limits for four hours operation in a day, as per ISO 2631-1 (1997) standard. The tested dumpers and dozers indicated potential for health risk from WBV. The vibration levels of shovels were within safe limits.

Eger et al. (2005) measured WBV exposure levels at the vehicle seat interface and the operator seat interface, during the operation of both small and larger load haul dumper (LHD) vehicles. Results were compared to the ISO 2631-1 (1997) health guidance caution zones to determine safe exposure durations. Preliminary test results indicated that LHD operators were exposed to whole-body vibration levels putting them at risk for injury. ISO 2631-1 (1997) exposure guidelines for the health caution zone were exceeded during the operation of several different vehicles. Some seats were also found to amplify the vibration signal resulting in a reduction in the recommended exposure duration.

Santos et al. (2008) determined the acute effects of whole-body vibration (WBV) on the sensorimotor system and potentially on the stability of the spine. Different biomechanical responses were tested before and after 60 minutes of sitting, with and without vertical WBV, on four different days. Postures adopted while sitting without WBV and the simulated WBV exposure corresponded to large mining load haul dump (LHD) vehicles as measured in the field. Twelve males performed trials of standing balance on a force plate and a sudden loading perturbation test to assess back muscle reflex response, using surface electromyography (EMG). They concluded exposure to WBV elicits significantly higher, though low-level, back muscle activity, compared to sitting without vibration. Muscle fatigue of the longissimus and iliocostalis lumborum muscles as well as some variables associated with balance was significantly affected after sitting for 60 minutes. However, WBV alone did not induce effects any more than sitting without vibration. This emphasizes that WBV per se is not necessarily responsible for such acute effects. Sitting without vibration appears to have the potential to influence back muscle fatigue and postural balance. However, this may only be attributed to the constrained trunk posture simulated during the 60 minutes of exposure.

Berezan et al. (2004) found that aggressive driving patterns, rough and poorly maintained roads and pit floors, along with the occasional bump and poorly placed load from a shovel can create intense and sometimes serious vibration levels on a heavy hauler. They proposed that an onboard vibration warning system based on the ISO 2631-1 (1997) standard could be used to help operators reduce the vibration levels experienced in a heavy hauler. The onboard system would consist of a screen that displays the instantaneous vibration in the form of three lights: green (safe zone), yellow (cautious zone), and red (danger zone), as well as an overall vibration exposure or dose for the entire shift. With the utilization of the warning system, it is anticipated that the overall vibration levels will be decreased resulting in improved operator health, a reduction of vibration-induced maintenance, and improved haul roads through reduced impact loading and repair for localized trouble areas.

1.3.6 Whole-body vibration in the South African mining industry

Van Niekerk et al. (2000) made the first comprehensive attempt to measure the vibration levels of a variety of tools and equipment in the South African mining industry to determine the effect thereof on the health of workers and operators. The scope of their research included measurements over a broad spectrum of tools, machines and vehicles used in the South African mining industry. Whole-body vibration was investigated and measured. They obtained WBV data from several mines in accordance with ISO 2631-1 (1997). The equipment with the highest vibration levels in the whole-body vibration were earth-moving equipment.

Mdlazi (2008) conducted further research to investigate the impact of whole-body vibration on the day to day activities at Anglo operations in South Africa. It was concluded that there is enough evidence that a number of vehicles and equipment at Anglo operations expose employees to high vibration levels and that vibration exposure levels have to be managed to minimize the risk of injury.

1.3.7 WBV with transient shock

For most people, vehicle vibration and shocks are low magnitude. However, for occupants in off road vehicles, such stress may be severe and frequent, leading to adverse health effects (Griffin, 1990; Nicol, 1996). Epidemiological studies suggest that exposure to shock and vibration can lead to fatigue, gastro intestinal/cardiovascular problems, and back disorders such as disk degeneration (Nicol, 1996). For vibration without transient shocks ISO 2631-1 (1997) is sufficient for evaluating the exposure levels. However, for high amplitude shocks experienced in off road vehicles a separate approach needs to be taken.

Nicol worked on modeling of the dynamic response of the human spine to mechanical shock and vibration, which involved the development of an artificial neural network (ANN) and two linear different models. This was presented as a proposed annex to the International Organization of Standardization for inclusion in the ISO 2631 (Morrison et al., 1998). ANNs are universal approximators capable of modeling any continuous function if trained with a sufficiently representative set of measured input-output data. Nicol (1996) used such an ANN to predict the z-axis (vertical) acceleration at the fourth lumbar vertebra based on measured z-axis seat acceleration.

Morrison et al. (1998) evaluated exposures to repeated mechanical shocks in tactical ground vehicles (TGV) using the health hazard assessment (HHA) method they developed in phase 5 of a project titled “Development of a standard for health hazard assessment (HHA) of mechanical shock and repeated impact in army vehicles”. Prior to this, in phase 1, a comprehensive review of the literature including field measurements of vehicle vibration, epidemiological data and existing standards were considered. In phase 2, they analyzed acceleration data obtained from military vehicles under a variety of operational conditions, developed unique methods for motion characterization and appropriate motion simulations for the experimental phase. In phase 3, a pilot study was conducted at the Multi-axis Ride Simulator (MARS) in Fort Rucker, Alabama, to develop suitable measures of human response to shock. In phase 4, measurement of human response to individual shocks of different duration and amplitude, and to daily exposures to repeated mechanical shocks were conducted at MARS in Fort Rucker, Alabama. Finally, in phase 5, a HHA method based on the information gathered in the previous phases of the project was developed. The method predicted the risk of injury to the crew of a TGV from its seat acceleration signature. The HHA identified both acute and chronic health risks resulting from either a few large amplitude shocks, or prolonged exposure to travel over rough terrain. They obtained experimental data from volunteers exposed to a range of repeated shocks exposures. The HHA consists of four components: dynamic response models predicting seat-to-spine transmission of acceleration; a biomechanical model which computes the compressive force in the lumbar spine in response to acceleration; a dose model for exposure to repeated shocks based on material fatigue characteristics and an injury risk model based on probability to failure. A software version of the HHA was developed in MATLAB.

Lewis and Griffin (1998) performed evaluations on the seat accelerations measured in nine different transport environments (bus, car, mobile crane, fork-lift truck, tank, ambulance, power boat, inflatable boat, mountain bike). These evaluations were carried out in conditions that might be considered severe using three standards to assess the vibration and shock transmitted by a vehicle seat with respect to possible effects on human health. The three standards used were ISO 2631/1 (1985), BS 6841 (1987) and ISO 2631-1 (1997). For each environment, limiting daily exposure durations were estimated by comparing the frequency weighted root mean square (RMS) accelerations and the vibration dose values (VDV), calculated according to each standard with the relevant exposure limits, action level and health guidance caution zones. They obtained different estimates of the limiting daily exposure duration obtained using the methods described in the three standards. Differences were observed due to variations in the shapes of the frequency weightings, the phase responses of the frequency weighting filters, the method of combining multi-axis vibration, the averaging method, and the assessment method. With the evaluated motions, differences in the shapes of the weighting filters resulted in up to about 31% difference in RMS acceleration between the ISO 2631/1 (1985) and the ISO 2631-1 (1997) standard and up to about 14% difference between BS 6841 (1987) and the ISO 2631-1 (1997). There were correspondingly greater differences in the estimates of safe daily exposure durations. With three of the more severe motions there was a difference of more then 250% between estimated safe daily exposure durations based on WRMS acceleration and those based on fourth power vibration dose values. The vibration dose values provided the more cautious assessments of the limiting daily exposure duration.

Khorshid et al. (2007) used speed control humps to introduce shocks and high vibration levels when a car passes over them if its speed is higher than the allowable limit. They based their assessment on two standard methods of measuring whole-body vibration: the British standard BS 6841 (1987) and the new ISO/DIS standard 2631-5. These methods were used to assess the effects of vehicle type, passenger location in the vehicle, vehicle speed, and speed control hump geometry. It was found that circular speed control humps currently installed on many public roads should be modified in order to eliminate hazards. They found the magnitude of shock parameters that might harm the health of vehicle occupants depended on the vehicle speed, hump geometry, vehicle type, position of occupants in the vehicles, and evaluation method. The whole-body vibration of the driver’s seat was affected greatly by hump geometry, especially the hump height. As the height increases, the health risk increases. The rear-seated passenger is also at high health risk, compared to the front-seated driver.

Kumar (2004) investigated if the vibration in x-, y- and z- axes of the seat pans of the heavy haul trucks used in overburden mining, and the vibration experienced by the drivers at the third lumbar and seventh cervical vertebral levels in operating these trucks, exceeded the ISO standards, and thereby posing a threat to safety. They found that heavy haul trucks (240 and 320 ton capacity) frequently generated vibrations in excess of ISO standards in overburden mining operations, representing a health hazard.

Ahn and Griffin (2008) studied the discomfort of seated subjects exposed to a wide range of vertical mechanical shocks. Shocks were produced from responses of single degree-of-freedom models with 16 fundamental frequencies (0.5–16 Hz) and four damping ratios (0.05, 0.1, 0.2 and 0.4) to half-sine force inputs. Shocks with a damping ratio of 0.4 were presented with both polarities. Each type of shock was presented at five unweighted vibration dose values (0.35–2.89 $m/s^{1.75}$). The magnitude estimates of 15 subjects to all 400 shocks showed that the rate of growth in discomfort (the exponent in Stevens' power law) decreased with increasing shock frequency from 0.5 to 4 Hz. Equivalent comfort contours showed greatest sensitivity from 4 to 12.5 Hz. At lower magnitudes, variations in discomfort with frequency were similar to weighting, W_b in British Standard 6841. At higher magnitudes, low frequencies were judged relatively more uncomfortable than predicted by this weighting. There were small but statistically significant differences in discomfort associated with variations in damping ratios and shock direction. They concluded that the frequency dependence of discomfort produced by vertical shocks depends on shock magnitude, but for shocks of low and moderate discomfort, the current evaluation methods are reasonable.

Alem et al. (2004) presented results of health risk prediction by the new multiple shocks standard (ISO 2631-5 (2004)) compared to predictions by the current WBV standard ISO 2631-1 (1997). The comparison focused on two current indices - the weighted root mean square (WRMS) and the vibration dose value (VDV) that was designed to emphasize the shocks embedded in WBV as well as the equivalent daily stress dose (S_{ed}) that was introduced in the new standard. They showed that the new standard is more sensitive to cross-country rough terrain signatures than WBV methods, but produces similar predictions for ride signatures obtained over paved or secondary roads. The health risk prediction based on S_{ed} was more stringent because of the high shocks or impacts encountered on the cross-country rough terrain.

Chen et al. (2009) carried out a study on riders of twelve motorcycles, comprising 6 full-scale motorbikes and 6 motor-scooters, and 5 sedan vehicles, performed test runs on a 20.6 km paved road. Their experimental data suggest that health risk predicted based on the daily dose of equivalent static compression stress of ISO 2631-5 (2004) is more stringent that based on the vibration dose value of ISO 2631-1 (1997). The health risk prediction based on S_{ed} was higher because of the high shocks or impacts encountered on the roads.

Johanning et al. (2006) illustrated typical work stations (cabs and seats) in US/Canadian type locomotives and assessed shock related exposure risk by calculations of the new proposed shock risk indicators according to the new ISO 2631-5 (2004). Field measurements were obtained during normal operations following generally accepted guidelines (ISO 2631-1 (1997)) on 50 locomotive operators. A sub-sample of 20 locomotives was selected for the calculation of proposed shock indicators (ISO 2631-5 (2004)). Different shock indicator values were computed based on both ISO standards. The health risk based on the new ISO 2631-5 (2004) method for evaluation of vibration containing multiple shocks as suggested in their calculations was lower than the exposure risk based on the ISO 2631-1 (1997) standard. North American railroad operators are exposed to vibration and shock (Johanning et al., 2002). They reported that 22 US railroad locomotives had low WRMS vibration levels. The highest WRMS value was 0.43 m/s^2 and a mean WRMS value of 0.32 m/s^2 which is below the EAV based on ISO 2631-1 (1997). However, they had crest factors above nine which indicted the presence of shocks. This was because the impacts were high relative to the low values of WRMS obtained from the data since crest factor is a ratio of the highest impact magnitude to the WRMS. Since the impacts or shocks were not high enough this led to low values of S_{ed} based on ISO 2631-5 (2004) which led to the lower risk predictions.

Cooperrider and Gordon (2008) measured shock and impacts on North American locomotives and evaluated the data through the vibration dose value (VDV) and spinal stress methods given in international standard ISO 2631-5 (2004). More than 90 h of measurement data are used in this analysis. This analysis found that shock and impact present a low probability of adverse health effects. They concluded the health guidance provided in ISO 2631-1 (1997) for the VDV is more stringent than the health guidance for the spinal stress in the ISO 2631-5 (2004).

Eger et al. (2008) compared health risks predicted by ISO 2631-1 (1997) and 2631-5 using the operation of load haul dump (LHD) vehicles. Whole-body vibration (WBV) exposure was measured according to procedures established in ISO 2631-1 (1997). A tri-axial seat pad accelerometer was used to measure vibration exposure at the operator/seat interface. According to ISO 2631-1 (1997) criteria, calculated 8-h equivalent vibration dose values placed three of the seven LHD operators above the health guidance caution zone (HGCZ) boundaries and four LHD operators within the HGCZ. However, health risks predicted by the ISO 2631-5 (2004) criteria were always lower than the risks predicted by ISO 2631-1 (1997) criteria. They suggested more dialogue is required to identify the appropriate application of ISO 2631-1 (1997) and 2631-5 given the different health risks predicted for a data set with high shock content. As earlier explained, the shock magnitude here was low in spite of the high crest factors obtained. This was because the impacts were high relative to the low values of WRMS obtained from the data since crest factor is a ratio of the highest impact magnitude to the WRMS. Hence, low magnitude impacts or shocks led to the prediction of the presence of shocks based on ISO 2631-1 (1997). However, because the shocks were of low magnitude this led to low values of S_{ed} based on ISO 2631-5 (2004) which also led to the lower risk predictions.

Notini et al. (2006) presented a quantitative assessment of WBV components below 1 Hz in WBV data acquired from a sample of earth moving machines. Assessment of the components occurs in terms of their contribution to ISO 2631-1 (1997) metrics and ISO 2631-5 (2004) determined risk of an adverse health effect. They concluded that components below 1 Hz make an important contribution to frequency weighted RMS and VDV values in the x- and y-axes, but a marginal one to the ISO 2631-5 (2004) determined risk of an adverse health effect.

Marjanen (2005) states that ISO 2631-1 (1997) standard is poor in taking into account transient shocks, especially those which occur rarely, thus giving a wrong indication of the potential health problems when shocks are present. It is also important to notice that WRMS and VDV values do not correlate with each other, because they emphasize amplitudes differently. Still the transient shocks are recognized to be dangerous to a lumbar spine, even though they would occur rarely.

In this study Marjanen used ISO 2631-5 (2004) as an additional evaluation method to determine how helpful it is and what kind of implications it has. The study used whole-body vibration measurements from 26 mobile work machines that were previously analyzed only using WRMS values based on ISO 2631-1 (1997). The results showed that ISO 2631-5 (2004) is useful especially when the result values are showed jointly with ISO 2631-1 (1997) WRMS values. From WRMS value alone it is very hard to conclude what kind of characteristics the vibration has. However, looking at the WRMS of ISO 2631-1 (1997) together with the acceleration dose or static compressive stress value from ISO 2631-5 (2004) also showed the results will be easier to evaluate.

There is a need to have more accurate values (from two standards like the ISO 2631-1 (1997) and ISO 2631-5 (2004)) for evaluation of vibration exposure instead of using only one standard (ISO 2631-1 (1997)). This could be possible if other values (S_{ed} and R factor values) would be shown with WRMS or VDV value. This might be helpful especially when evaluating vibration exposure based on literature or previous measurements alone. WRMS value itself does not include any information about the frequency or shock content of the vibration. It only shows statistical energy content of the vibration. Marjanen concluded the ISO 2631-5 (2004) standard is a complicated document. It takes a great deal of studying to understand it properly. Although there is a complete MATLAB script as an example in one of the annexes, it is not a straightforward procedure to use. This might restrain wider usage of the standard in the future. There is no direct correlation between ISO 2631-5 (2004) and WRMS values. The vector sum of WRMS values gives the closest correlation, but there still is a great variability between the values. This means that both methods can underestimate the health risks of the vibration exposure, if used separately for evaluation. The methods will become more useful if the values are shown together. The S_{ed} value shows the potential health problems of transient shocks and WRMS value (or VDV) the problems associated with the average level of vibration. If one of them exceeds their own limit value, then there is a great possibility of potential health problem. Also the information about the content of the measurement is more detailed if both values are calculated and saved. There is no doubt that the concept of ISO 2631-5 (2004) can be helpful for an employer and even for a researcher. How helpful it will be, depends on how widely it will be used and how easily it will be understood. Also there might be some scepticism if this method evaluates spinal column response and health problems correctly, because of the complex procedure of evaluating vibration.

Hiemenz and Wereley (2007) carried out a study on the newest United States Marine Corps amphibious vehicle, Expeditionary Fighting Vehicle (EFV), designed to operate over harsh off-road terrain as well as in oceans and rivers. Travelling over water, the EFV is capable of much higher speeds (3x) than its predecessors, which has lead to high shock loads being transmitted to the occupants when operating in high sea states. These shock loads are particularly problematic in the forward seating positions for the driver and troop crew commander. Shock and vibration may also be transmitted to the occupants when the vehicle is travelling over land and traversing rough terrain. Magneto-rheological (MR) shock absorbers have the advantage that their damping levels can be adjusted automatically in real-time with low power control signals, and accomplish controllability without additional moving parts over conventional hydraulic dampers (therefore highly reliable). They showed that, with a real-time controller developed specifically for this application, the system can reduce the ISO 2631-5 (2004) shock dosages applied to the occupant by up to 23% in water mode and reduce the vibration transmitted to the occupant by up to 65% as compared to the current passive suspension system. The study showed that the semi-active MR seat suspension enables a unique single solution for both shock and vibration environments that will provide optimal occupant protection from both harmful shock and vibration and thus significantly lengthen the allowable exposure time for soldiers in both training and tactical missions.

Li (2007) presented a constrained multi-body dynamics method to study musculoskeletal disorders due to human vibration, modifying Kane's equations to develop governing equations of a multi-body human-body model subjected to constraints. It is observed that the resulting generalized constraint force array is proportional to the transpose of the matrix of coefficients of the constraint equations. This theoretical method is used to obtain a computational simulation of a heavy equipment operator subjected to whole-body vibration due to multiple shocks in a working environment. He determined the mechanism of shock inducing low back pain and disorder by developing a quantitative relation between vibration excitation and human response. A multi-body sitting human body model subjected to lower amplitude and high amplitude acceleration exposures containing multiple shocks was used. The simulation results were compared to published data. The dissertation presented a vibration analysis procedure to conduct time domain and frequency domain human body dynamics.

Paddan and Griffin (2002) measured, evaluated and assessed vibration in 100 different vehicles according to British Standard BS 6841 (1987) and

International Standard ISO 2631-1 (1997). The vibration was measured in 14 categories of vehicle including cars, lift trucks, tractors, lorries, vans and buses. In each vehicle, the vibration was measured along five axes: vertical vibration beneath the seat, fore-and-aft, lateral and vertical vibration on the seat pan and fore-and-aft vibration at the backrest. Assessments made using the procedure defined in ISO 2631-1 (1997) tend to underestimate any risks from exposure to whole-body vibration compared to an evaluation made using the guidelines specified in BS 6841 (1987). Consequently, ISO 2631-1 (1997) “allows” appreciably longer daily exposures to whole-body vibration than BS 6841 (1987). They also found that with increasing magnitude, the growth rate in discomfort caused by vertical shocks decreased with increases in the fundamental frequencies of the shocks.

Burström et al. (2006) noted that the Scandinavian Airlines System (SAS) cabin attendants had reported an increase in health problems associated with landing. The European Union reports cover health problems related to neck, shoulder, and lower-back injuries. Moreover, analysis of these reports shows that the problems are often associated with specific airplanes that have a longer tail behind the rear wheels and appear more often in attendants who sit in the back of planes rather then the front. Against this background, this study measures and describes the vibration during landing in specific airplanes to evaluate the health risk for the cabin attendants. Measurements were conducted on regular flights with passengers in the type of airplane, Boeing 737-800, which was related to the highest per cent of reported health problems. All measurements were performed the same day during three landings in one airplane with the same pilots and cabin attendants. The measurements were carried out simultaneously on the cabin crew seats in the back and front of the passenger cabin. For the cabin attendants, the dominant direction for the vibration load during landing is the up-and-down direction although some vibration also occurs in the horizontal directions. The exposure to vibration is higher on the rear crew seat compared to the front seat. For instance, both the vibration dose value (VDV) and the frequency-weighted acceleration in the dominant direction are more than 50% higher on the rear seat than on the front seat. The frequency-weighted acceleration and the VDV measured at the crew seats are below the exposure limits as described by the European vibration directive. The evaluation of the cabin attendants' exposure to multiple shocks during landing shows that the potential of an adverse health effect for the cabin attendants is low in the front of the airplane and increases to moderate in the rear. They concluded that there could be a risk for cabin attendants due to the exposure of multiple shocks. Therefore, efforts should be spent to minimize their risk by developing a better seat cushion and back support to lessen the effects of shocks. In addition, attendants should be informed about the most suitable posture to take during landing.

1.4 Scope of the work

Employers are required to perform "a suitable and sufficient assessment of risk", including estimation of worker daily vibration exposure level, to determine whether the EAV or ELV are likely to be exceeded during normal work on these machines. It is therefore of considerable importance that an adequate, robust database of WBV levels and daily exposure data is developed to encompass as wide a range of machines and operations in the South African mining industry where working conditions are different from other parts of the world. Such a database may then be used by South African mines to assess the exposures/risks in these mines. Previous work has been carried out on whole-body vibration in the South African mines (Van Niekerk et al. 2000; MHSC 2004; Mdlazi 2008) using the ISO 2631-1 (1997) standard methodology. However, no work has been done using the new standard methodology.

Within the scope of this investigation, whole-body vibration was recorded on basically one or two of each type of machinery in an open cast mine. These machine types included load haul dumpers, excavators, graders, dragline, drills, off road vehicles, liquid conveyors, compactors, front end loaders and dozers.

Adverse effects on the lumbar spine are the dominating health risks of long-term exposure to vibration containing multiple shocks. ISO 2361-5 is therefore basically concerned with the lumbar spine response. The purpose of this standard is to define a method of quantifying whole-body vibration containing multiple shocks in relation to human health.

Static compressive stress, S_{ed}, and R factor parameters based on ISO 2631-5 (2004) were compared with the WRMS and VDV parameters obtained using ISO 2631-1 (1997) to bring out the differences between the two standards.

1.4.1 Objectives

Even though the new ISO 2631-5 (2004) standard methodology has been used in a few studies around the world, it has never been used to evaluate whole-body vibration in the South African mining industry. Several studies (Alem et al. (2004), Johanning et al. (2006), Cooperrider and Gordon (2008), Eger et al. (2008) and Chen et al. (2009)) carried out WBV using the new standard methodology; which led to conflicting results when compared with the established ISO 2631-1 (1997) methodology. This research study therefore tries to evaluate operator whole-body vibration and shock exposure using the two standard methodologies and critically comparing them.

The research endeavours to accomplish the following objectives:

- Assessing whole-body vibration based on ISO 2631-1 (1997) standard in an open cast mine;
- Assessing whole-body vibration with shock based on ISO 2631-5 (2004) standard in an open cast mine;
- Study of the effect of increasing magnitude of shocks on computation of S_{ed} and VDV values;
- Critical evaluation of results obtained using ISO 2631-1 (1997) and ISO 2631-5 (2004) standards in an open cast mine.

2. Measurement and analysis

2.1 Overview of the open cast mine

Vibration levels were measured in an open cast mining environment. These measurements were done on a wide range of mining machines at the a large mine in the Southern hemisphere in South Africa. This mine has three open cast mining sections. The WBV measurement was done on one or two examples of each of the different types of machines on the mine for subsequent WBV analysis.

The mine is one of the largest in the southern hemisphere and has a fleet of some 2000 mining vehicles. This investigation was commissioned by the open cast mine management to determine WBV emissions and operator exposure levels upon all the different types of machinery used in the three mining sections. The selected machinery measured in this investigation is representative of the typical machines that one will find on South African open cast mines.

2.2 The open cast mining process

Open cast or surface mines generally follow the same basic steps to produce coal. The mining process begins with removal of the topsoil which is stored for later use in the reclamation process. Many small holes are drilled through the overburden (dirt and rock above the coal seam) to the coal seam. The holes are then loaded with explosives which are discharged, shattering the rock in the overburden. Giant power shovels or draglines then clear away the overburden until the coal is exposed. Excavators (smaller shovels) and track dozers are then used to scoop up the coal and load it onto trucks or LHDs, which convey the coal to the temporary site or preparation or processing plant. Figure 2.1 shows the schematic of the basic open cast coal mining process.

2.3 Whole-body vibration (WBV) measurement and analysis

2.3.1 Measured parameters and transducers

Vibration measurements were done according to the measuring procedure outlined in ISO 2631-1 (1997), which is also applicable to ISO 2631-5 (2004). Acceleration levels were measured on the operator seat of the target machine in three perpendicular directions (seat x - longitudinal, seat y - transverse, seat z – vertical, see Figure 2.2) and on the floor beneath the seat.

2.3.1.1 Dytran tri-axial seat accelerometer

Vibration on the driver's seat was measured by placing the tri-axial seat accelerometer on the seat cushion. The seat accelerometer was attached to the seat cushion using duct tape (see Figure 2.3). Calibration details are provided in Table 2.1. The accelerometers and SVAN958 calibration was given by the manufacturer as approximately 100 mV/g and 100mV/m/s^2 respectively. The latter introduced a factor of square root of 2. The overall channel calibration (see Table 2.2) was therefore computed to be approximately 140m/s^2/V. The full instrumentation list is shown in Table 2.3.

2.3.1.2 Industrial ICP accelerometer

The industrial ICP accelerometer was attached to the machine floor under the seat of the operator as shown in Figure 2.4. Calibration detail is provided in Table 2.1. Overall channel calibration detail is provided in Table 2.2.

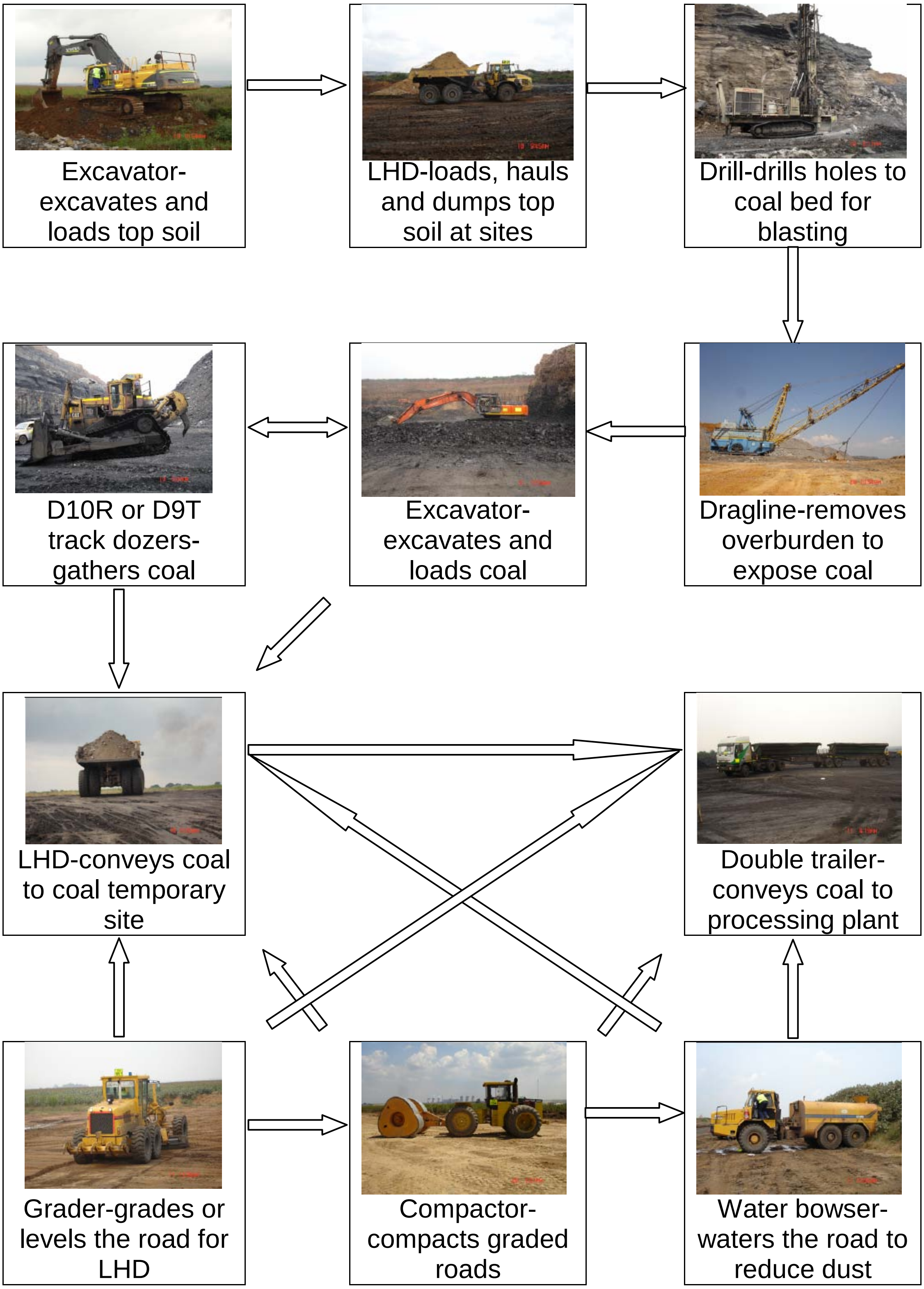
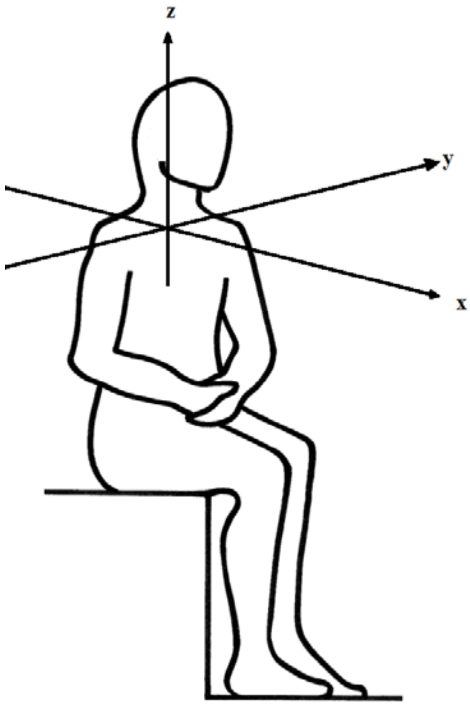


Figure 2.1: Basic open cast coal mining process



Principal basicentric axes for a seated person

Figure 2.2: Basicentric axes of the human body (ISO 2631-1 (1997))

Table 2.1 Transducer calibration

Transducer	Axis	Calibration
Dytran tri-axial seat accelerometer Model 5313A	x	100.0 mV/g
Dytran tri-axial seat accelerometer Model 5313A	y	98.9 mV/g
Dytran tri-axial seat accelerometer Model 5313A	z	97.7 mV/g
Industrial ICP accelerometer Model E327A01	z	100.0 mV/g

Table 2.2 Overall channel calibration

Transducer	Axis	Calibration
Dytran tri-axial seat accelerometer Model 5313A	x	138.7 $m/s^2/V$
Dytran tri-axial seat accelerometer Model 5313A	y	140.3 $m/s^2/V$
Dytran tri-axial seat accelerometer Model 5313A	z	142.0 $m/s^2/V$
Industrial ICP accelerometer Model E327A01	z	138.7 $m/s^2/V$

Table 2.3 Instrumentation

Instruments
Laptop Acer Extensa Model MS2205
SVAN958 Analyzer and cables Model 958
Sony Digital Camera
Calibrator
Accelerometers
Industrial ICP accelerometer Model E327A01
Dytran tri-axial seat accelerometer Model 5313A

Figure 2.3: Dytran tri-axial seat accelerometer

Figure 2.4: Floor ICP industrial accelerometer

Figure 2.5: SVAN958 HVM data acquisition system

2.3.2 Data acquisitioning and recording

Signals from the tri-axial accelerometer and the ICP industrial accelerometer were passed to a 4-channel SVAN958 Human Vibration Meter (HVM) which did the digital data recording (see Figure 2.5). A Kingston 16 GB flash storage disk was attached to the SVAN958 to enable it record data of long duration. High quality long life batteries were used to power the HVM data recorder to ensure sufficient recording times.

The sampling rate of the HVM is automatically fixed at 48 kHz. Anti-aliasing filters are embedded in the system. The HVM has ISO 2631 filters. For data acquisition purposes and accuracy, the enhanced memory of the HVM was used to record time data as well as the unweighted RMS averages of the acceleration signals. These data were downloaded to a PC for post processing and further analysis.

The time required for both fitting and removal of the transducers and the data acquisition system was about 10-20 minutes. As suggested by Mansfield and Atkinson (2003) a minimum of 10 minutes is required to record data. Therefore, to minimise disruption of the commercial operations for which the machines are used, the fitting and removal were performed during normal work breaks where possible. This led to overall data recording periods that were generally between 30 minutes and 1 hour.

2.4 Data analysis

The data time histories were recorded in Volts in waveform audio (WAV) file format. The calibration factors (Tables 2.1. and 2.2) were then applied to obtain the equivalent acceleration-time history in m/s^2 from the WAV format data obtained from the SVAN958 Human Vibration Meter (HVM). The data was subsequently downloaded to a PC and dedicated MATLAB based software was used to enable reading of large WAV files. The same data set was used for the analysis using the two standards ISO 2631-1 (1997) and ISO 2631-5 (2004).

2.4.1 Computation of ISO 2631-1 (1997) parameters

In accordance with the requirements of ISO 2631-1 (1997), the acceleration time histories recorded on the operator's seat and floor of the target machines were post-processed using dedicated MATLAB software to compute the following:

- Frequency and measurement axis-weighted acceleration RMS time histories;
- Estimated operator daily vibration exposure, presented in 8-hour energy-equivalent continuous, frequency-weighted RMS acceleration A(8) and VDV forms;
- Crest factor CF for each target machine;

- Time to reach the EAV and ELV, when specified both in A(8) and VDV forms;
- WRMS and VDV “SEAT” (seat effective amplitude transmissibility) values.

As a check on the integrity of the results obtained via MATLAB from the recorded time data, the RMS and VDV were computed and compared to the values displayed directly on the SVAN958 HVM. The VDVs for an 8-hour exposure period and the operating time to reach the exposure action and limit values (EAV and ELV), as defined in EU Directive 2002/44/EC (see Table 1.1) were also computed. The weighted acceleration histories were also plotted from the data obtained.

During the data collection period, questionnaires (see appendix J) were used to record operator and equipment details as well as other information (Vibration Injury Network, 2001). The vibration measurement times were recorded on the SVAN958. The data acquired was measured for 30 minutes to 1 hour period as earlier explained. However, this was measured in such a way as to represent the vibration levels experienced by the operator during the nominal 8-hour work period.

The required parameters were then computed and extrapolated to cover the entire duration of exposure using dedicated software developed in the MATLAB environment. The time domain data was read in MATLAB and then converted to m/s^2. The data was then weighted according to ISO 2631-1 (1997) whole-body vibration weighting filter. Subsequent to the weighting, the WRMS and VDV parameters were then computed. The software was validated by reproducing the whole-body vibration weighting curve in the ISO 2631-1 (1997) standard from artificially generated sinusoids over the range of frequencies between 1 Hz to 80 Hz.

The weighted Root Mean Square (WRMS) is the square root of the average of the squares of the weighted values. The weighted RMS acceleration is expressed in m/s^2 for translational vibration and calculated as follows:

$$a_w = \left[\frac{1}{T} \int_0^T a_w^2(t)\, dt \right]^{\frac{1}{2}} \tag{2.1}$$

where $a_w(t)$ is the weighted (see ISO 2631-1 (1997) Figure 2 for weighting curve) acceleration time history and T is the duration of the measurement.

The Crest Factor (CF) is the ratio of the maximum weighted acceleration value to the weighted RMS.

Vibration Dose Value (VDV) is defined as the fourth root of the integral of the fourth power of acceleration after it has been frequency weighted. The frequency weighted acceleration is measured in m/s^2 and the time over which the VDV is measured is in seconds yielding VDVs in m/s$^{1.75}$. The Vibration Dose Value (VDV) is computed as follows:

$$VDV = \left[\int_0^T [a_w(t)]^4\, dt \right]^{\frac{1}{4}} \tag{2.2}$$

where $a_w(t)$ is the weighted instantaneous acceleration magnitude and T is the duration of the measurement.

Seat Effective Amplitude Transmissibility (SEAT) is the ratio of the magnitudes of the vertical acceleration on the seat to the vertical acceleration at the floor.

2.4.2 Computation of ISO 2631-5 (2004) parameters

Dedicated MATLAB based software was also used to compute S_{ed} and R factors based on ISO 2631-5 (2004). These parameters were then used in predicting risk to health. The software was validated by reproducing the input seat acceleration and obtaining the lumbar x, y and z response in Annex D of the ISO 2631-5 (2004) standard.

The measurement was resampled to a sampling rate of 160 samples per second as required by the ISO 2631-5 (2004) standard methodology. The software only accepts data at a sampling frequency of 160 Hz. We are interested in frequencies between 0 to 80 Hz. Hence, to see the desirable frequency we need to sample at twice the frequency we wish to see, that is, 160 Hz.

2.4.3 Calculation of acceleration dose based on ISO 2631-5 (2004)

The acceleration dose, D_k, in the k-direction is given by equation 2.3

$$D_k = \left[\sum_i A_{ik}^6 \right]^{1/6} \tag{2.3}$$

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

A peak is defined as the maximum absolute value of the response acceleration between two consecutive zero crossings.

For assessment of health effects the average daily dose, D_{kd}, is determined using equation 2.4.

$$D_{kd} = D_k \left[\sum_i \frac{t_d}{t_m} \right]^{1/6} \tag{2.4}$$

where t_d is the duration of the daily exposure and t_m is the period over which D_k has been measured.

Equation 2.5 is used to compute average daily dose that consists of two or more periods of different magnitudes.

$$D_{kd} = \left[\sum_{j=1}^{n} D_{kj}^6 \frac{t_{dj}}{t_{mj}} \right]^{1/6} \tag{2.5}$$

where t_{dj} is the duration of the daily exposure to condition j and t_m is the period over which D_{kj} has been measured.

The procedure for the computation of acceleration dose is summarised in Figure 2.6.

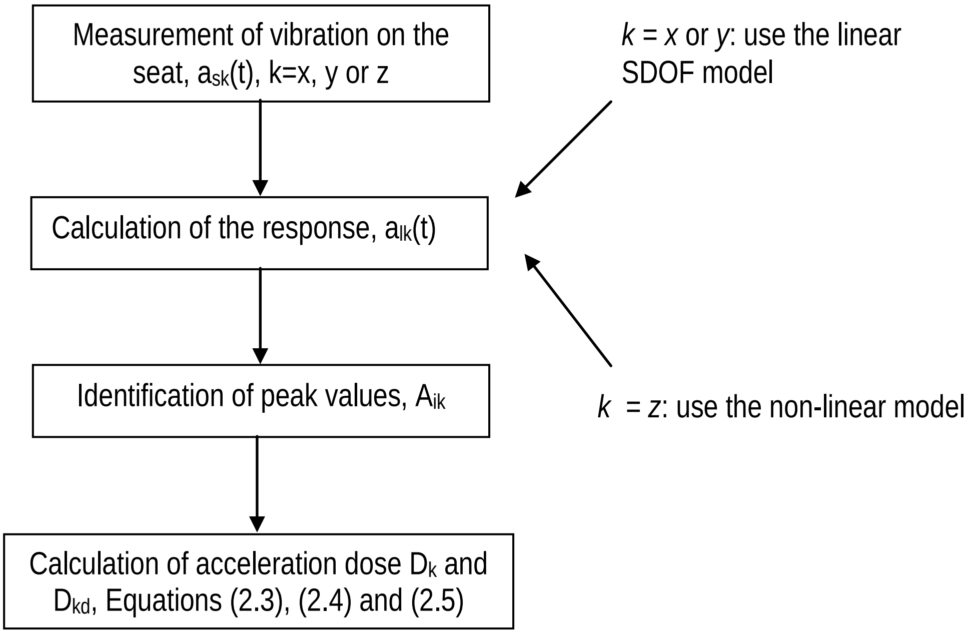


Figure 2.6: Flowchart for acceleration dose calculation (ISO 2631-5 (2004))

2.4.4 Assessment of health effects based on ISO 2631-5 (2004)

The equivalent static compressive stress, S_e, in MPa is given as shown in equation 2.9.

$$S_e = \left[\sum_{k=x,y,z} (m_k D_k)^6 \right]^{1/6} \tag{2.9}$$

The daily equivalent static compressive dose, S_{ed}, is given by equation 2.10.

$$S_{ed} = \left[\sum_{k=x,y,z} (m_k D_{kd})^6 \right]^{1/6} \tag{2.10}$$

The R factor is defined for use in adverse health effects related to the human response acceleration dose and is computed using equation 2.11.

$$R = \left[\sum_{i=1}^{n} \left(\frac{S_{ed} . N^{1/6}}{S_{ui} - c} \right)^6 \right]^{1/6} \tag{2.11}$$

where N is the number of exposure days per year; i is the year counter; n is the number of years of exposure; c is a constant representing the static stress due to gravitational force; S_{ui} is the ultimate strength of the lumbar spine for a person of age (b+i) years; b is the age at which exposure starts.

$$S_{ui} = 6.75 - 0.066(b + i) \tag{2.12}$$

2.5 Summary

The procedures and methodologies in the computation of parameters in the ISO 2631-1 (1997) and ISO 2631-5 (2004) standards were outlined together with their differences. The parameters were also properly defined.

3. Results

3.1 Target machines and applications

During the course of this study the target list was divided based on task and basically one or two of each machine type was measured on the open cast mine. The machines encompassed by the study are listed in Tables 3.1 to 3.9, together with brief descriptions of what they do.

Table 3.1 Load haul dumpers (LHDs)

Machine Type/ID	Machine Activity/Application
Volvo A35 LHD (A1)	Loading, transport and offloading
Mercedes Actros V8 LHD (A2)	Loading, conveying and offloading of topsoil and rocks
Caterpillar 785B (A3)	Loading, conveying and offloading of topsoil
Tata Novus Truck 3434 (A4)	Loading, conveying and offloading of topsoil
Bell Rear Dumper B25D (A5)	Loading, conveying, offloading of top soil and rocks
Bell Rear Dumper B40D (A6)	Loading, conveying, offloading of top soil and rocks
Bell Rear Dumper B50D (A7)	Loading, conveying, offloading of coal
Iveco Truck/Trailer(Double) (A8)	Loading, conveying, offloading of coal
MAN TGA 33.400 Trailer (A9)	Loading, conveying, offloading of coal
Dragline (A10)	Excavating of top soil and rocks to expose coal

Table 3.2 Excavators

Machine Type/ID	Machine Activity/Application
Hitachi Excavator Zaxis 670 LCR (B1)	Excavating and loading of top soil into LHDs
Volvo Excavator EC700Blc (B2)	Digging and loading of top soil into LHDs
CAT Excavator 320D (B3)	Pushing of coal into the tip
Hitachi Excavator Zaxis 370 LCR (B4)	Excavating and loading of top soil into LHDs
Hitachi Excavator Zaxis 500 LCR (B5)	Excavating and loading of top soil into LHDs
Komatsu Excavator PC1250SP (B6)	Excavating and loading of top soil and rocks into trucks
Hitachi Excavator Zaxis 670 LCR (B7)	Excavating and loading of top soil into LHDs

Table 3.3 Front End Loaders

Machine Type/ID	Machine Activity/Application
CAT FEL 992G (C1)	Carrying and tipping of coal into the tip
Kawasaki Safika FEL 852IV (C2)	Ripping and loading of coal into trucks
Kawasaki FEL (C3)	Ripping and loading of coal into trucks

Table 3.4 Dozers

Machine Type/ID	Machine Activity/Application
CAT Track Dozer D9T (D1)	Making a catch berm
CAT Caterpillar D10R (D2)	Ripping and pushing of coal into a hip
Bell TLB 315SG (D3)	Ripping of top soil.
Shantui (D4)	Ripping and loading of top soil and clearing of roads

Table 3.5 Drills

Machine Type/ID	Machine Activity/Application
Pit Viper (E1)	Drilling of holes to the coal bed
DMM 2 Drilling Machine (E2)	Drilling of holes to the coal bed

Table 3.6 Graders

Machine Type/ID	Machine Activity/Application
CAT Grader 16G (F1)	Grading of the road to make it level
Sany Grader (F2)	Grading of the road to make it level
Komatsu Grader 9D825A (F3)	Grading of the road to make it level

Table 3.7 Liquid Conveyers

Machine Type/ID	Machine Activity/Application
Bell Water Bowser B20C (G1)	Watering the road to reduce the amount of dust raised
Powerstar 2628 Refueler (G2)	Refueling of mine vehicles
CAT 740 Diesel Bowser (G3)	Refueling of mine vehicles

Table 3.8 4x4

Machine Type/ID	Machine Activity/Application
Toyota Fortuner (H1)	Driving around for inspection on dusty or gravel road

Table 3.9 Compactor

Machine Type/ID	Machine Activity/Application
Landpac Compactor (I1)	Compacting of soil

3.2 Time domain accelerations

Time domain accelerations for selected machinery are given below. The weighted acceleration histories of Volvo A35D LHD, Caterpillar 785B and Hitachi Excavator Zaxis 670 LCR are shown in Figures 3.1, 3.3 and 3.5 respectively. The remaining weighted acceleration histories of all the other machinery are shown in the appendices. These time histories were used in the computation of the WRMS and VDV dose values based on ISO 2631-1 (1997).

The unweighted acceleration histories of Volvo A35D LHD, Caterpillar 785B and Hitachi Excavator Zaxis 670 LCR are shown in Figures 3.2, 3.4 and 3.6 respectively. It can be seen that shocks are present in these time acceleration histories. For the Volvo A35D LHD and Caterpillar 785B, the shocks range roughly between -10 m/s^2 and 10 m/s^2 apiece. For Hitachi Excavator Zaxis 670 LCR the shocks range roughly between -15 m/s^2 and 15 m/s^2. ISO 2631-5 (2004) specifies that the dataset acceleration in the z direction should be in the range of -20 m/s^2 to 40 m/s^2 and 0.5 Hz to 40 Hz. This is because the z axis is modeled as a non linear recurrent artificial neural network (RNN) model and the RNN algorithm was trained for only data in the above mentioned range (Nicol, 1996; Morrison et al., 1998; ISO 2631-5 (2004). The standard does not specify any limit for the x and y direction. This is because the x and y axes are modeled as linear SDOF models.

Table 3.10 shows the dominant frequencies of all the machinery. It can be seen that all the frequencies along the z-axis are less than 40 Hz. These frequencies were obtained by conducting an FFT analysis on the weighted acceleration responses. Also, looking at Appendices A to I it can be seen that the vibration acceleration amplitudes of all shocks fall within the range for the applicability of the ISO 2631-5 (2004) standard. The unweighted acceleration data set were used in the computation of the S_{ed} and R factor parameters based on ISO 2631-5 (2004).

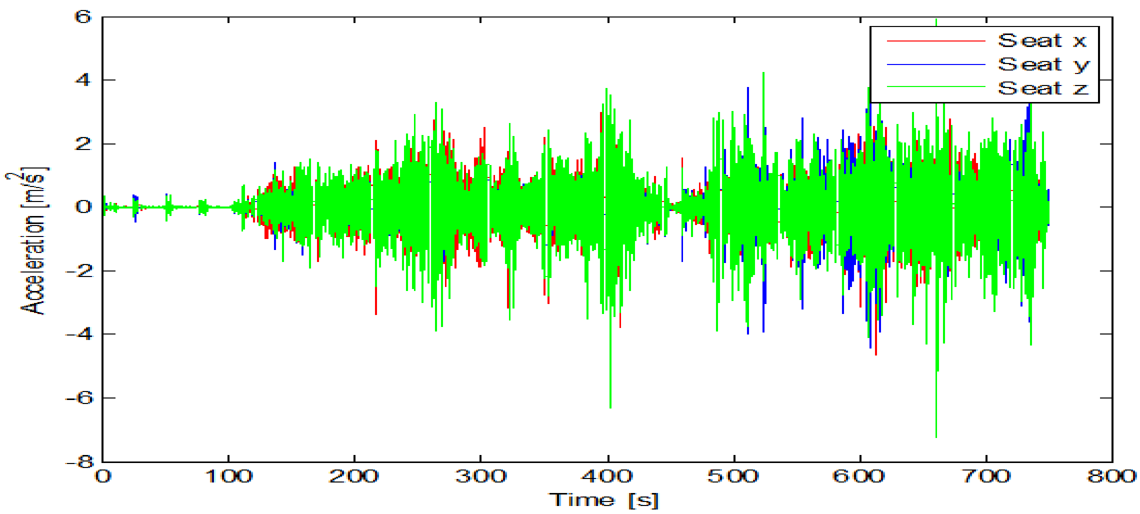


Figure 3.1: Weighted acceleration for x, y & z axes according to ISO 2631-1 (1997) for Volvo A35D LHD

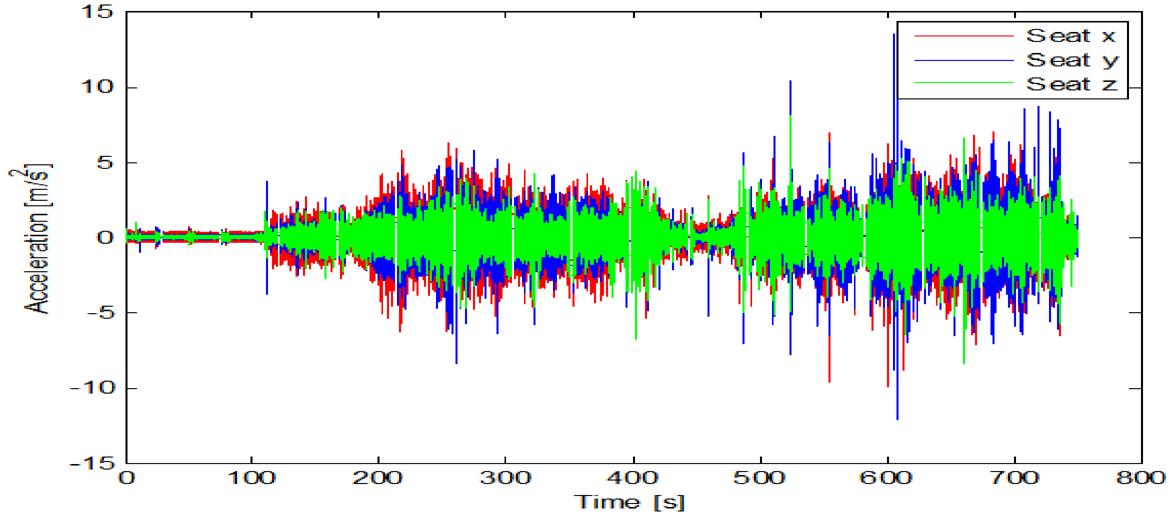


Figure 3.2: Unweighted acceleration for x, y & z-axes for Volvo A35D LHD

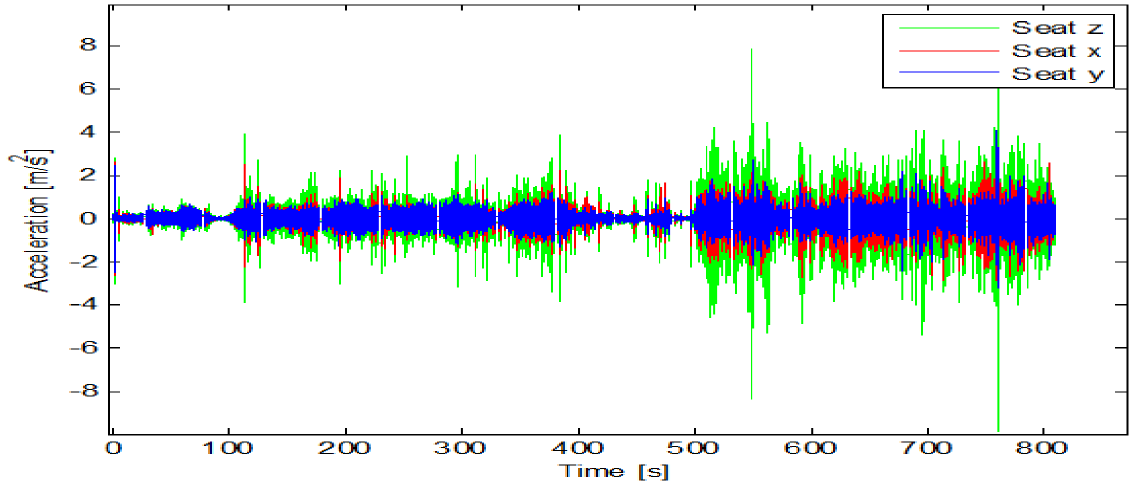


Figure 3.3: Weighted acceleration for x, y & z axes according to ISO 2631-1 (1997) Caterpillar 785B

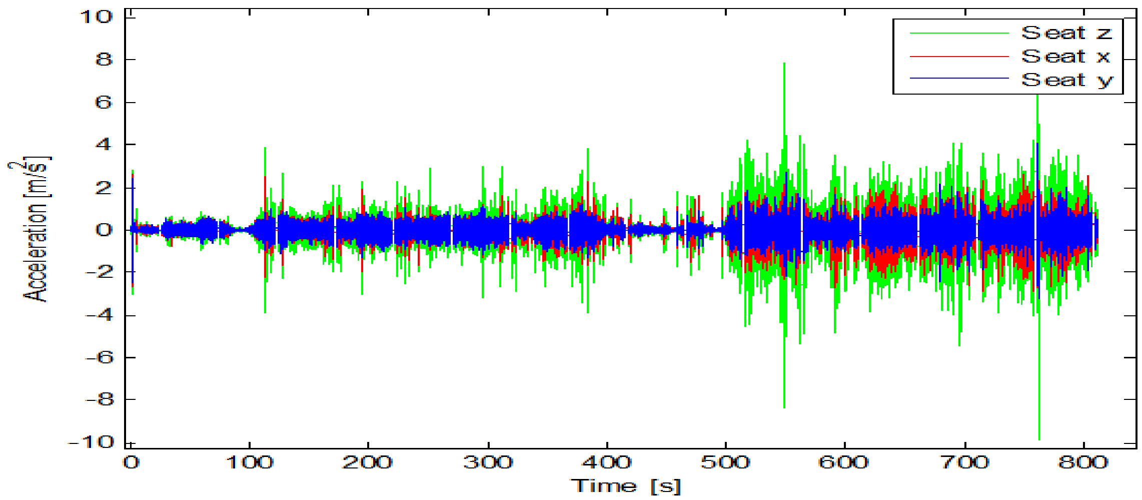


Figure 3.4: Unweighted acceleration for x, y & z-axes for Caterpillar 785B

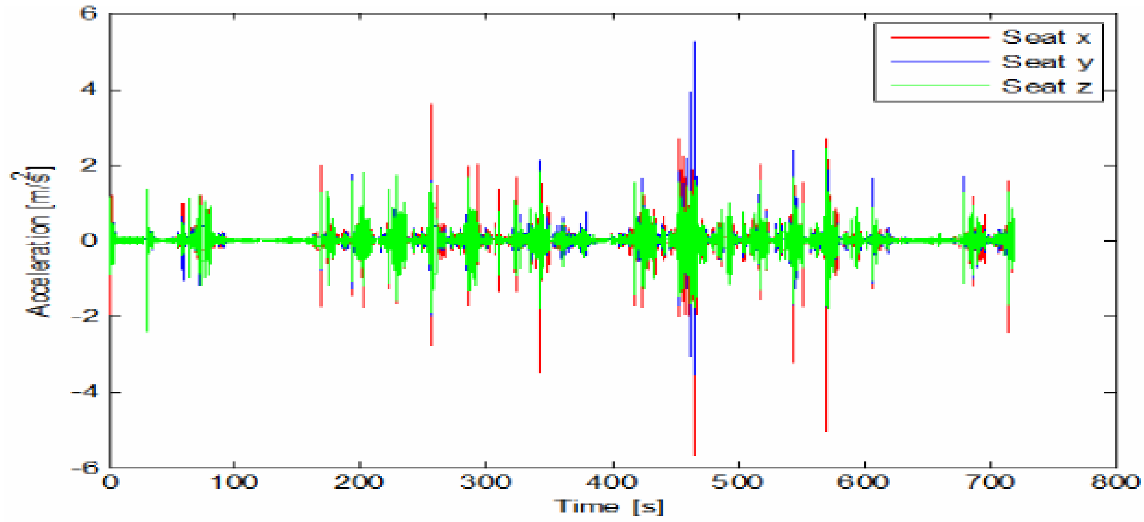


Figure 3.5: Weighted acceleration for x, y & z according to Hitachi Excavator Zaxis 670 LCR

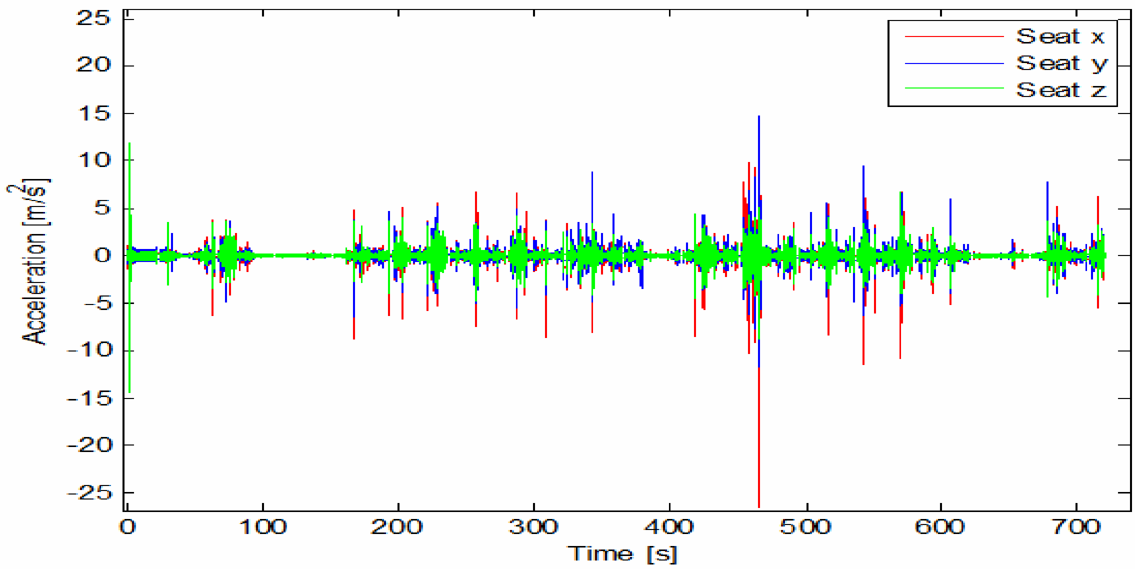


Figure 3.6: Unweighted acceleration for x, y & z-axes for Hitachi Excavator Zaxis 670 LCR

Table 3.10 Dominant frequencies of machines

Machines/ID	Freq. (Hz)			Machines/ID	Freq. (Hz)		
	x	y	z		x	y	z
Volvo A35 LHD (A1)	35	3	2	Hitachi Excavator Zaxis 670 LCR (B1)	45	45	25
Mercedes Actros V8 LHD (A2)	40	15	4	Volvo Excavator EC700Blc (B2)	40	40	20
Caterpillar 785B (A3)	40	35	20	CAT Excavator 320D (B3)	50	50	20
Tata Novus Truck 3434 (A4)	10	30	10	Hitachi Excavator Zaxis 370 LCR (B4)	15	2	5
Bell Rear Dumper B25D (A5)	30	30	2	Hitachi Excavator Zaxis 500 LCR (B5)	5	8	18
Bell Rear Dumper B40D (A6)	34	34	2	Komatsu Excavator PC1250SP (B6)	10	7	10
Bell Rear Dumper B50D (A7)	11	30	2	Hitachi Excavator Zaxis 670 LCR (B7)	45	20	30
Iveco Truck/Trailer (Double) (A8)	2	2	3	CAT FEL 992G (C1)	2	2	3
MAN TGA 33.400 Trailer (A9)	28	28	10	Kawasaki Safika FEL 852IV (C2)	7	30	7
Dragline (A10)	32	5	5	Kawasaki FEL (C3)	30	26	24
CAT Track Dozer D9T (D1)	2	2	2	Pit Viper (E1)	30	30	15
CAT Caterpillar D10R (D2)	15	10	4	DMM 2 Drilling Machine (E2)	50	50	25
Bell TLB 315SG (D3)	5	9	17	CAT Grader 16G (F1)	5	2	5
Shantui (D4)	2	2	2	Sany Grader (F2)	5	2	5
Bell Water Bowser B20C (G1)	35	35	35	Komatsu Grader 9D825A (F3)	44	26	2
Powerstar 2628 Refueler (G2)	20	20	20	Toyota Fortuner (H1)	10	2	2
CAT 740 Diesel Bowser (G3)	50	30	2	Landpac Compactor (I1)	5	2	5

3.3 Summary of machine whole-body vibration levels based on ISO 2631-1 (1997) using WRMS parameter

The recorded data comprised WBV levels measured with respect to time in three orthogonal axes (x, y and z) on the operator's seat and along the z axis on the floor beneath the seat. The weighted root mean square acceleration (WRMS), crest factor (CF), time to reach exposure action value (EAV) and exposure limit value (ELV), as well as the seat effective amplitude transmissibility (SEAT) values were calculated and tabulated separately for each machine / activity combination identified in Tables 3.1 to 3.9. A summary overview of the computed results is shown in Tables 3.11 to 3.19 for WRMS acceleration.

ISO 2631-1 (1997) states that for CF higher than 9; an additional parameter vibration dose value (VDV) needs to be calculated because the shock content of the vibration is high. Going through Tables 3.11 to 3.19 it can be seen that most of the CFs are higher than 9. Hence the additional parameter was computed and is tabulated in Tables 3.20 to 3.28.

Table 3.11 LHDs: WRMS, CF and A(8) acceleration summary of WBV seat data

Machine/ID	WRMS (m/s²) a_w			Crest Factor (CF)			EAV (A(8))	ELV (A(8))	SEAT value
	x	y	z	x	y	z			
Volvo A35 LHD (A1)	0.61	0.49	0.54	6.30	11.14	11.52	5.00	16.00	1.10
Mercedes Actros V8 LHD (A2)	0.44	0.55	0.65	8.18	8.64	8.19	5.00	16.00	0.94
Caterpillar 785B (A3)	0.50	0.54	0.70	11.08	9.59	9.15	4.00	14.00	1.89
Tata Novus Truck 3434 (A4)	0.33	0.43	0.59	13.21	12.40	11.41	5.00	16.00	1.64
Bell Rear Dumper B25D (A5)	0.41	0.43	0.38	11.10	9.48	11.40	12.00	>24.00	1.12
Bell Rear Dumper B40D (A6)	0.47	0.81	0.41	12.86	6.42	7.72	2.00	6.00	1.41
Bell Rear Dumper B50D (A7)	0.32	0.44	0.35	7.53	9.32	10.44	12.00	>24.00	1.59
Iveco Truck/Trailer (Double) (A8)	0.54	0.53	0.60	14.88	10.88	8.64	5.00	16.00	0.95
MAN TGA 33.400 Trailer (A9)	0.28	0.43	0.35	15.32	12.19	36.90	12.00	>24.00	0.88
Dragline (A10)	0.10	0.18	0.12	7.80	9.38	5.95	>24.00	>24.00	0.75

Table 3.12 Excavators: WRMS, CF and A(8) acceleration summary of WBV seat data

Machine/ID	WRMS (m/s^2) a_w			Crest Factor (CF)			EAV (A(8))	ELV (A(8))	SEAT value
	x	y	z	x	y	z			
Hitachi Excavator Zaxis 670 LCR (B1)	0.36	0.34	0.41	54.28	55.22	54.78	12.00	>24.00	1.46
Volvo Excavator EC700Blc (B2)	0.39	0.36	0.34	36.46	34.20	43.50	12.00	>24.00	1.55
CAT Excavator 320D (B3)	0.35	0.21	0.24	12.28	14.22	10.38	12.00	>24.00	0.71
Hitachi Excavator Zaxis 370 LCR (B4)	0.36	0.29	0.37	19.83	15.08	14.37	12.00	>24.00	1.32
Hitachi Excavator Zaxis 500 LCR (B5)	0.33	0.38	0.39	27.53	19.14	13.85	12.00	>24.00	0.80
Komatsu Excavator PC1250SP (B6)	0.45	0.47	0.51	19.36	15.84	12.53	8.00	24.00	0.86
Hitachi Excavator Zaxis 670 LCR (B7)	0.21	0.18	0.21	15.78	16.71	10.29	>24.00	>24.00	1.00

Table 3.13 Front End Loaders: WRMS, CF and A(8) acceleration summary of WBV seat data

Machine/ID	WRMS (m/s^2) a_w			Crest Factor (CF)			EAV (A(8))	ELV (A(8))	SEAT value
	x	y	z	x	y	z			
CAT FEL 992G (C1)	0.19	0.29	0.21	15.42	11.79	8.15	20.00	>24.00	1.05
Kawasaki Safika FEL 852IV (C2)	0.38	0.36	0.48	12.29	13.81	9.86	8.00	24.00	1.17
Kawasaki FEL (C3)	0.34	0.33	0.42	16.03	13.05	18.28	12.00	>24.00	1.35

Table 3.14 Dozers: WRMS, CF and A(8) acceleration summary of WBV seat data

Machine/ID	WRMS (m/s²) a_w			Crest Factor (CF)			EAV (A(8))	ELV (A(8))	SEAT value
	x	y	z	x	y	z			
CAT Track Dozer D9T (D1)	0.63	0.98	0.50	9.33	9.27	6.69	2.00	6.00	0.65
CAT Caterpillar D10R (D2)	0.76	0.77	0.76	17.40	11.81	8.39	4.50	15.00	0.55
Bell TLB 315SG (D3)	0.35	0.42	0.52	7.89	6.62	7.91	8.00	24.00	1.16
Shantui (D4)	0.63	0.98	0.50	9.33	9.27	6.69	2.00	6.00	0.65

Table 3.15 Drills: WRMS, CF and A(8) acceleration summary of WBV seat data

Machine/ID	WRMS (m/s²) a_w			Crest Factor (CF)			EAV (A(8))	ELV (A(8))	SEAT value
	x	y	z	x	y	z			
Pit Viper (E1)	0.38	0.36	0.21	8.33	23.28	19.79	12.00	>24.00	1.40
DMM 2 Drilling Machine (E2)	0.23	0.23	0.28	18.45	20.48	17.75	20.00	>24.00	1.87

Table 3.16 Graders: WRMS, CF and A(8) acceleration summary of WBV seat data

Machine/ID	WRMS (m/s²) a_w			Crest Factor (CF)			EAV (A(8))	ELV (A(8))	SEAT value
	x	y	z	x	y	z			
CAT Grader 16G (F1)	0.42	0.53	0.68	7.13	5.87	9.84	5.00	16.00	1.45
Sany Grader (F2)	0.19	0.26	0.26	8.36	6.00	6.13	24.00	>24.00	0.96
Komatsu Grader 9D825A (F3)	0.33	0.39	0.33	12.51	23.78	15.09	12.00	>24.00	1.10

Table 3.17 Liquid Conveyers: WRMS, CF and A(8) acceleration summary of WBV seat data

Machine/ID	WRMS (m/s²) a_w			Crest Factor (CF)			EAV (A(8))	ELV (A(8))	SEAT value
	x	y	z	x	y	z			
Bell Water Bowser B20C (G1)	0.54	0.85	0.55	9.66	15.57	9.83	2.50	8.00	0.93
Powerstar 2628 Refueler (G2)	0.78	0.68	0.89	17.68	17.69	17.42	2.50	8.00	2.53
CAT 740 Diesel Bowser (G3)	0.61	1.12	0.65	8.87	8.52	17.50	2.00	5.00	1.33

Table 3.18 4x4: WRMS, CF and A(8) acceleration summary of WBV seat data

Machine/ID	WRMS (m/s^2) a_w			Crest Factor (CF)			EAV (A(8))	ELV (A(8))	SEAT value
	x	y	z	x	y	z			
Toyota Fortuner (I1)	0.56	0.73	0.55	8.04	10.47	10.18	3.00	7.00	0.63

Table 3.19 Compactor: WRMS, CF and A(8) acceleration summary of WBV seat data

Machine/ID	WRMS (m/s^2) a_w			Crest Factor (CF)			EAV (A(8))	ELV (A(8))	SEAT value
	x	y	z	x	y	z			
Landpac Compactor (J1)	0.87	0.82	0.91	7.41	6.79	5.32	2.00	6.00	1.36

3.4 Summary of machine whole-body vibration levels based on ISO 2631-1 (1997) using VDV parameter

A summary overview of the VDV is shown below in Tables 3.20 to 3.28 for various set of machinery.

Table 3.20 LHDs: VDV summary of WBV seat data

Machine/ID	Estimated 8-hour VDV($m/s^{1.75}$)				EAV (VDV)	ELV (VDV)	SEAT value
	x	y	z	Main			
Volvo A35 LHD (A1)	11.21	9.02	9.84	x	3.5	>24.00	1.11
Mercedes Actros V8 LHD (A2)	8.05	9.97	11.80	z	2.83	>24.00	0.93
Caterpillar 785B (A3)	9.20	9.77	12.77	z	2.06	>24.00	1.89
Tata Novus Truck 3434 (A4)	6.09	7.78	10.81	z	4.02	>24.00	1.66
Bell Rear Dumper B25D (A5)	7.43	7.78	6.87	y	14.98	>24.00	1.11
Bell Rear Dumper B40D (A6)	8.61	14.80	7.46	y	1.14	>24.00	1.41
Bell Rear Dumper B50D (A7)	5.76	8.05	6.36	y	13.04	>24.00	1.56
Iveco Truck/Trailer(Double) (A8)	9.92	9.74	10.91	z	3.87	>24.00	0.94
MAN TGA 33.400 Trailer (A9)	5.06	7.87	6.39	y	14.30	>24.00	0.89
Dragline (A10)	1.88	3.35	2.23	y	>24.00	>24.00	0.74

Table 3.21 Excavators: VDV summary of WBV seat data

Machine/ID	Estimated 8-hour VDV($m/s^{1.75}$)				EAV (VDV)	ELV (VDV)	SEAT value
	x	y	z	Main			
Hitachi Excavator Zaxis 670 LCR (B1)	6.59	6.18	7.52	z	17.19	>24.00	1.48
Volvo Excavator EC700Blc (B2)	7.13	6.57	6.26	x	21.19	>24.00	1.53
CAT Excavator 320D (B3)	6.36	3.85	4.39	x	>24.00	>24.00	0.71
Hitachi Excavator Zaxis 370 LCR (B4)	6.65	5.25	6.81	z	>24.00	>24.00	1.32
Hitachi Excavator Zaxis 500 LCR (B5)	6.07	6.92	7.15	z	21.02	>24.00	0.79
Komatsu Excavator PC1250SP (B6)	8.14	8.55	9.25	z	7.49	>24.00	0.86
Hitachi Excavator Zaxis 670 LCR (B7)	3.88	3.24	3.84	x	>24.00	>24.00	1.00

Table 3.22 Front End Loaders: VDV summary of WBV seat data

Machine/ID	Estimated 8-hour VDV($m/s^{1.75}$)				EAV (VDV)	ELV (VDV)	SEAT value
	x	y	z	Main			
CAT FEL 992G (C1)	3.42	5.25	3.89	y	>24.00	>24.00	1.06
Kawasaki Safika FEL 852IV (C2)	7.00	6.63	8.82	z	9.05	>24.00	1.19
Kawasaki FEL (C3)	6.15	6.04	7.65	z	16.01	>24.00	1.34

Table 3.23 Dozers: VDV summary of WBV seat data

Machine/ID	Estimated 8-hour VDV($m/s^{1.75}$)				EAV (VDV)	ELV (VDV)	SEAT value
	x	y	z	Main			
CAT Track Dozer D9T (D1)	11.41	17.83	9.11	y	0.54	>24.00	0.65
CAT Caterpillar D10R (D2)	13.86	14.07	13.94	y	1.40	>24.00	0.55
Bell TLB 315SG (D3)	6.33	7.73	9.55	z	6.60	>24.00	1.16
Shantui (D4)	13.36	19.46	8.89	y	0.38	>24.00	0.38

Table 3.24 Drills: VDV summary of WBV seat data

Machine/ID	Estimated 8-hour VDV($m/s^{1.75}$)				EAV (VDV)	ELV (VDV)	SEAT value
	x	y	z	Main			
Pit Viper (E1)	6.94	6.57	3.85	x	>24.00	>24.00	1.44
DMM 2 Drilling Machine (E2)	4.14	4.11	5.18	z	>24.00	>24.00	1.86

Table 3.25 Graders: VDV summary of WBV seat data

Machine/ID	Estimated 8-hour VDV($m/s^{1.75}$)				EAV (VDV)	ELV (VDV)	SEAT value
	x	y	z	Main			
CAT Grader 16G (F1)	7.70	9.60	12.45	z	2.28	>24.00	1.44
Sany Grader (F2)	3.47	4.68	4.72	z	>24.00	>24.00	0.98
Komatsu Grader 9D825A (F3)	6.06	7.16	6.10	y	20.90	>24.00	1.13

Table 3.26 Liquid Conveyers: VDV summary of WBV seat data

Machine/ID	Estimated 8-hour VDV($m/s^{1.75}$)				EAV	ELV	SEAT
	x	y	z	Main	(VDV)	(VDV)	value
Bell Water Bowser B20C (G1)	9.81	15.57	10.05	y	0.93	>24.00	0.93
Powerstar 2628 Refueler (G2)	22.24	21.04	25.68	z	0.22	7.93	2.55
CAT 740 Diesel Bowser (G3)	11.06	20.43	11.91	y	0.31	>24.00	1.32

Table 3.27 4x4: VDV summary of WBV seat data

Machine/ID	Estimated 8-hour VDV($m/s^{1.75}$)				EAV	ELV	SEAT
	x	y	z	Main	(VDV)	(VDV)	value
Toyota Fortuner (I1)	10.28	13.27	10.08	y	1.77	>24.00	0.62

Table 3.28 Compactor: VDV summary of WBV seat data

Machine/ID	Estimated 8-hour VDV($m/s^{1.75}$)				EAV	ELV	SEAT
	x	y	z	Main	(VDV)	(VDV)	value
Landpac Compactor (J1)	15.95	14.98	16.62	z	0.72	>24.00	1.36

3.5 Summary of machine whole-body vibration levels using ISO 2631-5 (2004) using S_{ed} and R factor parameters

WBV levels measured with respect to time along three orthogonal axes (x, y and z) on the operator's seat were used in the computation of the acceleration dose, D_k, for the x, y, z-axes, daily equivalent static compressive stress, S_{ed}, and R factor values and tabulated separately for each machine / activity combination identified in Tables 3.1 to 3.9. A summary overview of the computed values is shown in Tables 3.29 to 3.37.

Table 3.29 LHDs: Summary of D_k for the x-, y-, z- axes and S_{ed} and R factors

Machine/ID	D_k (m/s²)				S_{ed}(MPa)	R
	x	y	z	Main		
Volvo A35 LHD (A1)	19.73	20.03	23.21	z	1.33	2.08
Mercedes Actros V8 LHD (A2)	12.45	13.87	15.96	z	0.95	1.49
Caterpillar 785B (A3)	14.53	14.39	34.52	z	1.79	2.80
Tata Novus Truck 3434 (A4)	9.40	14.89	22.39	z	1.26	1.92
Bell Rear Dumper B25D (A5)	12.58	19.35	25.01	z	1.30	2.04
Bell Rear Dumper B40D (A6)	15.75	20.77	29.49	z	1.59	2.48
Bell Rear Dumper B50D (A7)	14.95	17.83	19.54	y	1.18	1.85
Iveco Truck/Trailer(Double) (A8)	10.38	10.52	20.45	z	1.12	1.75
MAN TGA 33.400 Trailer (A9)	8.94	18.70	37.26	z	1.90	2.97
Dragline (A10)	2.77	3.88	2.65	y	0.28	0.44

Table 3.30 Excavators: Summary of D_k for the x-, y-, z- axes and S_{ed} and R factors

Machine/ID	D_k (m/s²)				S_{ed}(MPa)	R
	x	y	z	Main		
Hitachi Excavator Zaxis 670 LCR (B1)	10.29	7.61	13.53	z	0.71	1.11
Volvo Excavator EC700Blc (B2)	11.86	8.64	7.47	x	0.55	0.86
CAT Excavator 320D (B3)	3.60	3.31	6.53	z	0.42	1.06
Hitachi Excavator Zaxis 370 LCR (B4)	15.65	12.15	16.41	z	0.99	1.54
Hitachi Excavator Zaxis 500 LCR (B5)	13.77	21.92	39.23	z	2.32	3.62
Komatsu Excavator PC1250SP(B6)	20.54	16.05	21.54	z	1.19	1.86
Hitachi Excavator Zaxis 670 LCR (B7)	8.73	3.44	7.62	x	0.48	0.76

Table 3.31 Front End Loaders: Summary of D_k for the x-, y-, z- axes and S_{ed} and R factors

Machine/ID	D_k (m/s²)				S_{ed}(MPa)	R
	x	y	z	Main		
CAT FEL 992G (C1)	8.73	10.91	5.47	y	0.70	1.09
Kawasaki Safika FEL 852IV (C2)	25.45	10.31	16.45	x	1.00	1.57
Kawasaki FEL (C3)	23.70	9.42	22.93	x	1.39	2.17

Table 3.32 Dozers: Summary of D_k for the x-, y-, z- axes and S_{ed} and R factors

Machine/ID	D_k (m/s²)				S_{ed}(MPa)	R
	x	y	z	Main		
CAT Track Dozer D9T (D1)	20.96	13.30	10.20	x	0.83	1.30
CAT Caterpillar D10R (D2)	14.40	16.86	30.42	z	1.70	2.65
Bell TLB 315SG (D3)	10.57	9.45	14.22	z	0.87	1.36
Shantui (D4)	15.30	17.78	9.89	y	1.19	1.86

Table 3.33 Drills: Summary of D_k for the x-, y-, z- axes and S_{ed} and R factors

Machine/ID	D_k (m/s²)				S_{ed}(MPa)	R
	x	y	z	Main		
Pit Viper (E1)	10.89	8.15	18.10	z	0.99	1.54
DMM 2 Drilling Machine (E2)	16.44	16.41	17.16	z	0.40	0.63

Table 3.34 Graders: Summary of D_k for the x-, y-, z- axes and S_{ed} and R factors

Machine/ID	D_k (m/s²)				S_{ed}(MPa)	R
	x	y	z	Main		
CAT Grader 16G (F1)	24.03	13.69	24.27	z	1.37	2.14
Sany Grader (F2)	9.37	8.38	6.18	x	0.54	0.85
Komatsu Grader 9D825A (F3)	11.48	10.76	14.96	z	0.93	1.46

Table 3.35 Liquid Conveyers: Summary of D_k for the x-, y-, z- axes and S_{ed} and R factors

Machine/ID	D_k (m/s²)				S_{ed}(MPa)	R
	x	y	z	Main		
Bell Water Bowser B20C (G1)	12.91	13.57	28.30	z	1.43	2.23
Powerstar 2628 Refueler (G2)	88.24	79.43	162.13	z	11.30	17.68
CAT 740 Diesel Bowser (G3)	14.51	15.34	36.68	z	2.23	3.50

Table 3.36 4x4: Summary of D_k for the x-, y-, z- axes and S_{ed} and R factors

Machine/ID	D_k (m/s²)				S_{ed}(MPa)	R
	x	y	z	Main		
Toyota Fortuner (I1)	8.54	13.30	18.21	z	1.03	1.61

Table 3.37 Compactor: Summary of D_k for the x-, y-, z- axes and S_{ed} and R factors

Machine/ID	D_k (m/s²)				S_{ed}(MPa)	R
	x	y	z	Main		
Landpac Compactor (J1)	23.09	24.63	26.27	z	2.23	3.50

3.6 Summary

Experimental data was obtained on each set of machinery. The parameters of interest from ISO 2631-1 (1997) and ISO 2631-5 (2004) standard methodologies were computed and tabulated for further analysis. The results obtained are similar to those obtained earlier on South African mines (Van Niekerk et al., 2000; MHSC, 2004; Mdlazi 2008) using the ISO 2631-1 (1997) standard methodology. This dataset will subsequently be used in analysis to obtain the various parameters for the ISO 2631-1 (1997) and ISO 2631-5 (2004) standard methodologies and compare them.

4. Numerical investigation of parameters

To investigate the effect of shocks on the WBV response parameters used in the ISO 2631-1 (1997) and ISO 2631-5 (2004) standards, a series of numerical investigations were conducted using very simplified simulations to capture the essential nature of various operational conditions, and qualitatively explain the trends in the response parameters. Signals were therefore artificially generated in the laboratory to explore the parameters of the two standards. Vibration signals of more-or-less steady periodic processes can be approximated by superposition of sinusoids. Pure sinusoidal data was first generated without shocks being present and investigated. Subsequently, sinusoidal signals with higher amplitudes were generated and investigated. Sinusoidal signals with increasing shock amplitude up to and exceeding the crest factor of 9 based on ISO 2631-1 (1997) were generated and analyzed. Finally, simulated data with different shock magnitudes for five typical example cases were generated and analyzed.

To conduct the numerical investigation of the parameters based on the two standards, pure sinusoidal data was first artificially generated using a signal generator at amplitudes and frequencies which are similar to the field observed frequencies shown earlier in Table 3.2 and Table 4.1. A subset of the data, comprising 5 cases, was considered based on frequencies and amplitudes (Table 4.1) obtained in the field, so as to have a representative data set on which investigations could be carried out. Shock data was equally generated and introduced to the pure sinusoidal data to obtain data with transient shocks. The signals were generated at different frequencies along the three basicentric axes for each signal as shown in Table 4.1. The z axis data was generated in accordance with the requirement of ISO 2631-5 (2004) that the frequency and amplitude should be in the range of -20 m/s^2 to 40 m/s^2 and 0.5 Hz to 40 Hz respectively. The artificially generated data was measured back using the SVAN958 human vibration meter. Further analysis was done on the generated signals in the MATLAB environment and the results obtained are tabulated in Tables 4.3 to 4.7.

Table 4.1 Frequencies and amplitudes of selected field signals

Signal	Frequency (Hz)			Amplitude (m/s²)			Shock amplitude (m/s²)		
	x	y	z	x	y	z	x	y	z
Case 1	45	45	25	0.5	0.7	0.3	1.3	1.3	1.4
Case 2	35	3	2	1.3	1.4	1.3	2.2	2.0	2.0
Case 3	40	15	4	1.5	1.4	1.3	2.7	2.1	2.0
Case 4	40	40	20	0.6	0.7	0.7	1.9	1.9	2.0
Case 5	40	35	20	2.0	1.4	1.4	3.3	2.7	2.7

To facilitate interpretation, the calculated WRMS, VDV, S_{ed} and R factor parameters were normalized with respect to the exposure upper limit values reported in Table 1.1. This led to normalized HGCZ lower and upper limits or boundaries which are shown in Table 4.2 and plotted as the HGCZ boundaries shown in Figures 4.2 to 4.6. The normalized upper limits are all unity for the four parameters. A line with slope of magnitude one (1) originates at (0,0) and passes through a point defined by the normalized upper limits (1,1) on both axes as shown in Figures 4.2 to 4.6.

Table 4.2 Table of normalized exposure action and limit values and health guidance caution zone values for whole-body vibration

Normalized Exposure= Exposure/HGCZ upper limit	ISO 2631-1 (1997)		ISO 2631-5 (2004)	
	$WRMS_n$	VDV_n	S_{edn}	R_n
EAV_n=EAV/HGCZ upper limit	0.43	0.43	0.63	0.67
ELV_n=ELV/HGCZ upper limit	1.00	1.00	1.00	1.00

4.1 Results of simulation of data without shocks

The WRMS, VDV, S_{ed} and R factor parameters based on pure sinusoids corresponding to cases 1 to 5, are tabulated in Table 4.3. Health risk is evaluated based on the above parameters as low, medium or high depending on whether the exposure values are below the EAV, between the EAV and ELV or above ELV as earlier discussed in Section 1.1. Low risk to health is predicted based on the values of WRMS and VDV parameters of ISO 2631-1 (1997) for cases 1 and 4. Medium risk to health is predicted for the remaining cases as shown in Table 4.3. However, low risk to health is predicted based on the values of S_{ed} and R factor parameters of ISO 2631-5 (2004) for all the five cases. This is because of the absence of transient shocks.

According to ISO 2631-1 (1997) based on the WRMS and VDV values, cases 1 and 4 correspond to vibration levels below the health guidance caution zone (HGCZ) boundaries. The remaining three cases are within the HGCZ (Table 4.3, Figure 4.2). When the S_{ed} and R factor values are used in the prediction of health risks, all five cases are associated with vibration levels below the HGCZ. There is agreement between the WRMS and VDV values and the S_{ed} and R factor values for cases 1 and 4, as low risk to operator health is predicted since the vibration levels are below the HGCZ.

For data without shocks, it can be seen from Table 4.3 that the health risk prediction based on VDV is more conservative than that based on the static compressive stress, S_{ed}, values. This is because the computation of sixth power based S_{ed} emphasizes transient shocks (equations 2.3, 2.4, 2.5) whenever present in a vibration signal. However, these shocks are absent in the generated data, and low values of S_{ed} are obtained. The health risk assessments based on the VDV of the signals are relatively higher than that based on S_{ed} because of the absence of transient shocks. The results in Table 4.3 are normalized and plotted for better visual appreciation in Figure 4.2. $A(8)_n$ and VDV_n parameters are plotted on the x- and y- axes respectively in Figure 4.2 (a). In Figure 4.2 (b) S_{edn} and R_n factor parameters are plotted on the x- and y- axes respectively. S_{edn} and $A(8)_n$ parameters are plotted on the x- and y-axes respectively in Figure 4.2 (c). Finally, S_{edn} and R_n factor parameters are plotted on the x- and y-axes respectively in Figure 4.2 (d). The VDV_n versus $A(8)_n$ values, R_n factor versus S_{edn} values, $A(8)_n$ versus S_{edn} values and VDV_n versus S_{edn} values plots are all proportional as shown in Figures 4.2(a), (b), (c) and (d) respectively. The subscript n refers to the normalization.

In Figure 4.2 (a) both parameters are from ISO2631-1. Since the slope is 1 and the lower and upper HGCZ values correspond exactly, i.e. 0.43 and 1 on both axes, it is clear that the two parameters from the same standard are consistent in their health risk assessments.

Figure 4.2 (b) considers two parameters from ISO2631-5. The lower HGCZ values are 0.63 and 0.67 for S_{edn} and the R factor respectively. The upper HGCZ values correspond at exactly 1 on both axes. The slope is greater than 1 even though the two parameters are from the same standard. This is because the S_{edn} is a daily value whereas the R factor is an accumulative value which is a function of S_{ed}. The R factor is an accumulative factor because it takes into account 240 days a year for a maximum operator working life of 45 years (aged 20–65 years) as suggested by the ISO 2631-5 (2004) standard. Hence, the two parameters from the same standard are not consistent in their health risk assessments.

Figure 4.3 (c) considers a parameter from ISO2631-1 and another from ISO2631-5. The lower HGCZ values are 0.43 and 0.63 for $A(8)_n$ and S_{edn} respectively. The upper HGCZ values again correspond to 1 on both axes. The slope is greater than 1. It is obvious that the two parameters from different standards are not consistent in their health risk assessments.

Finally, Figure 4.3 (d) also gives parameters from ISO2631-1 and ISO2631-5. The lower HGCZ values are 0.43 and 0.63 for VDV_n and S_{edn} respectively. The upper HGCZ values correspond exactly at 1 on both axes. The slope is greater than 1. Again it is clear that the two parameters from the different standards are not consistent in their health risk assessments. In spite of the inconsistencies, all the parameters plotted in Figures 4.2 to 4.6 are essentially proportional. According to ISO 2631-1 (1997), for events with CF greater than 9 which indicate the presence of shocks, the VDV parameter should be used whereas S_{ed} is the daily parameter for assessing shock based on ISO 2631-5 (2004). Hence, VDV parameter will ultimately be compared to S_{ed} for transient shock events.

Again, despite the approximate proportionality it is clearly seen that the VDV_n values provide more conservative health risk assessments than the S_{edn} values in Figure 4.2 (d) in the absence of shocks. It is noteworthy that the plotted values are all above the unity slope line, indicating a steep slope with a gradient greater than 1 in the insignificant or no shock situation, meaning the VDV predicts higher risk to health.

Table 4.3 Results for simulated sinusoidal data without shocks

Signal	WRMS		VDV		Comment on risk	S_{ed} MPa	R	Comment on risk
	m/s^2	Main	$m/s^{1.75}$	Main				
Case 1	0.13	y	2.43	y	Low	0.04	0.07	Low
Case 2	0.91	y, z	16.65	y, z	Moderate	0.35	0.55	Low
Case 3	0.91	z	16.65	z	Moderate	0.34	0.54	Low
Case 4	0.31	z	5.61	z	Low	0.11	0.17	Low
Case 5	0.61	z	11.21	z	Moderate	0.21	0.33	Low

4.2 Results of simulation of sinusoidal data with higher amplitude

For simulated data with higher amplitude but still without shocks, it can be seen that the risk to health predicted based on S_{ed} values continues to be lower than risk based on VDVs, as shown in Table 4.4. Even, though the generated sinusoidal data may have the same magnitude as typical shocks, the crest factor is just two; hence lower values of S_{ed} are again obtained. The values of the parameters in Table 4.4 are normalized and plotted in Figure 4.3.

Again the normalized VDV_n versus $A(8)_n$, R_n factor versus S_{edn}, $A(8)_n$ versus S_{edn} and VDV_n versus S_{edn} plots are all proportional as shown in Figures 4.3(a), (b), (c) and (d) respectively. Again, in spite of the proportionality it is clearly seen from Figure 4.3 (d) that the VDV_n health risk assessments are more conservative than the those based on S_{edn} , in the absence of shocks. Again, it is noteworthy that proportionality is with a gradient greater than 1 (steep slope) as was obtained in Section 4.2 corresponding to the no shock situation.

Table 4.4 Results for simulated sinusoidal data with higher amplitude

Signal	WRMS		VDV		Comment on risk	S_{ed} MPa	R	Comment on risk
	m/s^2	Main	$m/s^{1.75}$	Main				
Case 1	0.50	z	9.04	z	Low	0.19	0.30	Low
Case 2	1.37	z	25.02	z	High	0.53	0.83	Moderate
Case 3	1.37	z	25.02	z	High	0.52	0.82	Moderate
Case 4	0.92	z	16.84	z	Moderate	0.31	0.49	Low
Case 5	1.23	z	22.42	z	High	0.42	0.65	Low

4.3 Effect of increasing amplitude of shocks on computed values S_{ed} and VDV

Subsequently, to increase the magnitude of shocks, the amplitude of shock over 1 cycle in every harmonic number of cycles (for example over 1 cycle in every 16 cycles for case 3 in z direction as shown in Figure 4.1) was increased by multiplying the original data within the shock cycle with values of 1.5, 2, 2.5 and 3 for cases 3b, 3c, 3d and 3f respectively. The number of cycles within each harmonic period was selected based on physically observed data. Figure 4.1 is an example plot of the generated shock signal. The results in Table 4.5 are normalized and plotted in Figure 4.4.

It is interesting to note that once again the VDV_n versus $A(8)_n$, R_n factor versus S_{edn}, $A(8)_n$ versus S_{edn} and VDV_n versus S_{edn} plots are all proportional as shown in Figures 4.4 (a), (b), (c) and (d) respectively. However, in spite of the approximate proportionality it is clearly seen that the predicted health risk based on VDVs are less conservative than the predicted risk based on S_{ed} values as shown in Figure 4.4 (d) in the presence of shocks. Now the plotted values are below the unity slope line except for the first value. The slope is now less than 1 which means the S_{ed} predicts higher risk to health. This is as a result of higher weighting once the presence of high impact or shock is detected in the ISO 2631-5 (2004) standard procedure which leads to higher values of S_{ed} and hence a slope of less than 1. Also, in Figure 4.4 (c) and (d) there is a very large offset i.e. the graph no longer goes through 0. This is due to the presence of transient shocks which leads to a gradient less than 1.

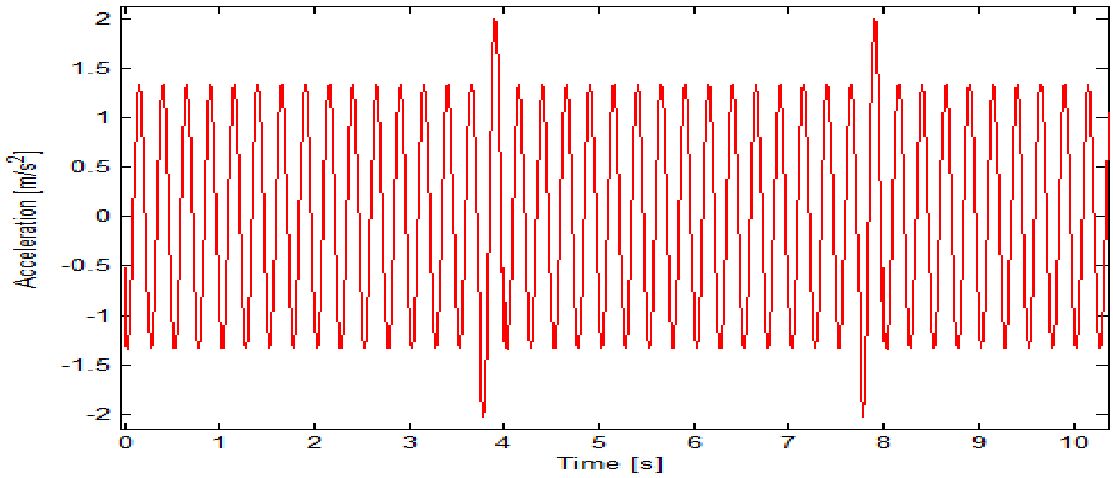


Figure 4.1: Simulated sinusoidal signal with equally spaced shocks for dominant z-axis for case 3

Table 4.5 Signals in increasing order of shock amplitude for case 3

Signal	WRMS	VDV		Comment on risk	S_{ed} MPa	R	Comment on risk	Comment (magnitude)
	m/s^2	$m/s^{1.75}$	Main					
Case 3a	0.98	17.34	z	Moderate	0.52	0.81	Moderate	Original signal
Case 3b	1.03	18.78	z	Moderate	0.79	1.23	Moderate	×1.5 signal
Case 3c	1.13	20.64	z	Moderate	1.08	1.68	High	×2 signal
Case 3d	1.25	22.80	z	High	1.40	2.19	High	×2.5 signal
Case 3f	1.38	25.19	z	High	1.79	2.79	High	×3 signal

4.4 Effect of increasing amplitude of shocks above crest factor (CF) of 9 on computed values S_{ed} and VDV

The magnitude of shocks was further increased so as to obtain crest factors higher than 9. To do this; the amplitude of shock over 1 cycle in every harmonic number of cycles as discussed in Section 4.3 was increased by multiplying the original data within the shock cycle with values of 2.5, 3, 9, 18 and 20 for cases 3d, 3e, 3f, 3g and 3h respectively. Parameters of interest were then computed and tabulated in Table 4.6. The values of the parameters in Table 4.6 are normalized and plotted in Figure 4.5. It is interesting to note that once again the VDV_n versus $A(8)_n$ R_n factor versus S_{edn}, $A(8)_n$ versus S_{edn} and VDV_n versus S_{edn} plots are all proportional, despite obtaining crest factors greater than 9 as shown in Figures 4.5 (a), (b), (c) and (d) respectively. However, in spite of the proportionality it is clearly seen that health risk prediction based on the VDVs are less conservative than those based on the

S_{ed} values in Figure 4.5 (d) in the presence of shocks as before. All the plotted values are below unity slope line and with a slope less than 1 corresponding to the significant shock situation meaning the S_{ed} predicts higher risk to health. This is consistent with findings by Alem et al. (2004) and Chen et al. (2009) who obtained higher predictions of health risk based on the S_{ed} values than on VDVs in the presence of high impacts or shocks, in their study as discussed in Section 1.3.

Table 4.6 Signal with increasing shock amplitude below and above CF of 9 for case 3

Signal	WRMS	VDV		Comment	S_{ed}	R	Comment	Comment
	m/s^2	$m/s^{1.75}$	Main	on risk	MPa		on risk	(magnitude)
Case 3d	1.25	22.80	z	High	1.40	2.19	High	×2.5 signal
Case 3e	1.38	25.19	z	High	1.79	2.79	High	×3 signal
Case 3f	3.31	60.31	z	High	5.31	8.31	High	×9 signal
Case 3g	6.43	117.4	z	High	12.30	19.24	High	×18 signal
Case 3h	7.14	130.2	z	High	13.61	21.30	High	×20 signal

4.5 Simulated data with different amplitude and low shock magnitude for five typical example cases

Simulated data with different amplitudes; low shock magnitudes and CFs above and below 9 for five typical cases were generated. The various parameters obtained from results of analysis are tabulated in Table 4.7. The values of the parameters are then normalized and plotted in Figure 4.6. It is interesting to note that the VDV_n versus $A(8)_n$ and R_n factor versus S_{edn}, are proportional; however, the $A(8)_n$ versus S_{edn} and VDV_n versus S_{edn} plots are roughly proportional as shown in Figures 4.6 (a), (b), (c) and (d) respectively. Figures 4.6 (c) and 4.6 (d) are roughly proportional because of the stochastic nature of the data. However, in spite of the rough proportionality it is clearly seen that predicted risk based on VDVs is more stringent than the predicted risk based on the S_{ed} values as shown in Figure 4.6 (d) in the presence of low shocks. All the plotted values are above the unity slope line with a slope greater than 1 corresponding to the low or no significant shock content situation. This means that health risk predictions based on VDV are higher.

This is consistent with findings by Johanning et al. (2006), Cooperrider and Gordon (2008) and Eger et al. (2008) who obtained higher predictions of health risk based on the VDVs than risk based on S_{ed} values in the presence of low shock magnitude.

Table 4.7 Results for simulated data with different amplitude and low shock magnitude for five typical example cases

Signal	WRMS		VDV		Comment on risk	S_{ed} MPa	R	Comment on risk
	m/s^2	Main	$m/s^{1.75}$	Main				
Case 1	0.37	z	8.57	z	Low	0.19	0.30	Low
Case 2	0.61	z	11.11	z	Moderate	0.39	0.62	Low
Case 3	0.94	z	17.20	z	Moderate	0.47	0.73	Low
Case 4	0.35	z	5.65	z	Low	0.16	0.21	Low
Case 5	0.52	z	9.47	z	Moderate	0.47	0.73	Low

4.6 Simulated data with different amplitude and shock magnitude for five typical example cases

Data with different amplitudes and shock magnitudes for the five typical cases were generated. The various parameters obtained from results of analysis are tabulated in Table 4.8. The values of the parameters are then normalized and plotted in Figure 4.7. It is interesting to note that the VDV_n versus $A(8)_n$ and R_n factor versus S_{edn}, are proportional; however, the $A(8)_n$ versus S_{edn} and VDV_n versus S_{edn} plots are roughly proportional with some scatter as shown in Figures 4.7 (a), (b), (c) and (d) respectively. Figures 4.7 (c) and 4.7 (d) are roughly proportional because of the stochastic nature of the data. However, in spite of the rough proportionality it is clearly seen that health risk prediction based on the VDVs is less conservative than that based on the S_{ed} values in Figure 4.7 (d) in the presence of shocks as before. All the plotted values are below the unity slope line with a slope less than 1 corresponding to the high or significant shock content situation. This means the S_{ed} predicts higher risk to health. This is further consistent with findings by Alem et al. (2004) and Chen et al. (2009) who obtained higher predictions of the risk based on the S_{ed} values than on VDVs in the presence of high shock magnitude on rough terrain.

Table 4.8 Results for simulated data with different amplitude and shock magnitude for five typical example cases

Signal	WRMS		VDV		Comment on risk	S_{ed} MPa	R	Comment on risk
	m/s^2	Main	$m/s^{1.75}$	Main				
Case 1	0.40	z	7.33	z	Low	0.95	1.49	High
Case 2	1.14	z	20.73	z	Moderate	6.28	9.82	High
Case 3	1.08	z	19.73	z	Moderate	1.15	1.81	High
Case 4	0.72	z	13.07	z	Moderate	1.73	2.71	High
Case 5	1.39	z	25.44	z	High	2.36	3.69	High

4.7 Summary

The two parameters of the two standard methodologies were computed using simulated numerically generated signals. The trends in each of the parameters corresponding to each of the standards were monitored using various scenarios obtained by varying the signal parameters and comparing these against each other. For shock evaluation the VDV parameter is used with respect to ISO 2631-1 (1997) whereas the S_{ed} parameter is used with respect to ISO 2631-5 (2004). The two parameters (VDV and S_{ed}) were proportional with varying slopes for each scenario. The graphs with values above the unity slope line and slopes or gradients higher than 1 (steep) corresponded to signals with low or no shock content meaning that health risk prediction based on the VDV is higher; whereas the graphs with values below the unity slope line and gradients less than 1 (gradual) corresponded to signals with high or significant shock content meaning the health risk prediction based on S_{ed} is higher.

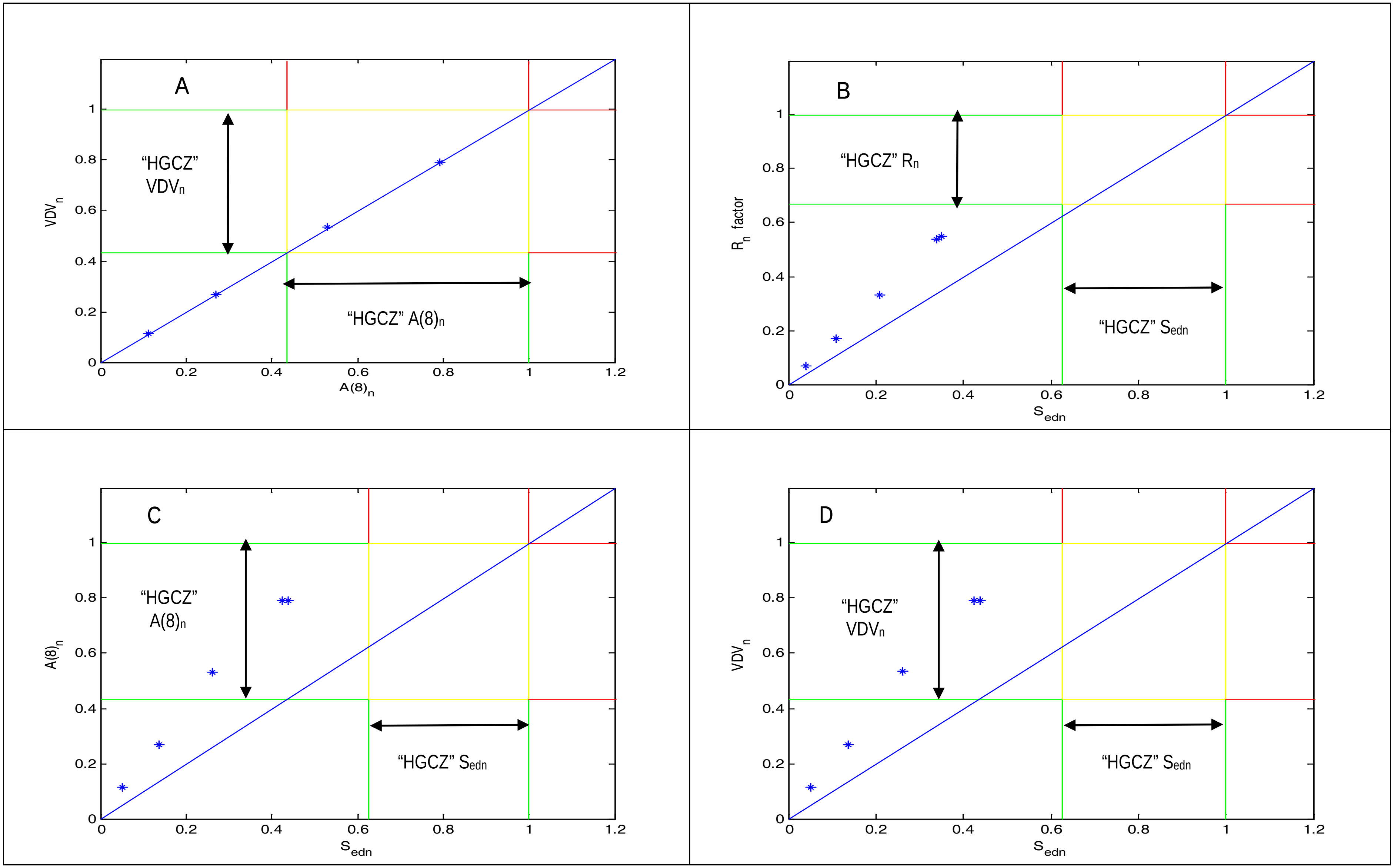


Figure 4.2: Relationship between health predicted by (a) VDV_n versus $A(8)_n$ values, (b) R_n factor versus S_{edn} values, (c) $A(8)_n$ versus S_{edn} values and (d) VDV_n versus S_{edn} values for signals without shocks. The associated HGCZ are also indicated in the figures.

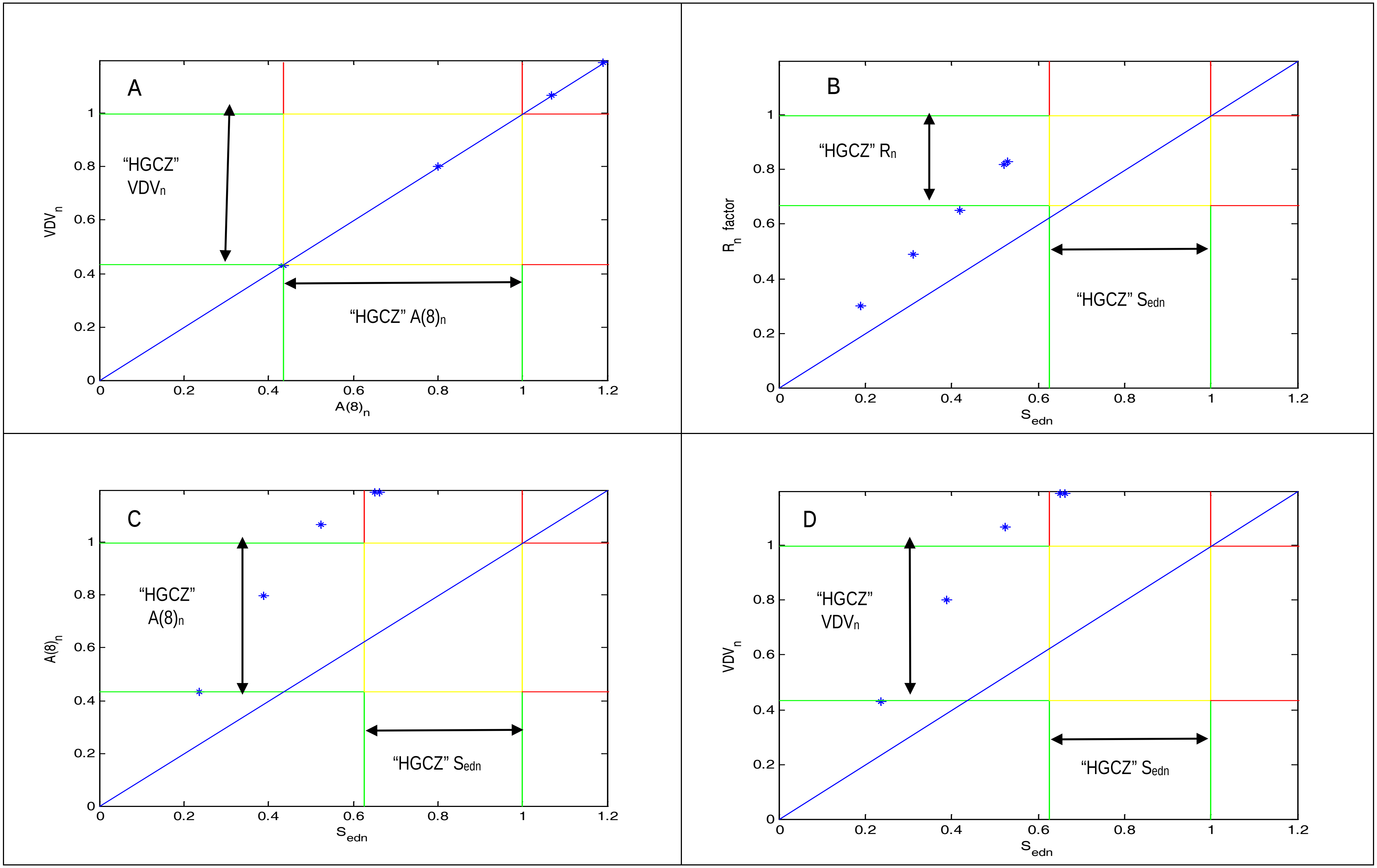


Figure 4.3: Relationship between health predicted by (a) VDV_n versus $A(8)_n$ values, (b) R_n factor versus S_{edn} values, (c) $A(8)_n$ versus S_{edn} values and (d) VDV_n versus S_{edn} values for sinusoidal signals with higher amplitude. The associated HGCZ are also indicated in the figures.

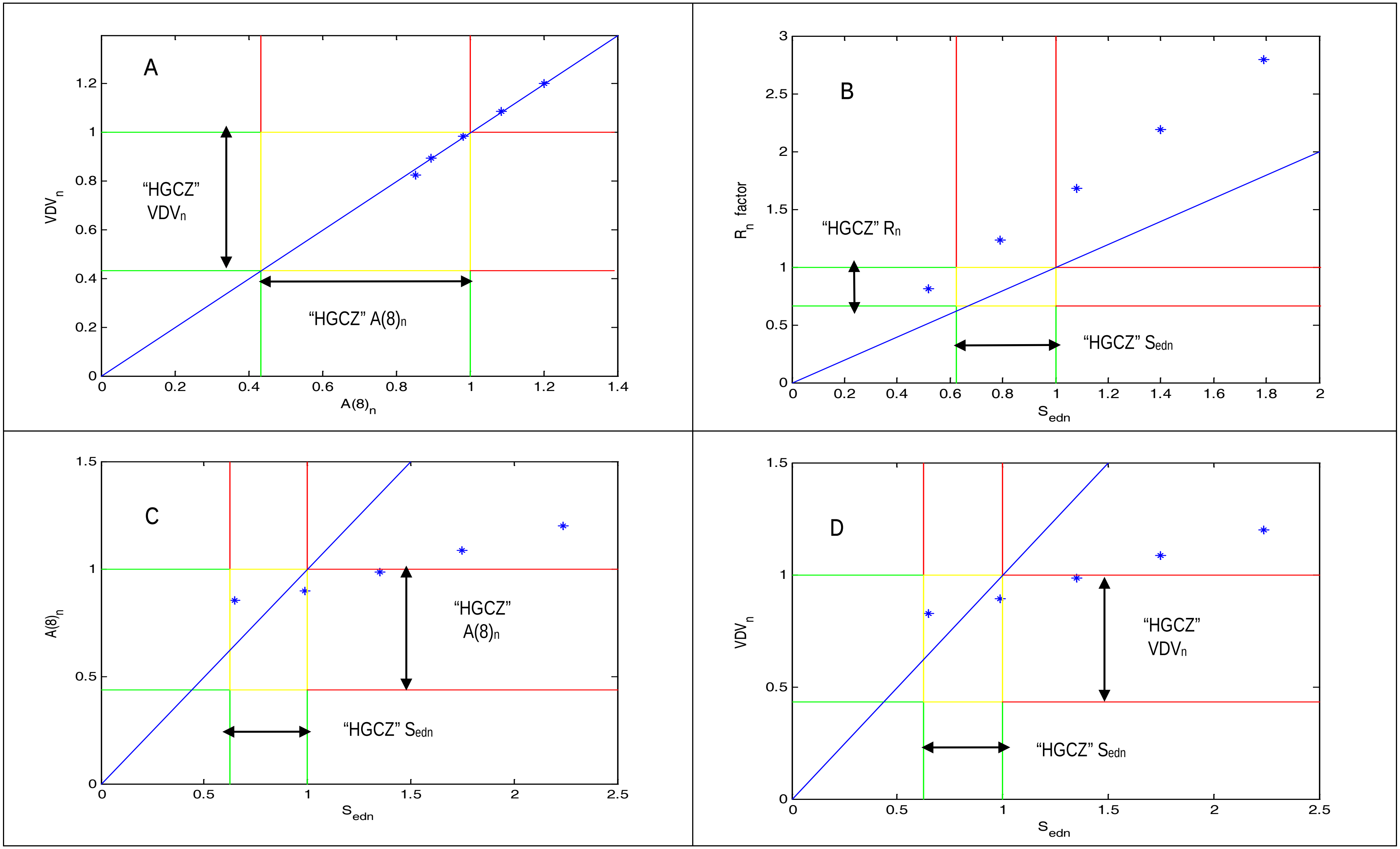


Figure 4.4: **Relationship between health predicted by (a) VDV_n versus $A(8)_n$ values, (b) R_n factor versus S_{edn} values, (c) $A(8)_n$ versus S_{edn} values and (d) VDV_n versus S_{edn} values for signals with transient shocks in order of increasing amplitude. The associated HGCZ are also indicated in the figures.**

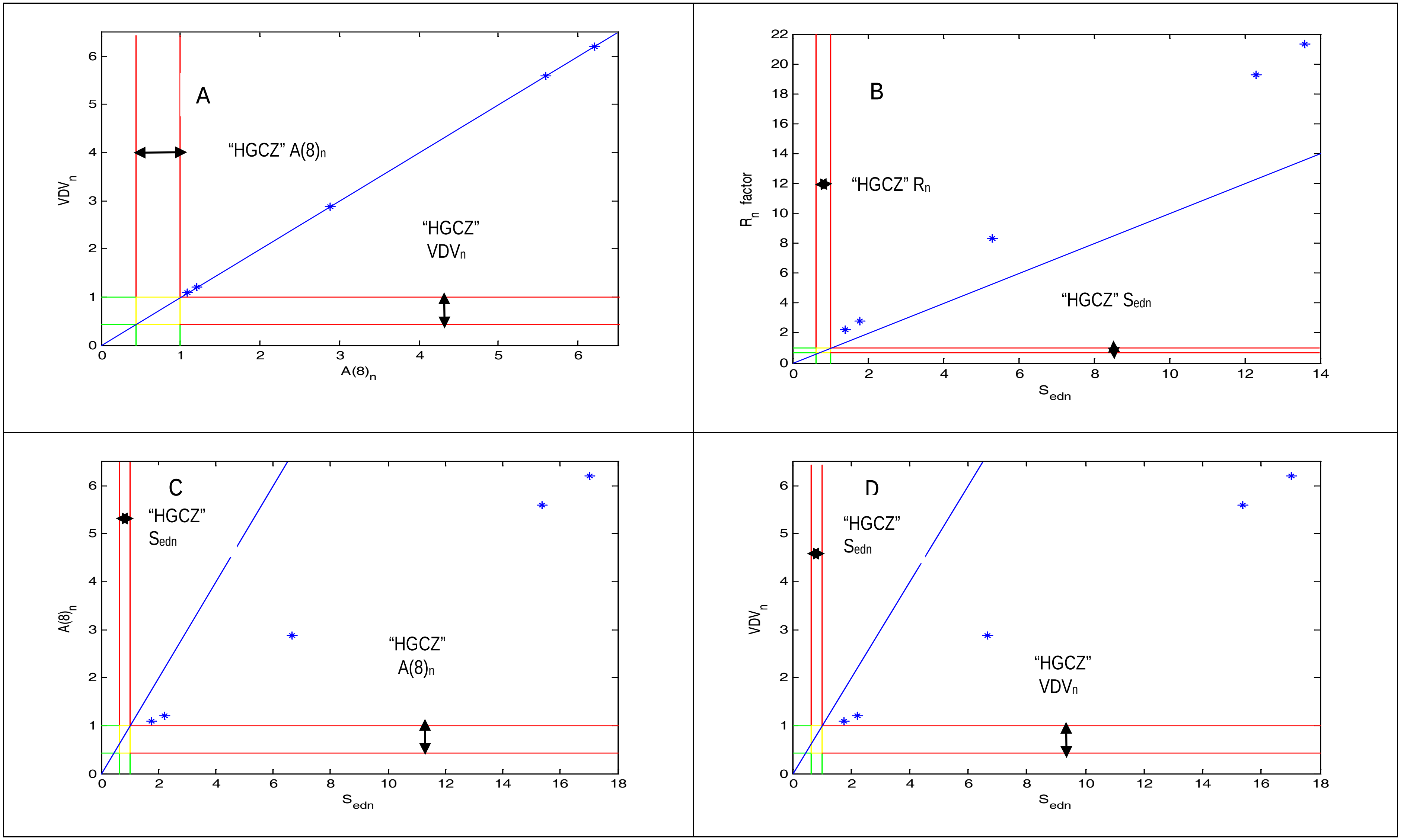


Figure 4.5: Relationship between health predicted by (a) VDV_n versus $A(8)_n$ values, (b) R_n factor versus S_{edn} values, (c) $A(8)_n$ versus S_{edn} values and (d) VDV_n versus S_{edn} values for signal with transient shocks above the CF of 9 respectively. The associated HGCZ are also indicated in the figures.

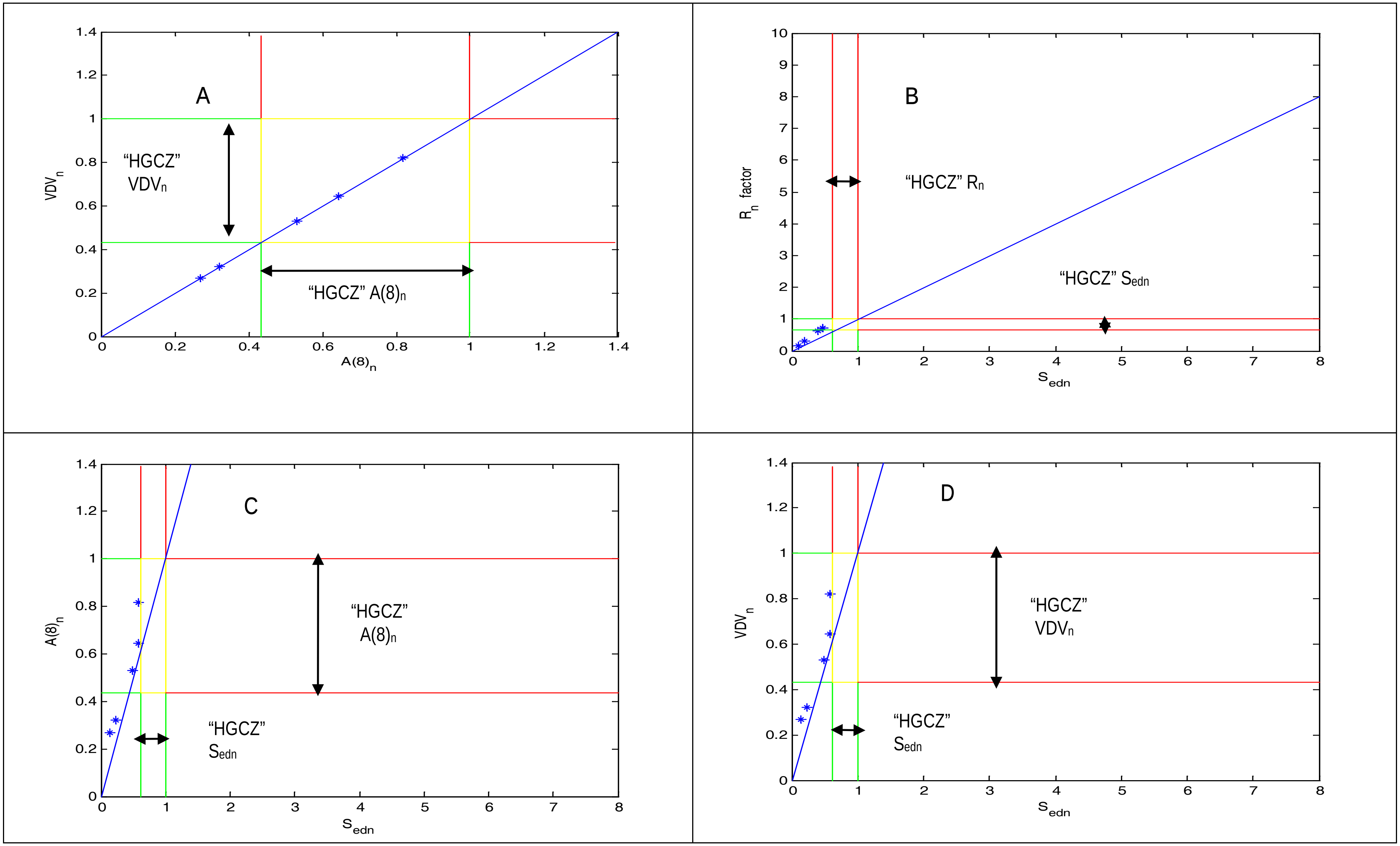


Figure 4.6: **Relationship between health predicted by (a) VDV_n versus $A(8)_n$ values, (b) R_n factor versus S_{edn} values, (c) $A(8)_n$ versus S_{edn} values and (d) VDV_n versus S_{edn} values for simulated data with different amplitude and low shock magnitude for five typical example cases. The associated HGCZ are also indicated in the figures.**

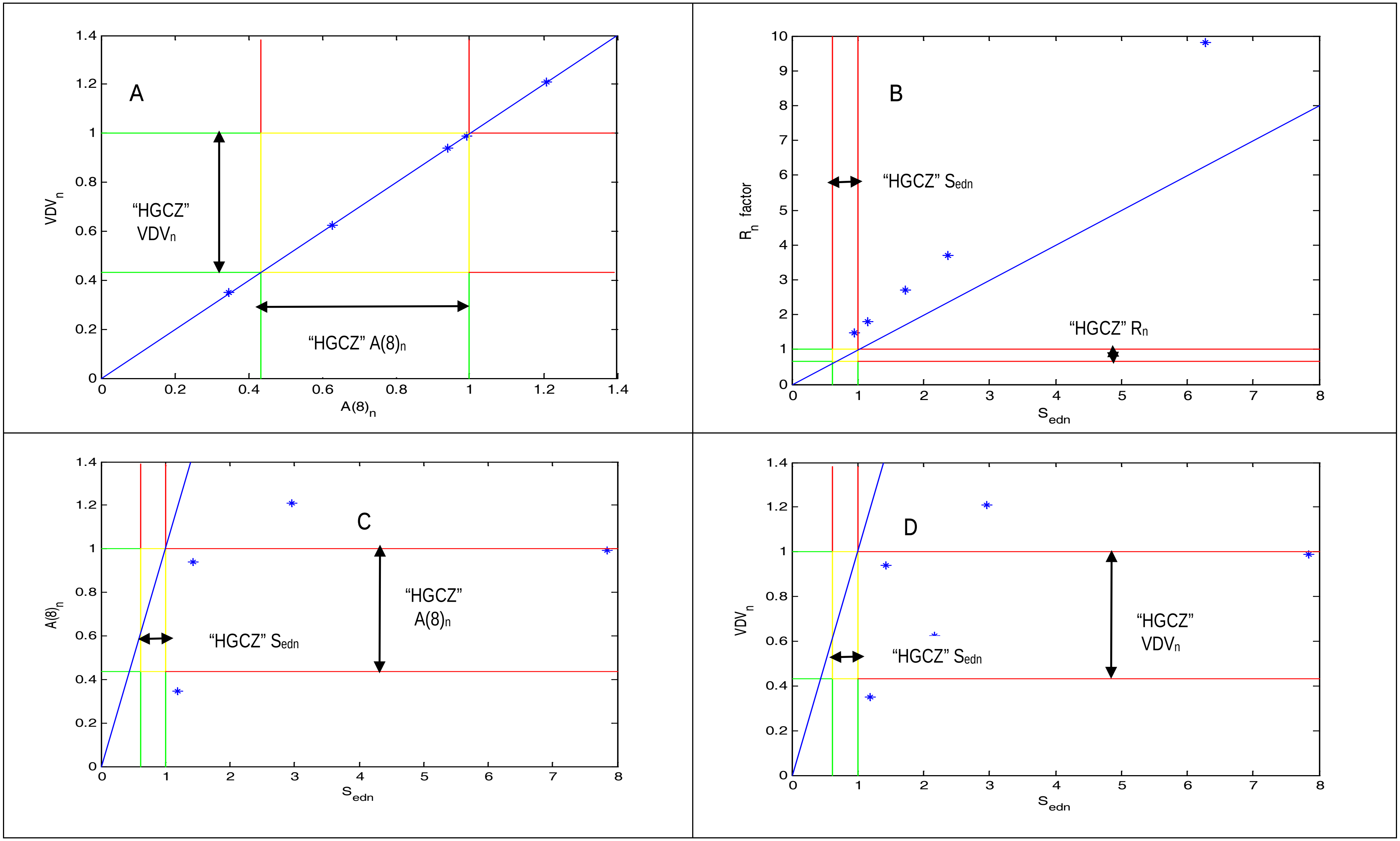


Figure 4.7: **Relationship between health predicted by (a) VDV_n versus $A(8)_n$ values, (b) R_n factor versus S_{edn} values, (c) $A(8)_n$ versus S_{edn} values and (d) VDV_n versus S_{edn} values for simulated data with different amplitude and shock magnitude for five typical example cases. The associated HGCZ are also indicated in the figures.**

5. Evaluation of results of investigation

5.1 Whole-body vibration results based on ISO 2631-1 (1997) using WRMS

Figures 5.1 to 5.9 graphically summarizes the machinery whose WBV levels are either below the WRMS action (HGCZ lower limit) value of 0.5 m/s^2 or between the WRMS action and limit values of 0.5 m/s^2 and 1.15 m/s^2 respectively. None of the equipment has WRMS values above the HGCZ upper limit value of 1.15 m/s^2. In all the following cases, reference should be made to Tables 3.11 to 3.19 for a summary of operator seat vibration magnitudes and the operating periods before the WRMS action values and limit values are reached.

Of the ten LHDs evaluated four had values below the HGCZ lower limit value and the remaining six had values between the HGCZ limit values. All the excavators had vibration values below the HGCZ. Of the remaining equipment, seven had vibration values below the HGCZ and the remaining ten had vibration values above the HGCZ.

All the machinery have vibration values that are either below the WRMS action value or between the WRMS action and limit values. Fifty three percent of the machinery/equipment have vibration values below the WRMS action value. The remaining forty seven percent have exposure values between the WRMS action and limit values (between the HGCZ limit values). The WRMS values are similar to those obtained earlier on the South African mines (Van Niekerk et al., 2000; MHSC, 2004; Mdlazi 2008) using the ISO 2631-1 (1997) standard methodology.

Mdlazi 2008 obtained WRMS values which were all below the limit value. However, Van Niekerk et al. (2000) and MHSC (2004) had some values above the WRMS limit value. This was as a result of the dominant frequency being within 4-8 Hz and higher weighting factor being attached to this frequency range because of the serious effect on health.

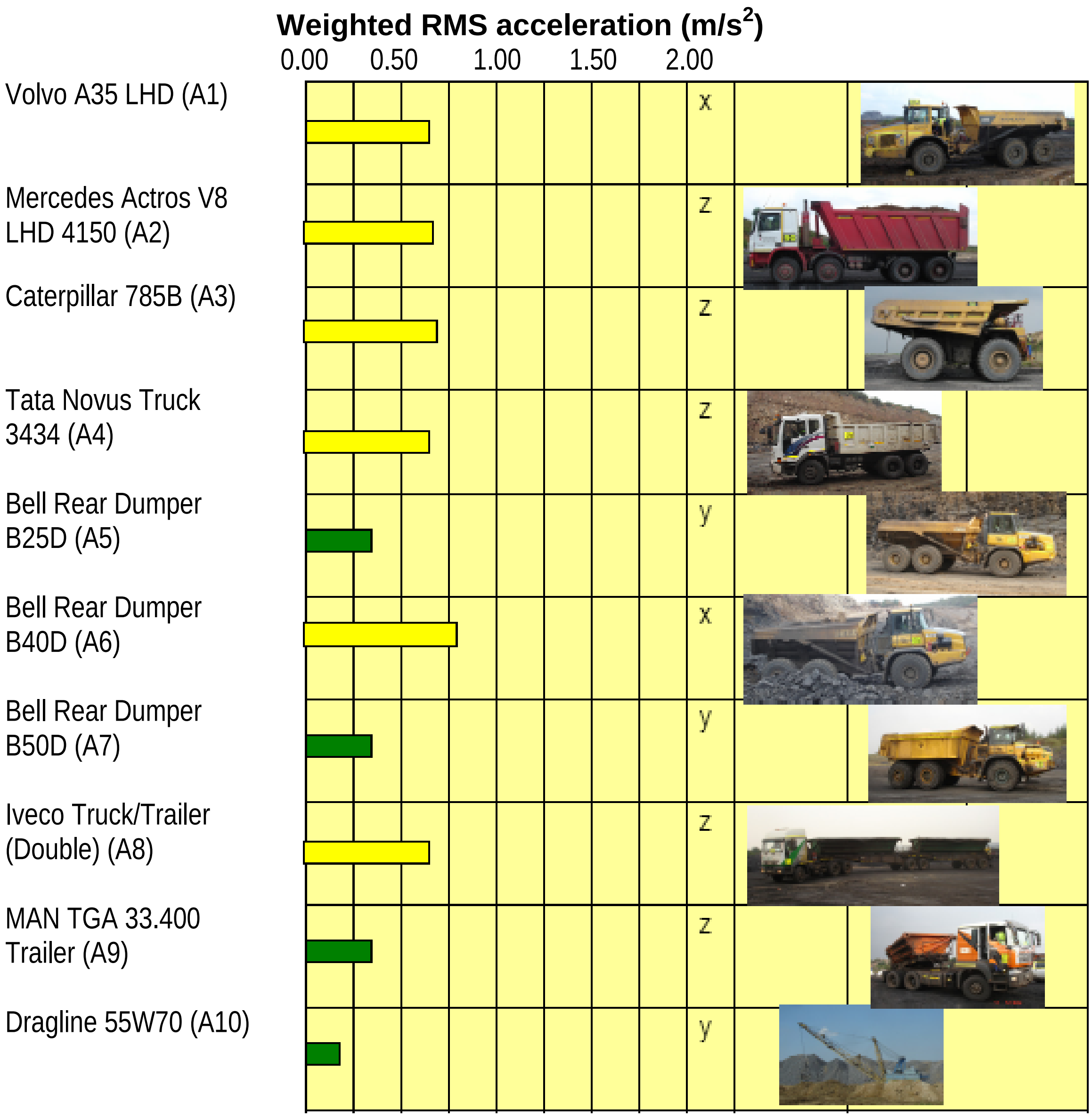
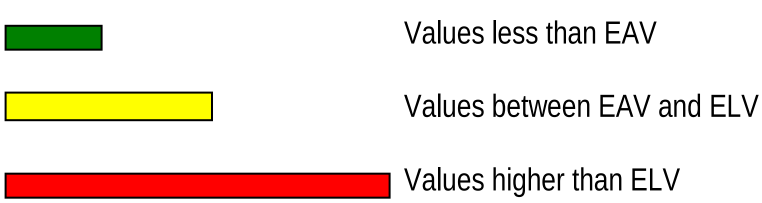


Figure 5.1: Weighted RMS acceleration magnitudes for LHDs



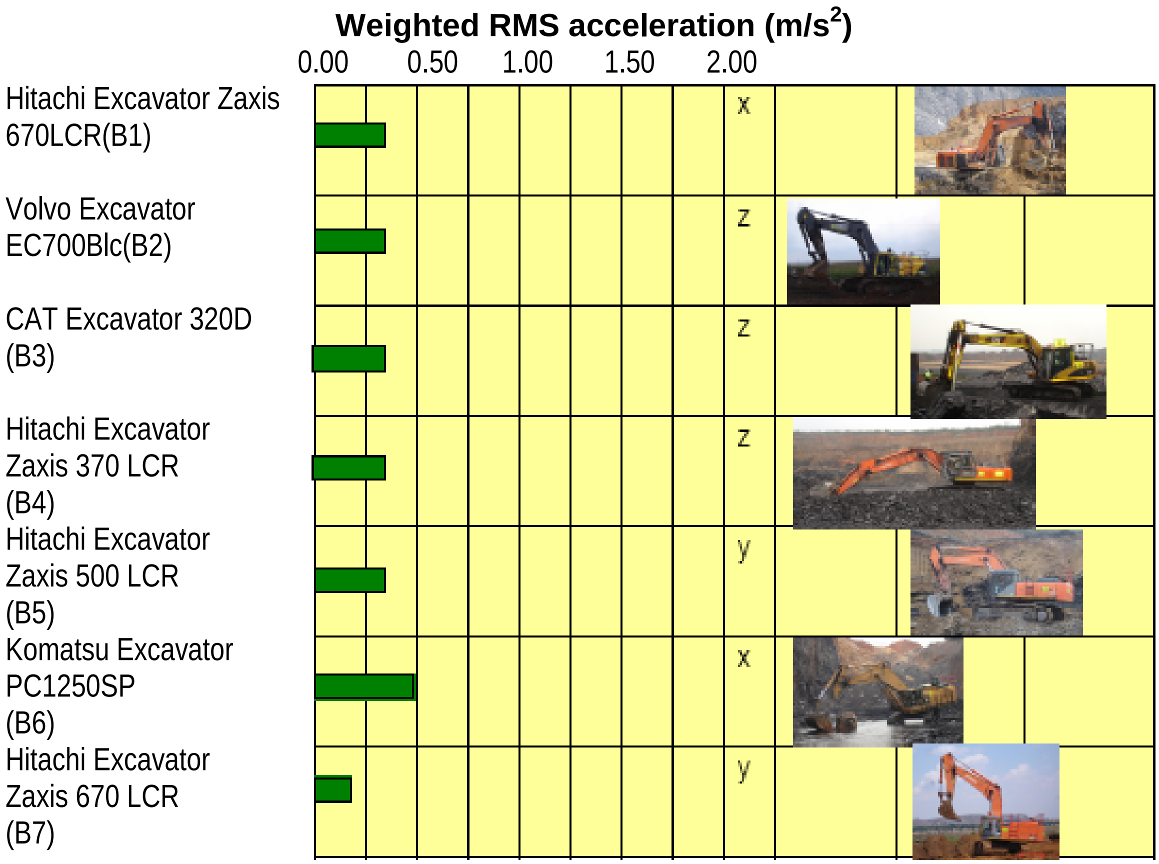


Figure 5.2: Weighted RMS acceleration magnitudes for Excavators

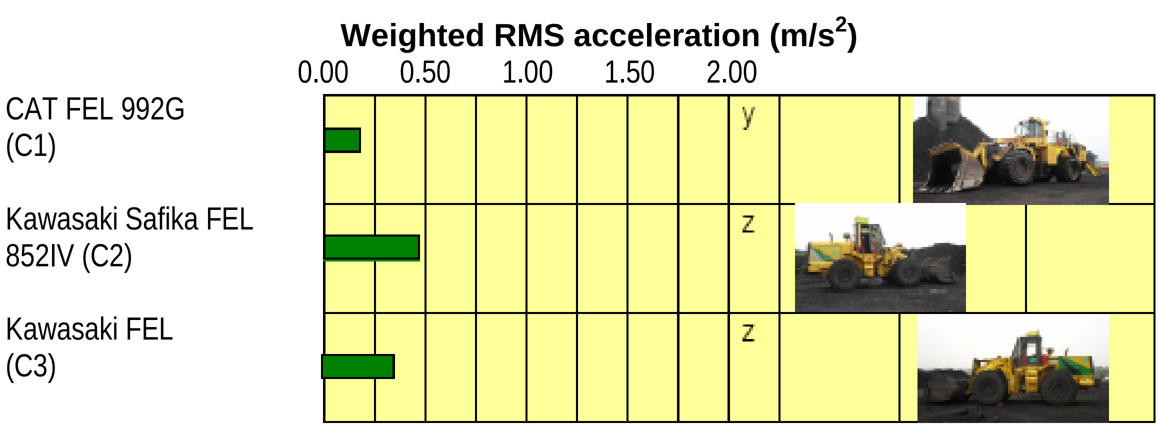


Figure 5.3: Weighted RMS acceleration magnitudes for Front End Loaders

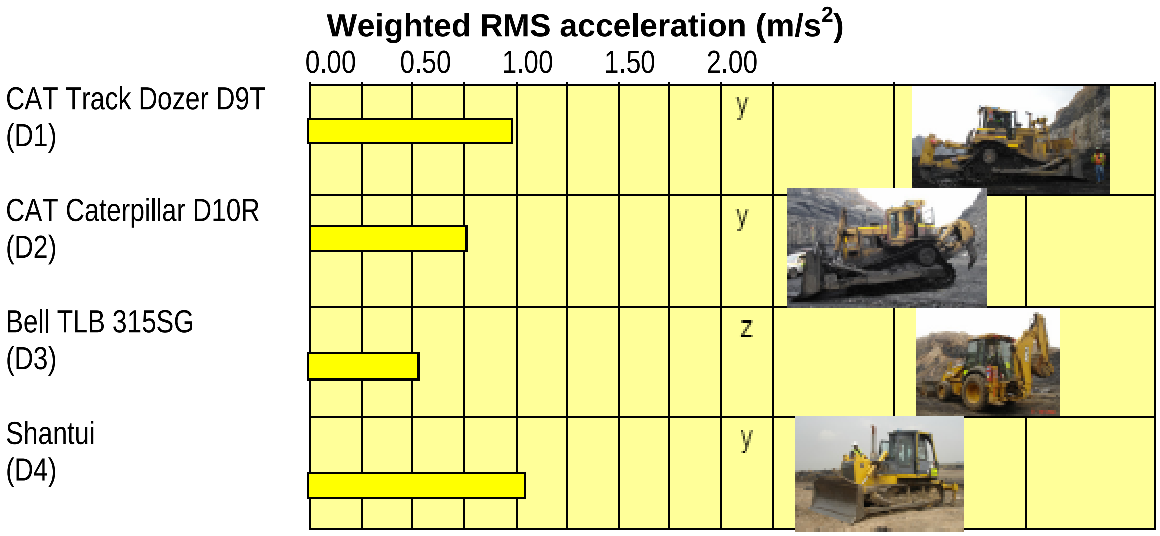


Figure 5.4: Weighted RMS acceleration magnitudes for Dozers

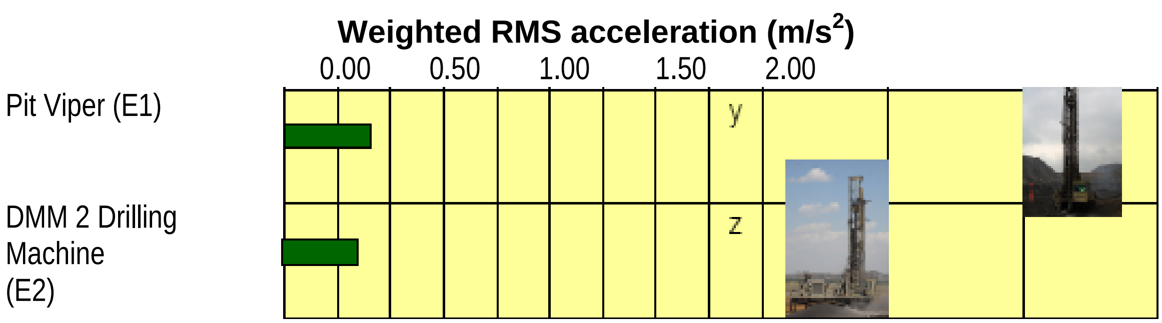


Figure 5.5: Weighted RMS acceleration magnitudes for Drills

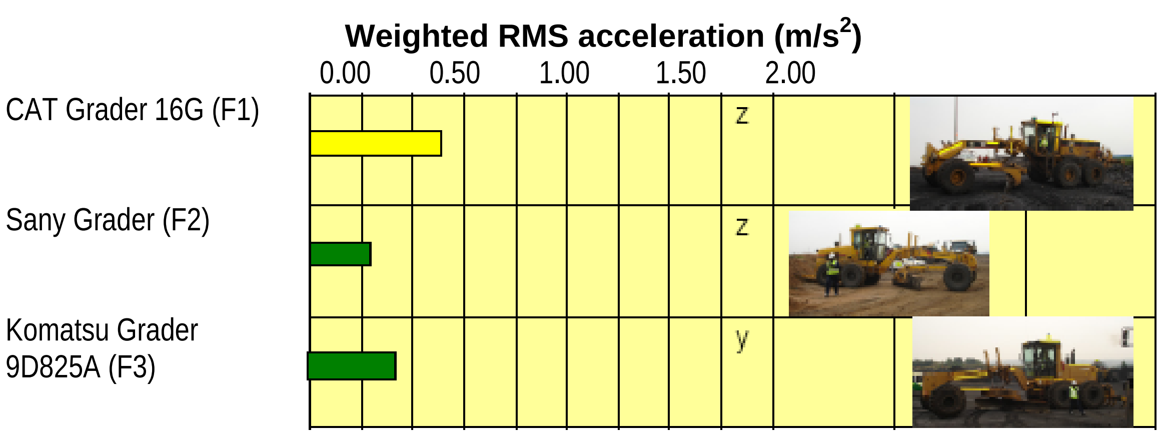


Figure 5.6: Weighted RMS acceleration magnitudes for Graders

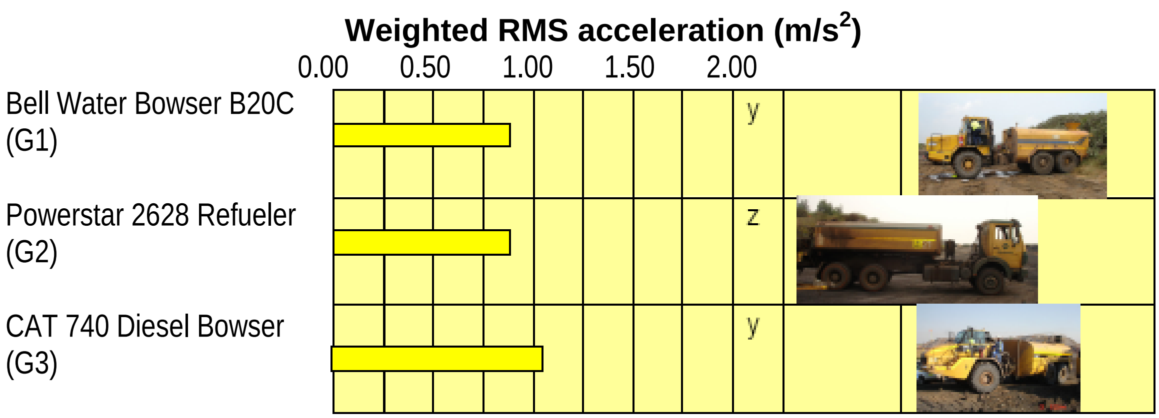


Figure 5.7: Weighted RMS acceleration magnitudes for Liquid Conveyers

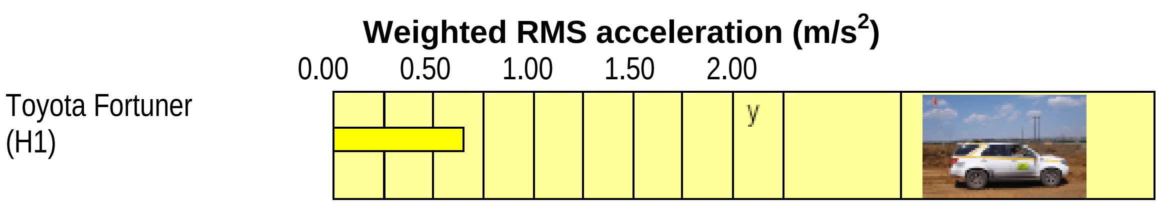


Figure 5.8: Weighted RMS acceleration magnitude for 4x4

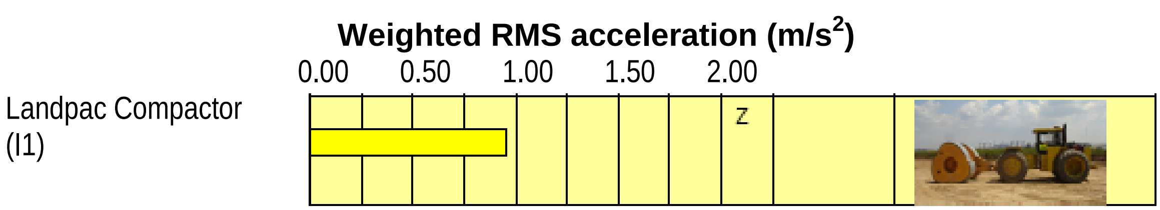


Figure 5.9: Weighted RMS acceleration magnitude for Compactor

5.2 WBV results based on ISO 2631-1 (1997) using VDV

The ISO 2631-1 (1997) standard requires that if the crest factor is higher than 9, then the vibration dose value needs to be calculated. Crest factors higher than 9 indicate the presence of shock.

Figures 5.10 to 5.18 show the summaries of the machinery whose WBV levels are either below the VDV action (HGCZ lower limit) value of 9.1 $m/s^{1.75}$ or between the VDV action and limit values of 9.1 $m/s^{1.75}$ and 21 $m/s^{1.75}$ respectively or above the VDV limit (HGCZ upper limit) values of 21 $m/s^{1.75}$. In all the following cases, reference should be made to Tables 3.20 to 3.28 for summary of operator seat vibration magnitudes and operating periods to the VDV action value and limit value.

Of the ten LHDs evaluated four had values below the HGCZ lower limit value and the remaining six had values between the HGCZ limit values. Six of the excavators had vibration values below the HGCZ whereas one excavator had a value between the HGCZ boundaries. Of the remaining equipment, seven had vibration values below the HGCZ; nine had values between the HGCZ boundaries and the remaining one had vibration values above the HGCZ.

Half the numbers of machinery/equipment have VDVs below the VDV action value. Forty seven percent of the machinery have VDVs between the VDV action and limit value. The remaining three percent of the machinery have VDVs above the VDV limit values.

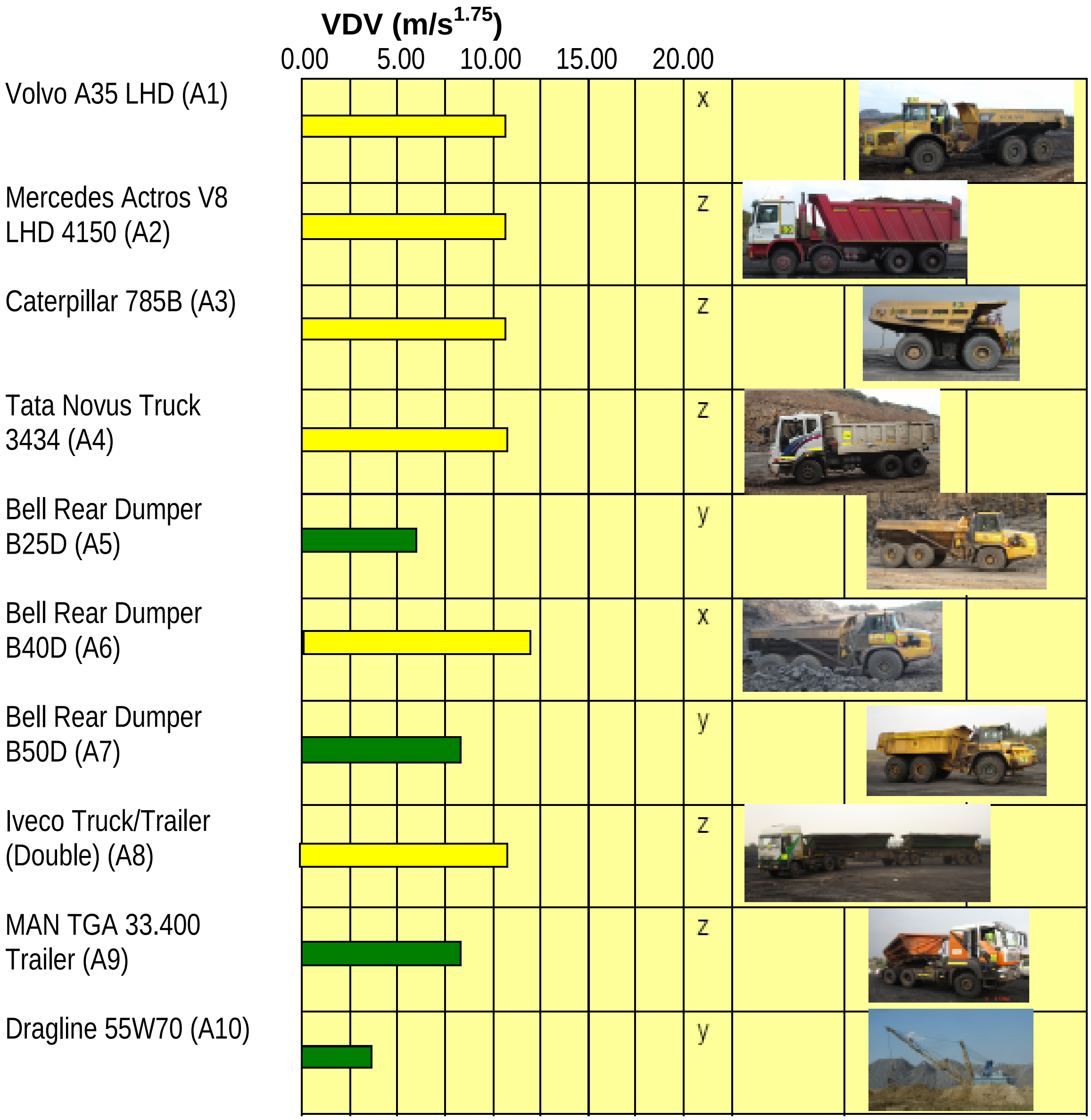


Figure 5.10: VDV magnitudes for LHDs

Values less than VDV action value

Values between VDV action and limit values

Values higher than VDV limit value

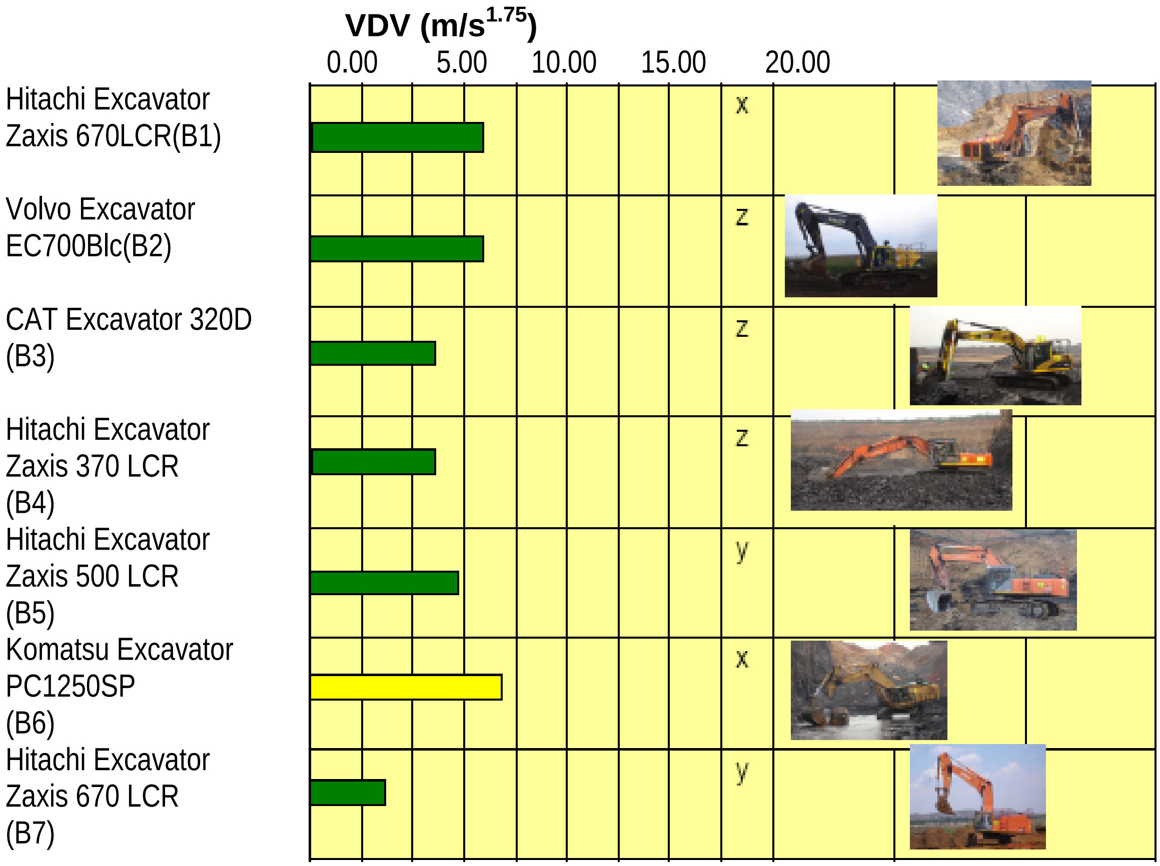


Figure 5.11: VDV magnitudes for Excavators

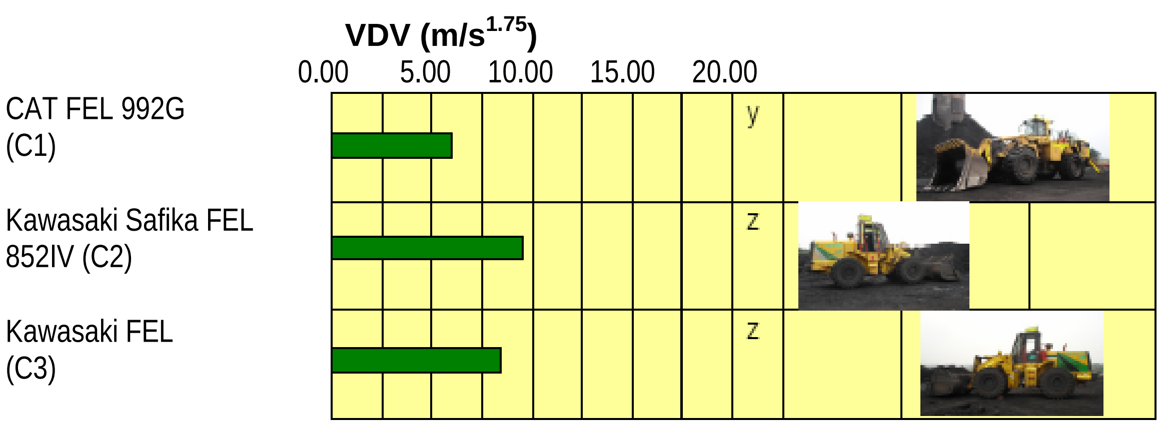


Figure 5.12: VDV magnitudes for Front End Loaders

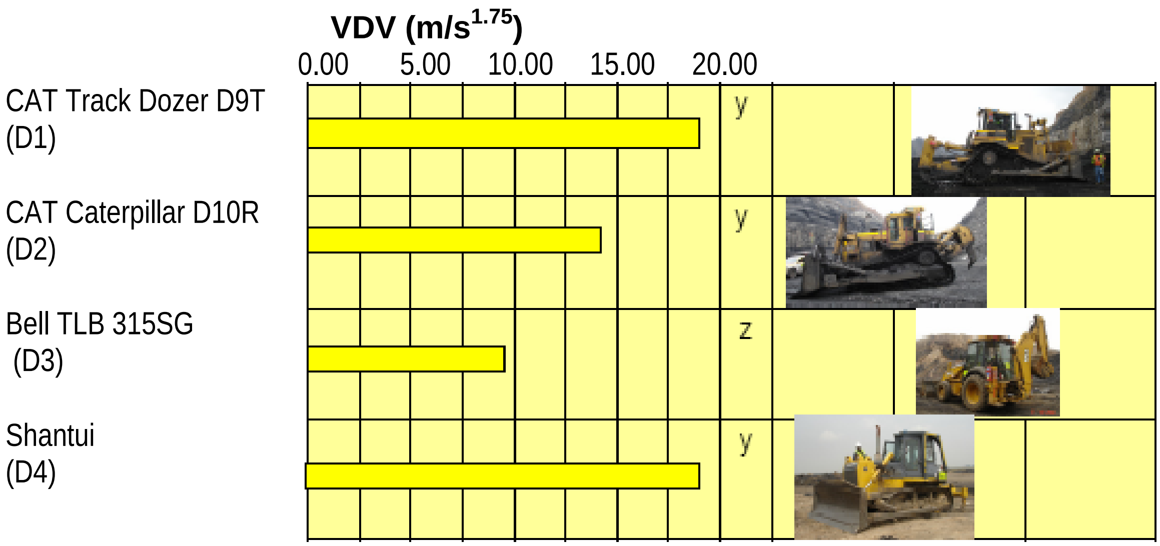


Figure 5.13: VDV magnitudes for Dozers

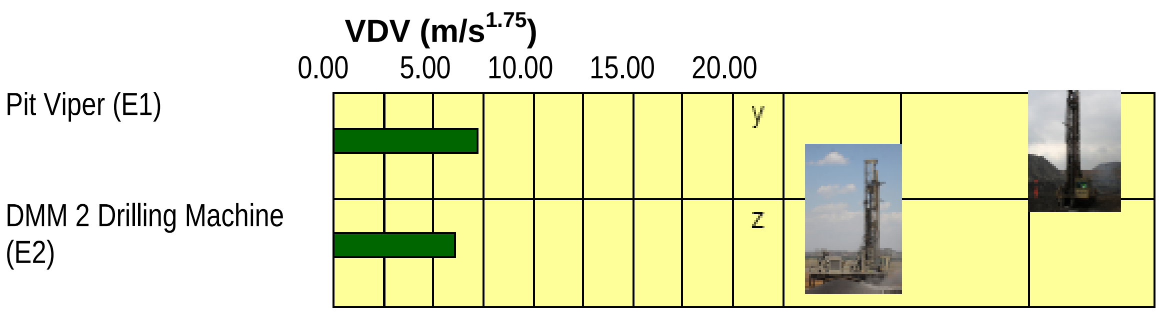


Figure 5.14: VDV magnitudes for Drills

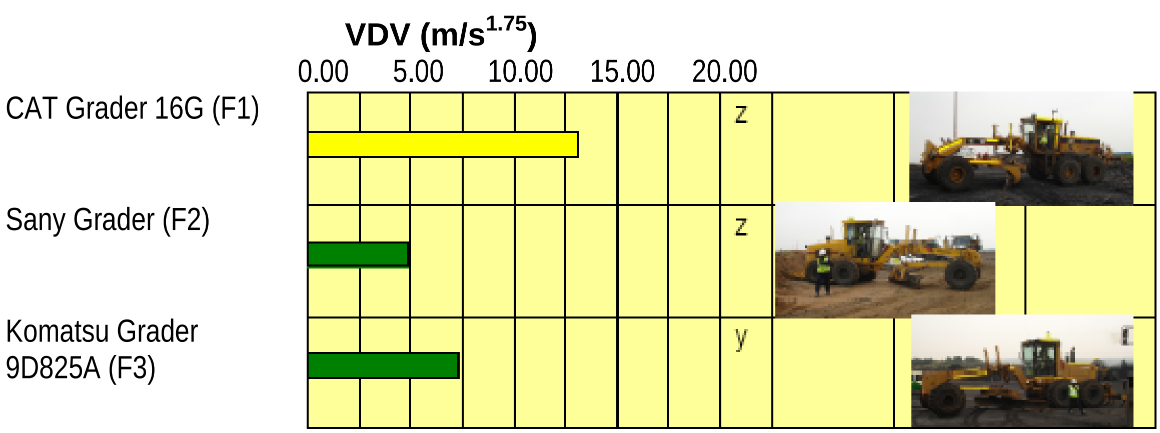


Figure 5.15: VDV magnitudes for Graders

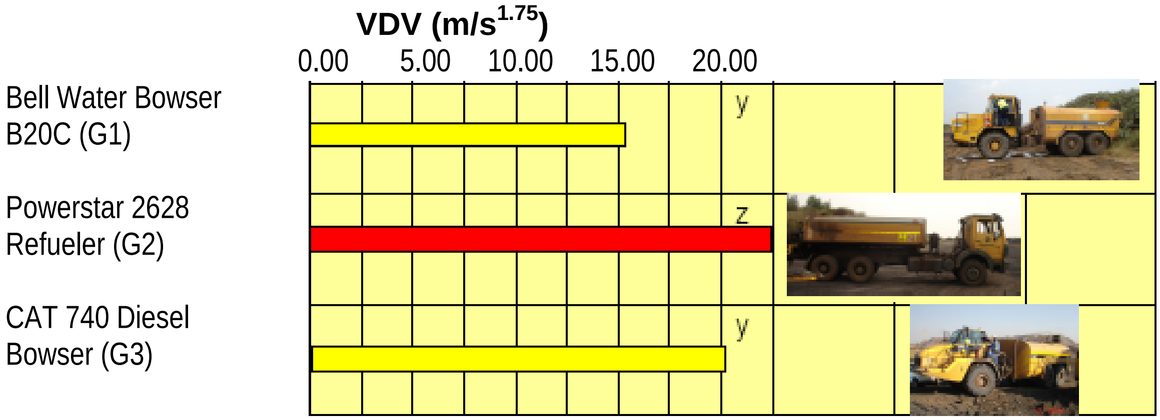


Figure 5.16: VDV magnitudes for Liquid Conveyers

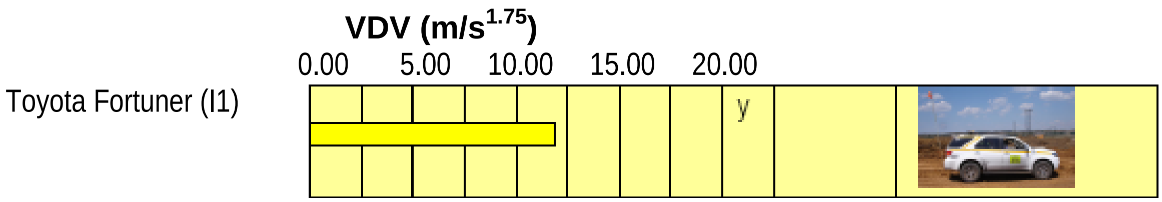


Figure 5.17: VDV magnitude for 4x4

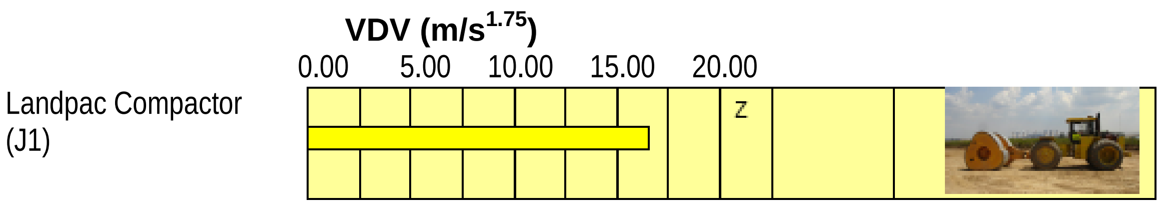


Figure 5.18: VDV magnitude for Compactor

5.3 WBV results based on ISO 2631-5 (2004) using S_{ed}

The ISO 2631-5 (2004) standard gives examples of conditions resulting in vibration containing multiple shocks to include machinery travelling over rough surfaces, small boats in rough sea, aircrafts in buffeting, presses and mechanical hammers. The machineries whose results are shown below fall in these categories.

Figures 5.19 to 5.27 show the summaries of the machinery whose WBV levels are either below the S_{ed} value of 0.5 MPa; between the S_{ed} values of 0.5 MPa and 0.8 MPa or above the S_{ed} value of 0.8 MPa.

Of the ten LHDs evaluated only one had a value below the HGCZ lower limit value and the remaining nine had values above the HGCZ upper limit value. Two of the excavators had vibration values below the HGCZ; two excavators had values between the HGCZ boundaries and three had vibration values above the HGCZ upper limit value. Of the remaining equipment, one had a vibration value below the HGCZ; two had values between the HGCZ boundaries and the remaining fourteen had vibration values above the HGCZ.

In all the following cases, reference should be made to Tables 3.29 to 3.37 for summary of operator seat vibration magnitudes and operating periods to the S_{ed} values. The graphical presentation of the lumbar response acceleration histories are presented in Appendix A-I.

About twelve percent of the numbers of machinery/equipment have S_{ed} values below 0.6 MPa which give an indication of low probability of an adverse health effect. Another twelve percent of the machinery have S_{ed} values between 0.6 MPa and 0.8 MPa give an indication of moderate probability of an adverse health effect. The remaining seventy six percent of the machinery have S_{ed} values above 0.8 MPa give an indication of high probability of an adverse health effect.

S_{ed} (MPa)

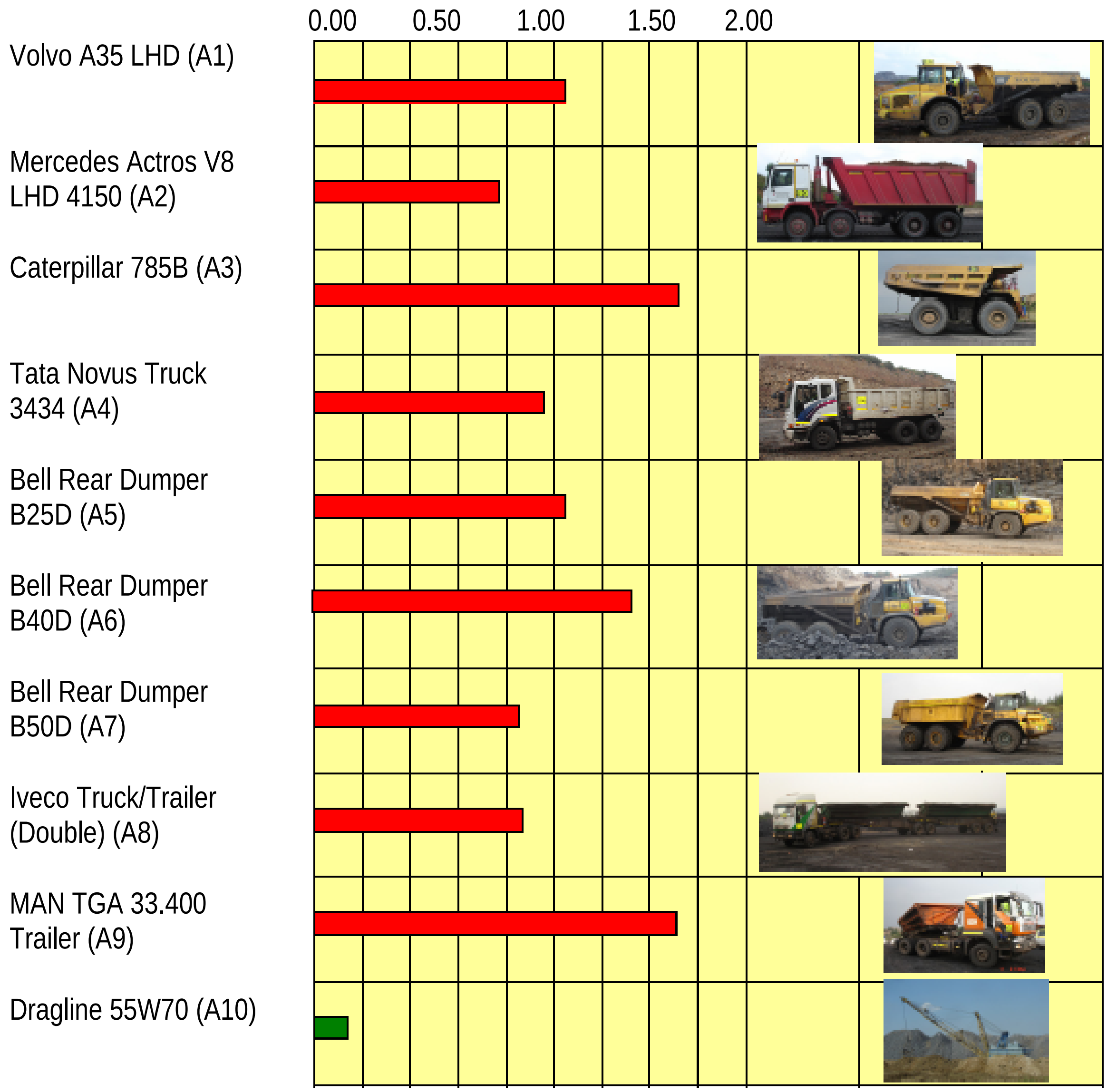
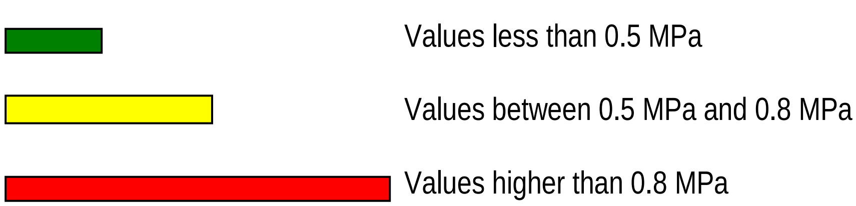


Figure 5.19: S_{ed} magnitudes for LHDs



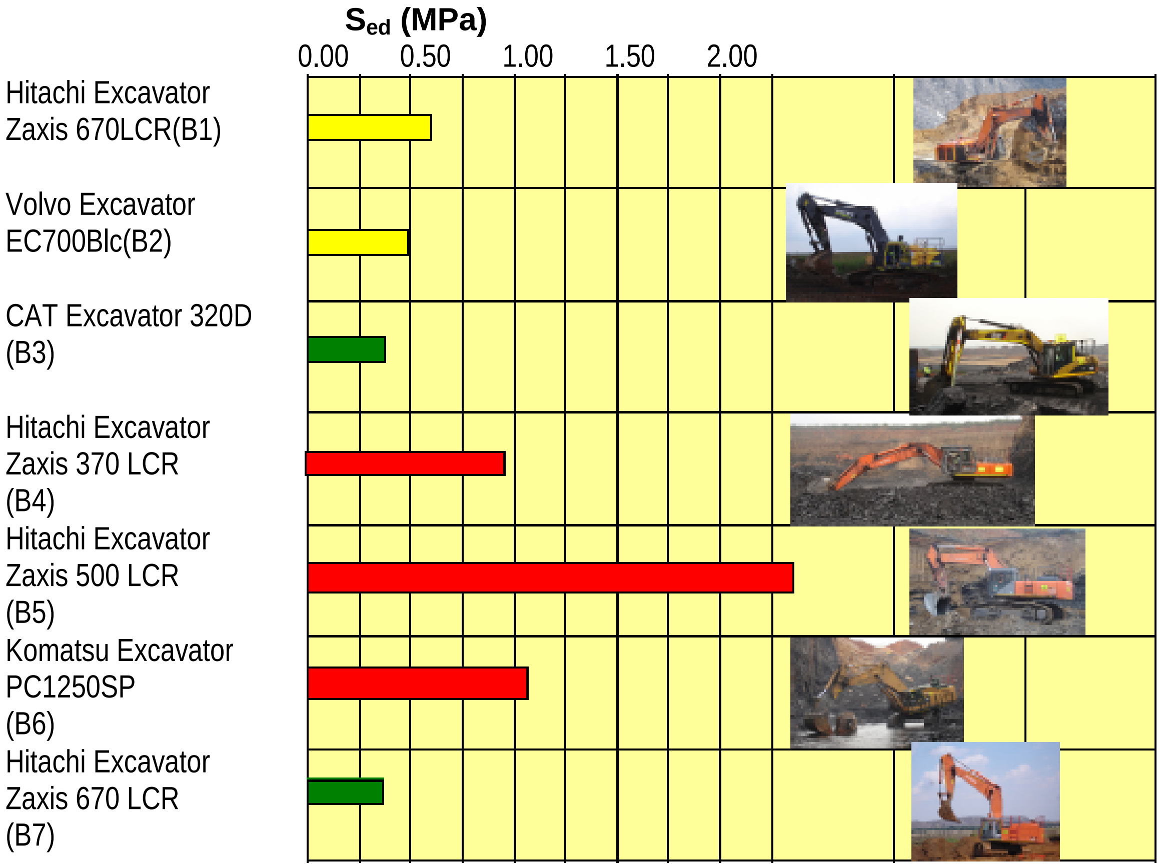


Figure 5.20: S_{ed} magnitudes for Excavators

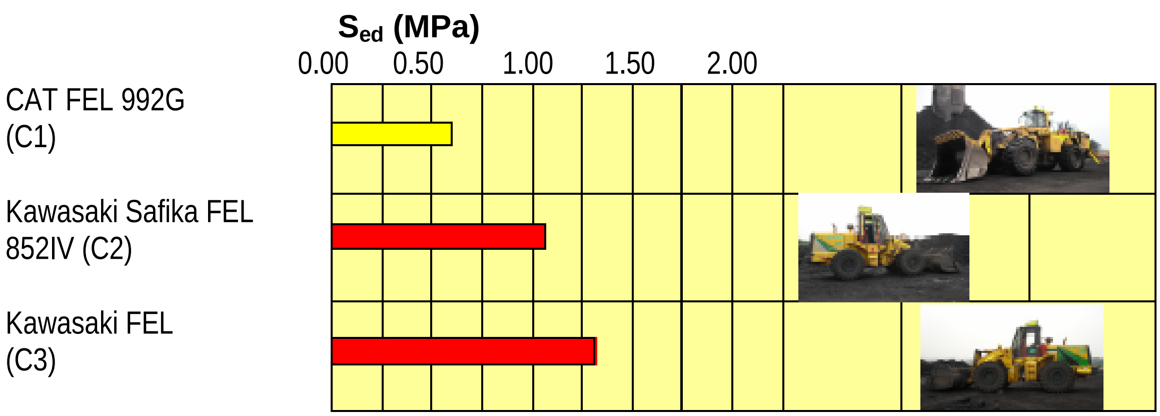


Figure 5.21: S_{ed} magnitudes for Front End Loaders

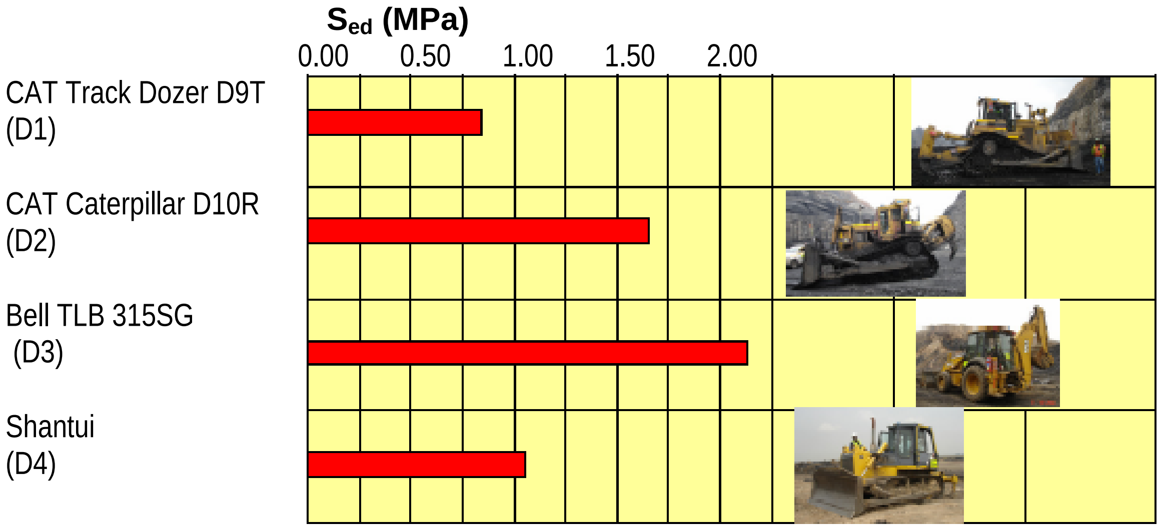


Figure 5.22: S_{ed} magnitudes for Dozers

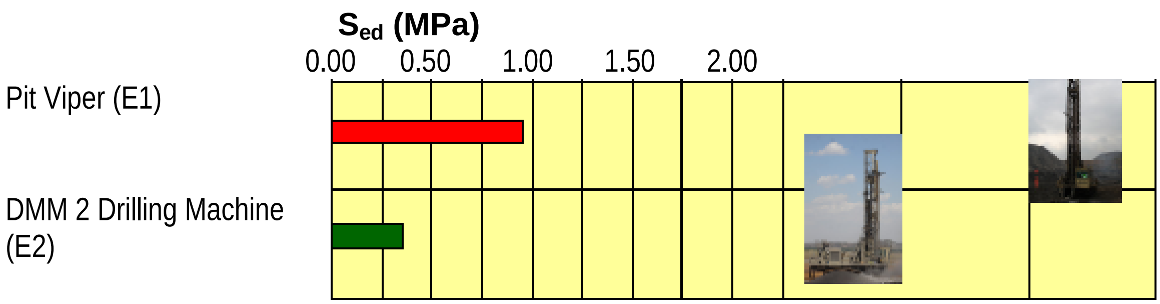


Figure 5.23: S_{ed} magnitudes for Drills

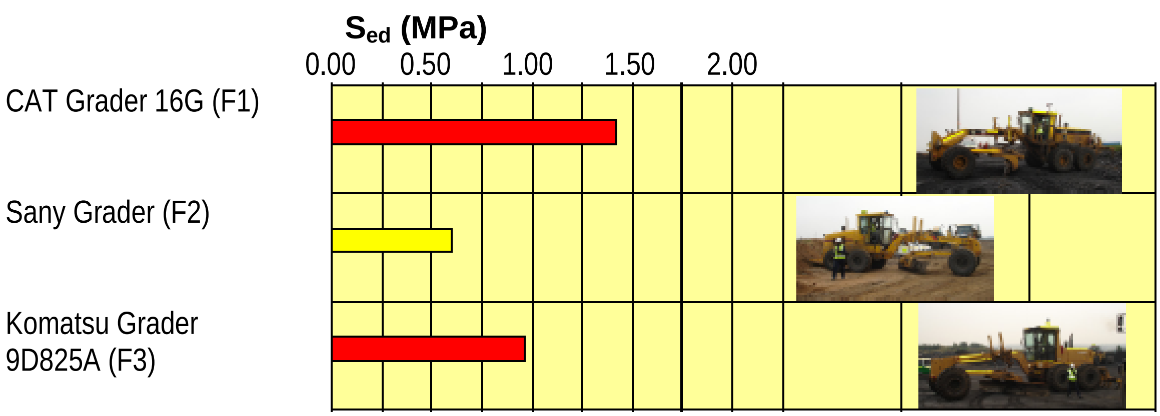


Figure 5.24: S_{ed} magnitudes for Graders

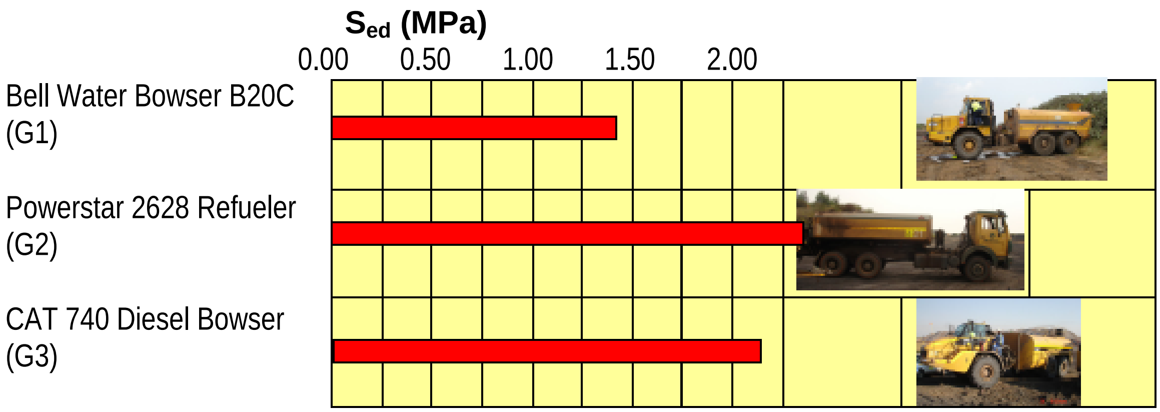


Figure 5.25: S_{ed} magnitudes for Liquid Conveyers

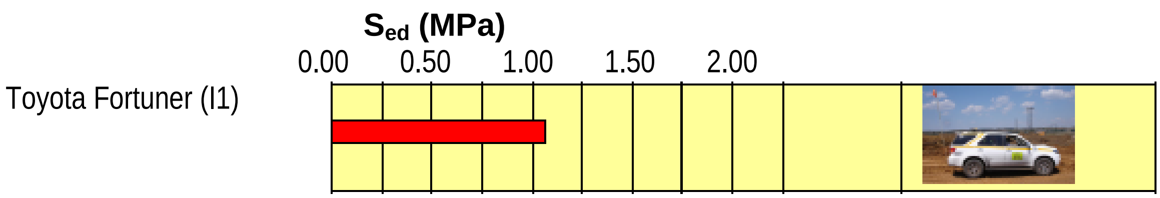


Figure 5.26: S_{ed} magnitude for 4x4

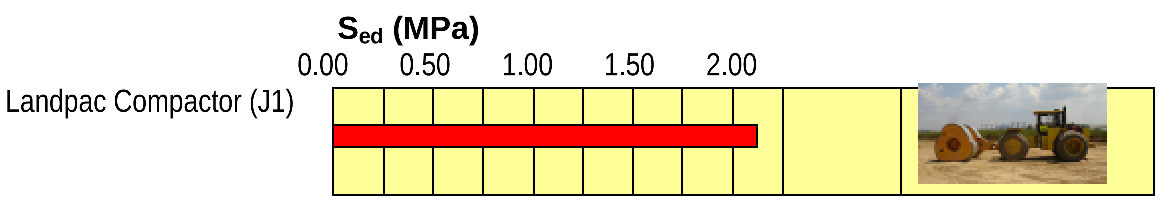


Figure 5.27: S_{ed} magnitude for Compactor

5.4 WBV results based on ISO 2631-5 (2004) using R factor

Figures 5.28 to 5.36 show the summaries of the machinery whose WBV levels are either below the R factor of 0.8 or between the R factors of 0.8 and 1.2 or above the R factor of 1.2. In all the following cases, reference should be made to Tables 3.29 to 3.37 for summary of operator seat vibration magnitudes and operating periods to the R factors.

Of the ten LHDs evaluated only one had a value below the HGCZ lower limit value and the remaining nine had values above the HGCZ upper limit value. One of the excavators had a vibration value below the HGCZ; three excavators had values between the HGCZ boundaries and three had vibration values above the HGCZ upper limit value. Of the remaining equipment, one had a vibration value below the HGCZ; two had values between the HGCZ boundaries and the remaining fourteen had vibration values above the HGCZ.

About nine percent of the numbers of machinery/equipment have R factors below 0.8 which give an indication of low probability of an adverse health effect. Another fifteen percent of the machinery have R factors between 0.8 and 1.2 give an indication of moderate probability of an adverse health effect. The remaining seventy six percent of the machinery have R factors above 1.2 give an indication of high probability of an adverse health effect.

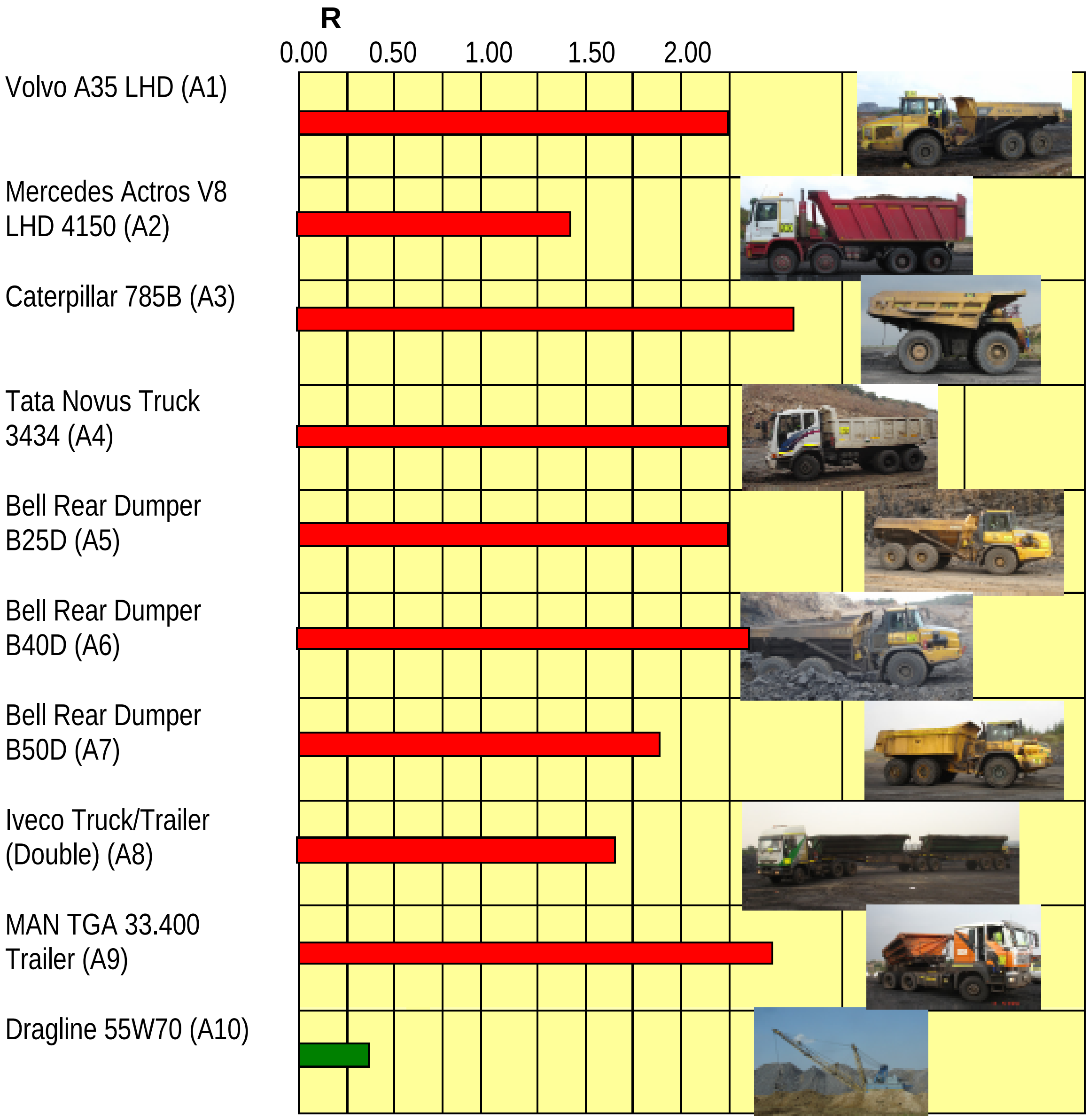


Figure 5.28: R magnitudes for LHDs

Values less than 0.8

Values between 0.8 and 1.2

Values higher than 1.2

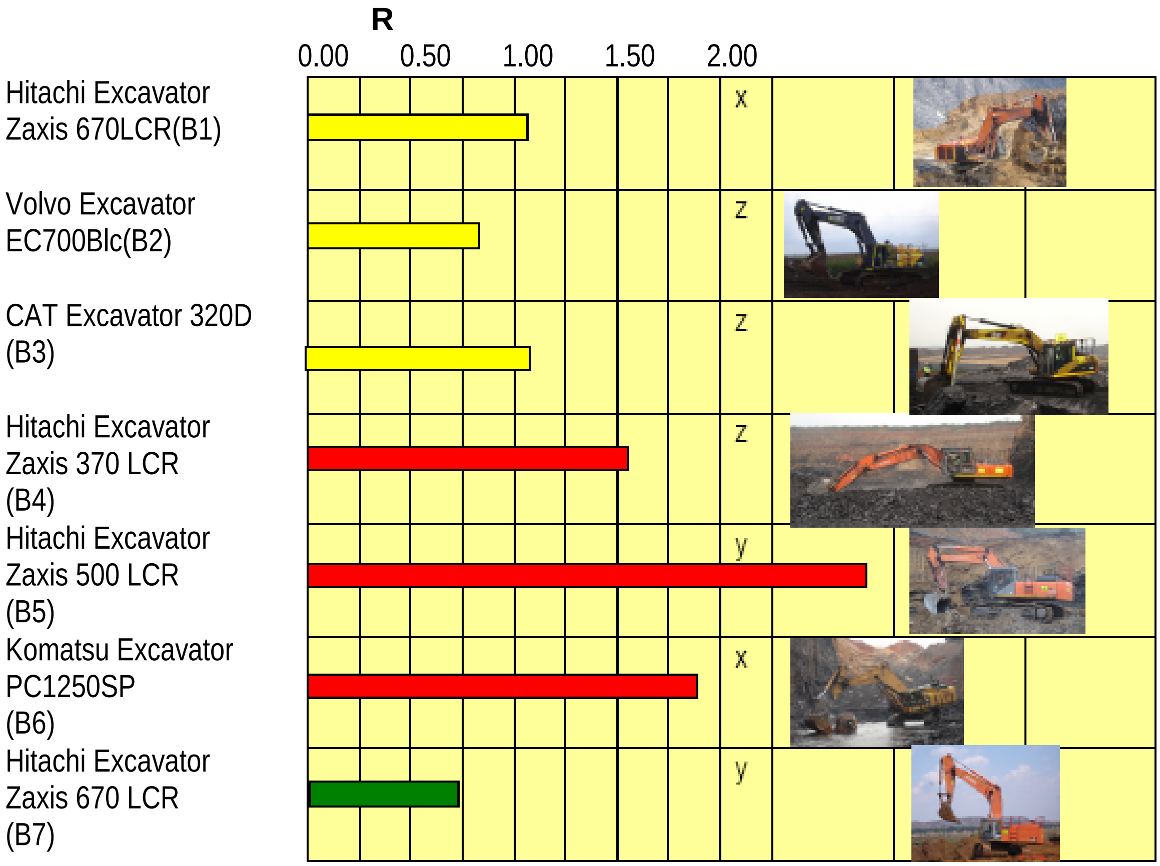


Figure 5.29: R magnitudes for Excavators

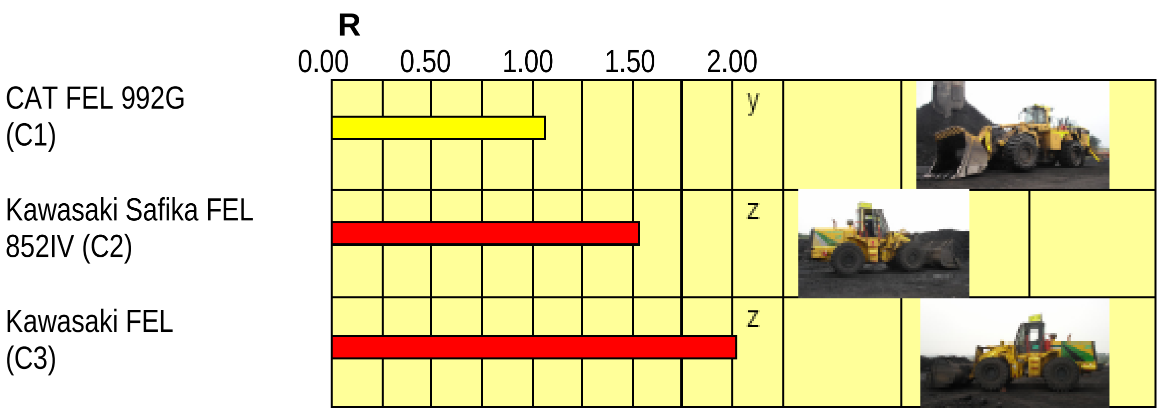


Figure 5.30: R magnitudes for Front End Loaders

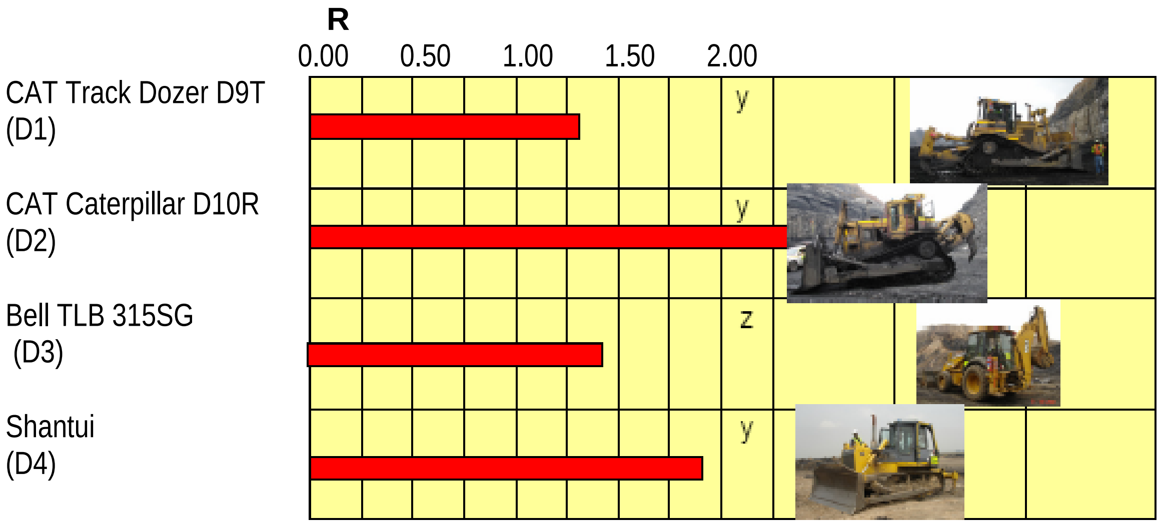


Figure 5.31: R magnitudes for Dozers

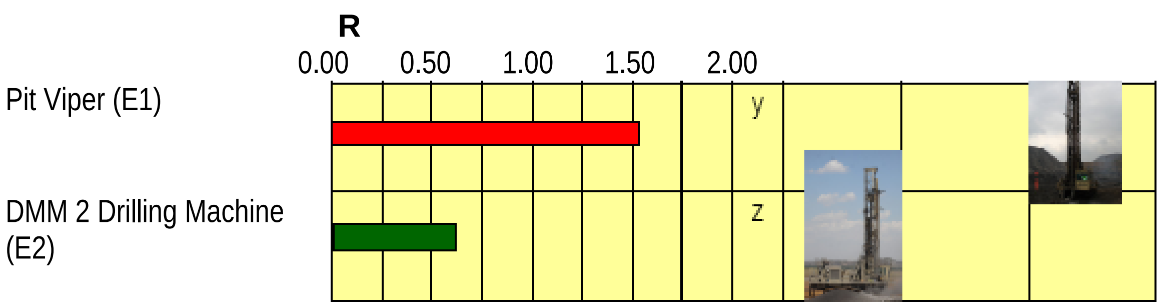


Figure 5.32: R magnitudes for Drills

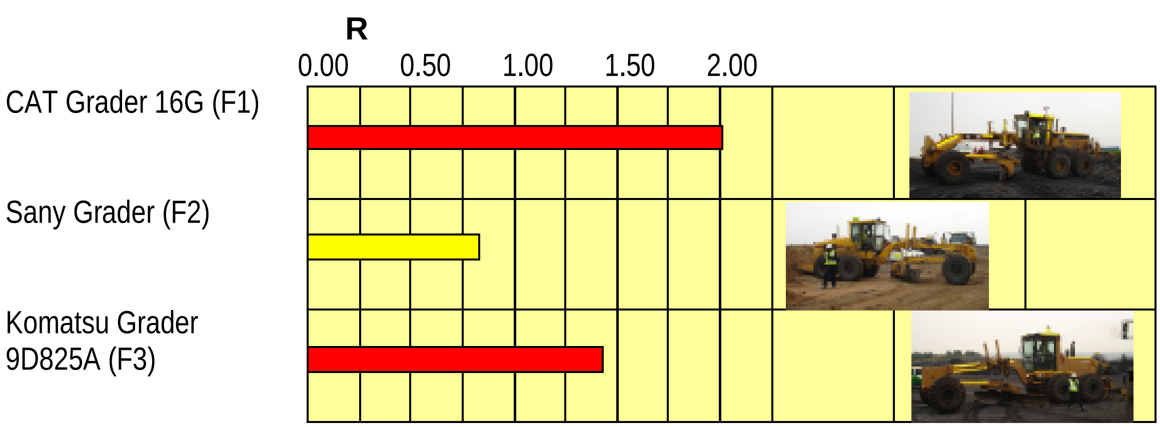


Figure 5.33: R magnitudes for Graders

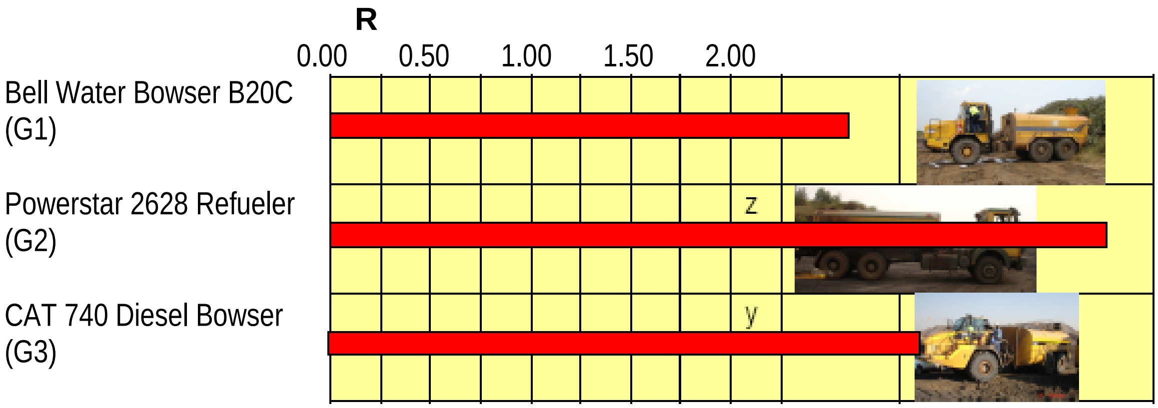


Figure 5.34: R magnitudes for Liquid Conveyers

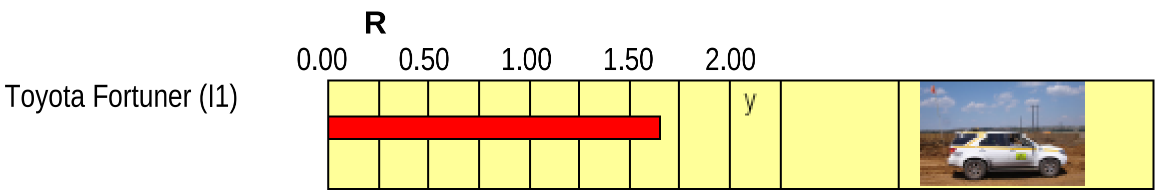


Figure 5.35: R magnitude for 4x4

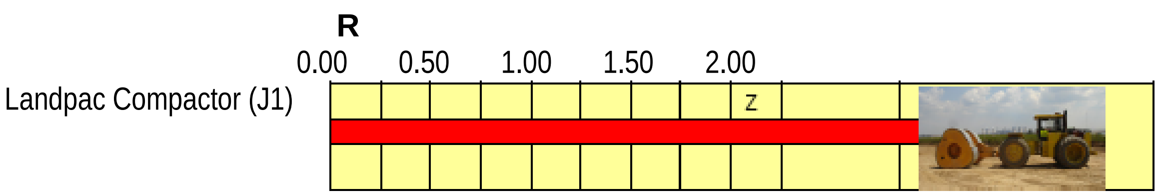


Figure 5.36: R magnitude for Compactor

5.5 Comparison of results based on ISO 2631-1 (1997) and ISO 2631-5 (2004)

It should be recalled that the ISO 2631-1 (1997) standard requires that if the crest factor is higher than 9, then the vibration dose value needs to be calculated. Crest factors higher than 9 indicate the presence of shock. However, as stated earlier, the ISO 2631-5 (2004) standard gives examples of conditions resulting in vibration containing multiple shocks. The machineries whose results are compared below fall in these categories.

$A(8)_n$ and VDV_n parameters are plotted on the x- and y- axes respectively in Figure 5.37 (a). In Figure 5.37 (b) S_{edn} and R_n factor parameters are plotted on the x- and y- axes respectively. S_{edn} and $A(8)_n$ parameters are plotted on the x- and y-axes respectively in Figure 5.37 (c). Finally, S_{edn} and R_n factor parameters are plotted on the x- and y-axes respectively in Figure 5.37 (d).

In Figure 5.37 (a) both parameters are from ISO2631-1. Since the gradient is 1 and the lower and upper HGCZ values correspond exactly, i.e. 0.43 and 1 on both axes; it is clear that the two parameters from the same standard are consistent in their health risk assessments as earlier shown Section 4.1.

Also, Figure 5.37 (b) gives two parameters from ISO2631-5. The lower HGCZ values are 0.63 and 0.67 for S_{edn} and R factor respectively. The upper HGCZ values correspond exactly at 1 on both axes. The gradient is greater than 1 even though the two parameters are from the same standard. This is because the S_{edn} is a daily value whereas the R factor is an accumulative value which is a function of S_{ed}. The R factor is an accumulative factor because it takes into account the number of days in a year and number of years of exposure for a maximum operator working life of 45 years (aged 20–65 years) as suggested by the ISO 2631-5 (2004) standard. It is therefore obvious that the two parameters from the same standard are not consistent in their health risk assessments.

Figure 5.37 (c) gives a parameter from ISO2631-1 and from ISO2631-5. The lower HGCZ values are 0.43 and 0.63 for $A(8)_n$ and S_{edn} respectively. The upper HGCZ values correspond exactly at 1 on both axes. The gradient is less than 1. Again it is evident that the two parameters from the twodifferent standards under consideration are not consistent in their health risk assessments.

Figure 5.37 (d) gives parameters from ISO2631-1 and ISO2631-5. The lower HGCZ values are 0.43 and 0.63 for VDV_n and S_{edn} respectively. The upper HGCZ values correspond exactly at 1 on both axes. The gradient is less than 1. It is clear that the two parameters from the different standards are not consistent in their health risk assessments. In spite of the inconsistency all the parameters plotted in Figures 5.37 to 5.39 are roughly proportional. According to ISO 2631-1 (1997), for events with CF greater 9 which indicate the presence of shocks, the VDV parameter should be used whereas S_{ed} is the daily parameter for assessing shock based on ISO 2631-5 (2004). Hence, VDV parameter will ultimately be compared to S_{ed} for transient shock events.

For the 10 LHDs measured, the RMS, VDV, Sed and R factor ranges are 0.10-0.81 m/s^2, 1.88-12.77 $m/s^{1.75}$, 0.28-1.90 MPa, 0.44-2.97 respectively. The minimum CF value was 5.95 and the maximum CF value was 36.90 indicating the presence of shocks. The various parameters obtained from results of analysis as tabulated in Tables 3.11, 3.20 and 3.29 are normalized and plotted in Figure 5.37. It is interesting to note that the VDV_n versus $A(8)_n$ and R_n factor versus S_{edn}, are proportional as shown in Figures 5.37 (a) and (b); however, the $A(8)_n$ versus S_{edn} and VDV_n versus S_{edn} plots are roughly proportional as shown in Figures 5.37 (c) and (d) respectively. Figures 5.37 (c) and 5.37 (d) are roughly proportional with some scatter because of the stochastic nature of the field data as can be seen in Figure 4.7 of Section 4.6. All the plotted values are below the unity slope line with a slope less than 1 corresponding to the high or significant shock content situation meaning S_{ed} predicts higher risk to health as earlier obtained in Section 4.6. It is clearly seen that health risk prediction based on the

VDVs is less conservative than that based on the S_{ed} values in Figure 5.37 (d) in the presence of shocks. This is consistent with findings by Alem et al. (2004) and Chen et al. (2009) who obtained higher predictions of the risk based on the S_{ed} values than on VDVs in the presence high impacts or shocks.

Some studies had earlier carried out health risk prediction prior to this study. Johanning et al. (2006) reported higher predicted risks based on ISO 2631-1 (1997) variables than ISO 2631-5 (2004) variables for 20 locomotive operators. Cooperrider and Gordon (2008) also reported higher risks for locomotive operators, based on VDVs from an ISO 2631-1 (1997) analysis when compared to S_{ed} values from an ISO 2631-5 (2004) analysis. In their study, four locomotive operators had VDVs that placed them within the HGCZ (for an 8-h working shift); however, all the S_{ed} values were below the boundary for low probability of adverse health effects. Another study by Eger et al. (2008) in the operation of mining vehicles equally found that the risk indicated by values obtained by using ISO 2631-1 (1997) was higher than that based on ISO 2631-5 (2004). This was because of the presence of low shock or impact as opposed to our study which was carried in a high shock environment. Their studies had crest factors above nine which indicted the presence of shocks. However, this was because the impacts were high relative to the lower values of WRMS obtained from the data since crest factor is a ratio of the highest impact magnitude to the WRMS. When the shocks are low this could still lead to lower values of S_{ed} which led to the prediction of lower risk to health based on ISO 2631-5 (2004) in such low shock environments.

The 7 excavators measured had WRMS, VDV, S_{ed} and R factor in the ranges of 0.18-0.51 m/s^2, 3.24-9.25 $m/s^{1.75}$, 0.42-2.32 MPa and 0.76-3.62 respectively. The minimum CF value was 10.29 and the maximum CF value was 55.22. For the other 15 machinery, which include front end loaders, dozers, drills, graders, liquid conveyors, 4x4 and compactor, the RMS, VDV, S_{ed} and R factor ranges are 0.19-1.12 m/s^2, 3.42-25.68 $m/s^{1.75}$, 0.40-11.30 MPa, 0.63-17.68 respectively. The minimum CF value was 6.00 and the maximum CF value was 23.78 indicating the presence of high shock for both excavators and other machinery. The data for the excavators and the other machinery as tabulated in Tables 3.12, 3.21 and 3.30 and Tables 3.13-3.19, 3.22-3.28 and 3.31-3.37 respectively are also normalized and subsequently plotted in Figures 5.38 and 5.39 respectively. Again, the $A(8)_n$ versus S_{edn} and VDV_n versus S_{edn} plots are roughly proportional with some scatter because of the stochastic nature of the field data as shown in Figures 5.38 (c) and (d) and Figures 5.39 (c) and (d) for the excavators and other machinery respectively. All the plotted values are below the unity slope line with a slope less than 1 corresponding to the high or significant shock content situation as earlier demonstrated in Section 4.6. The health risk prediction based on the VDVs is less conservative than that based on the S_{ed} values as shown in Figure 5.38 (d) and 5.39 (d) in the presence of shocks for all the equipment. Also, in Figures 5.38 (c) and (d) and Figures 5.39 (c) and (d) it is evidently clear that there is a very large offset i.e. the graph no longer goes through 0. This is due to the presence of transient shocks which leads to a gradient less than 1 as similarly illustrated in Figure 4.4 (c) and (d) of Section 4.3.

When using ISO 2631-1 (1997) it can be seen that over ninety five percent of the machinery fall within or below the health guidance caution zone (HGCZ) indicating less risk to occupational hazard as shown in Figures 5.37 (a) to 5.39 (a). However, when ISO 2631-5 (2004) is used it can be seen that over seventy percent of the machinery fall above the HGCZ indicating a high probability to risk due to occupational hazard as shown in Figures 5.37 (d) to 5.39 (d). It can therefore be stated that health risk assessment based on S_{ed} parameter of ISO 2631-5 (2004) standard is more conservative than risk assessment based on the VDV of the ISO 2631-1 (1997) standard in the presence of shocks. This is due to the fact that the ISO 2631-5 (2004) standard takes into account the transient and high magnitude shock events which are handled better than the ISO 2631-1 (1997) standard.

5.6 Summary

The parameters (VDV and S_{ed}) corresponding to the two ISO 2631-1 (1997) and ISO 2631-5 (2004) standard methodologies were compared to see if the same trend obtained from the numerically obtained sinusoidal signals could be validated. It was found that there was approximate correlation between the plots of values obtained for each set of machinery and the numerically generated values. For each set of machinery, there was a band correlation between the VDV and S_{ed} parameters with all values below the unity slope line and with gradients less than one indicating the presence of transient shocks as shown in Figures 5.37 (d), 5.38 (d) and 5.39 (d) for LHDs, excavators and other machinery respectively. The gradual slope band graphs with gradients less than one corresponded to high shock content thereby validating the numerical findings. In the study, the two parameters from the different standards are not consistent in their health risk assessments as the assessment based on S_{ed} values are more conservative than those based on the VDVs.

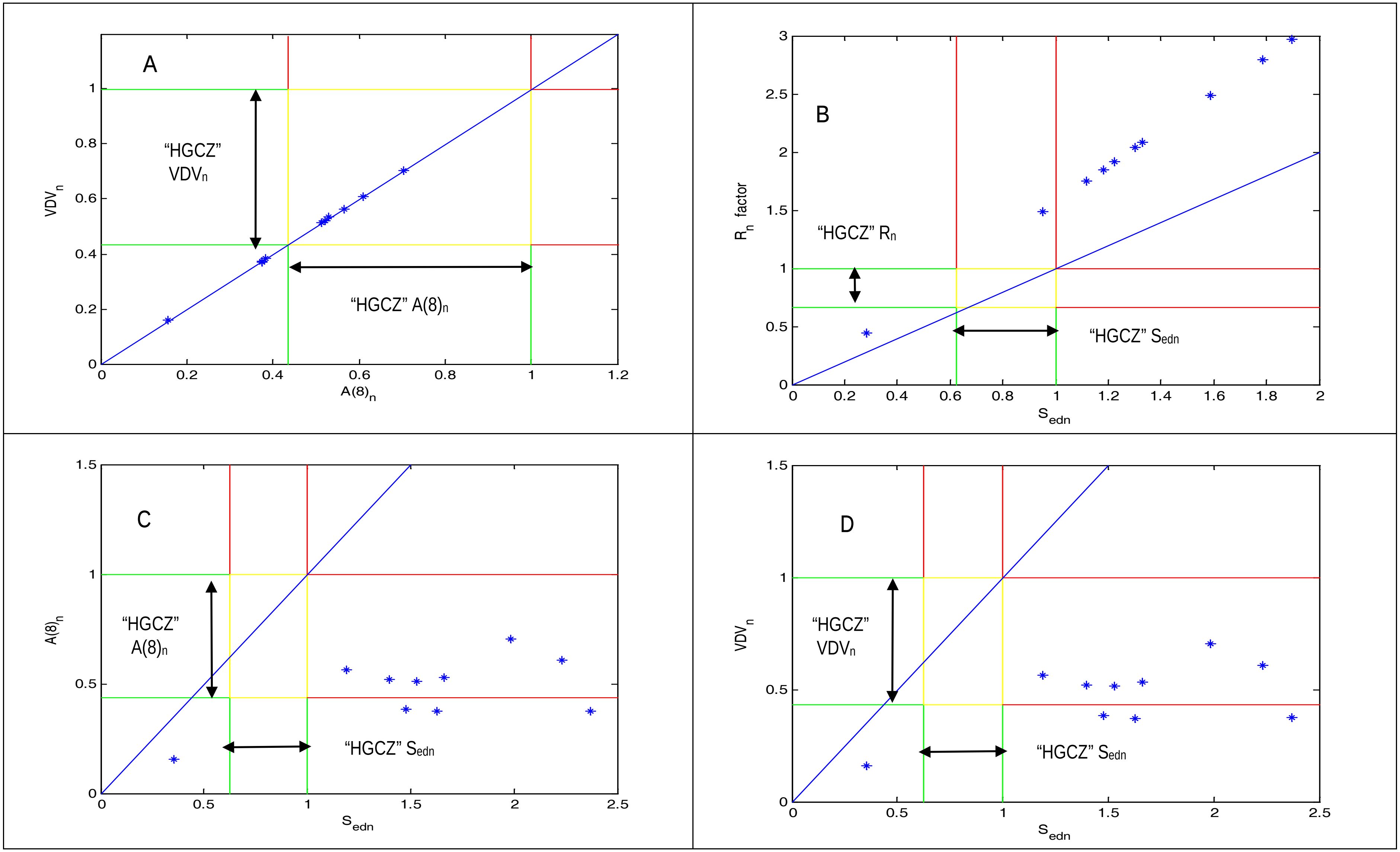


Figure 5.37: **Relationship between health predicted by (a) VDV_nversus $A(8)_n$ values, (b) R_n factor versus S_{edn} values, (c) $A(8)_n$ versus S_{edn} values and (d) VDV_n versus S_{edn} values for LHDs. The associated HGCZ are also indicated in the figures.**

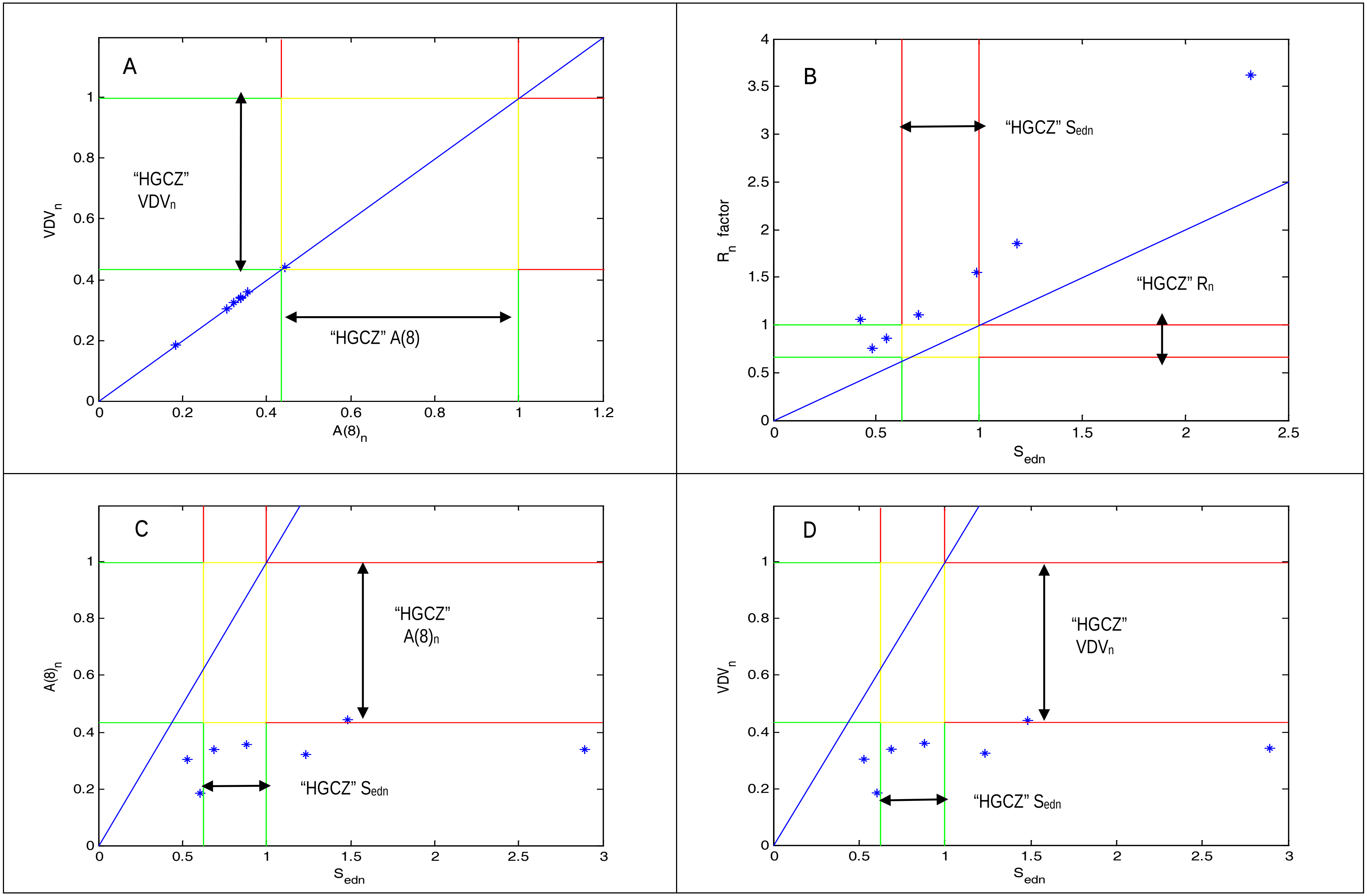


Figure 5.38: **Relationship between health predicted by (a) VDV_n versus $A(8)_n$ values, (b) R_n factor versus S_{edn} values, (c) A(8) versus S_{edn} values and (d) VDV_n versus S_{edn} values for Excavators. The associated HGCZ are also indicated in the figures.**

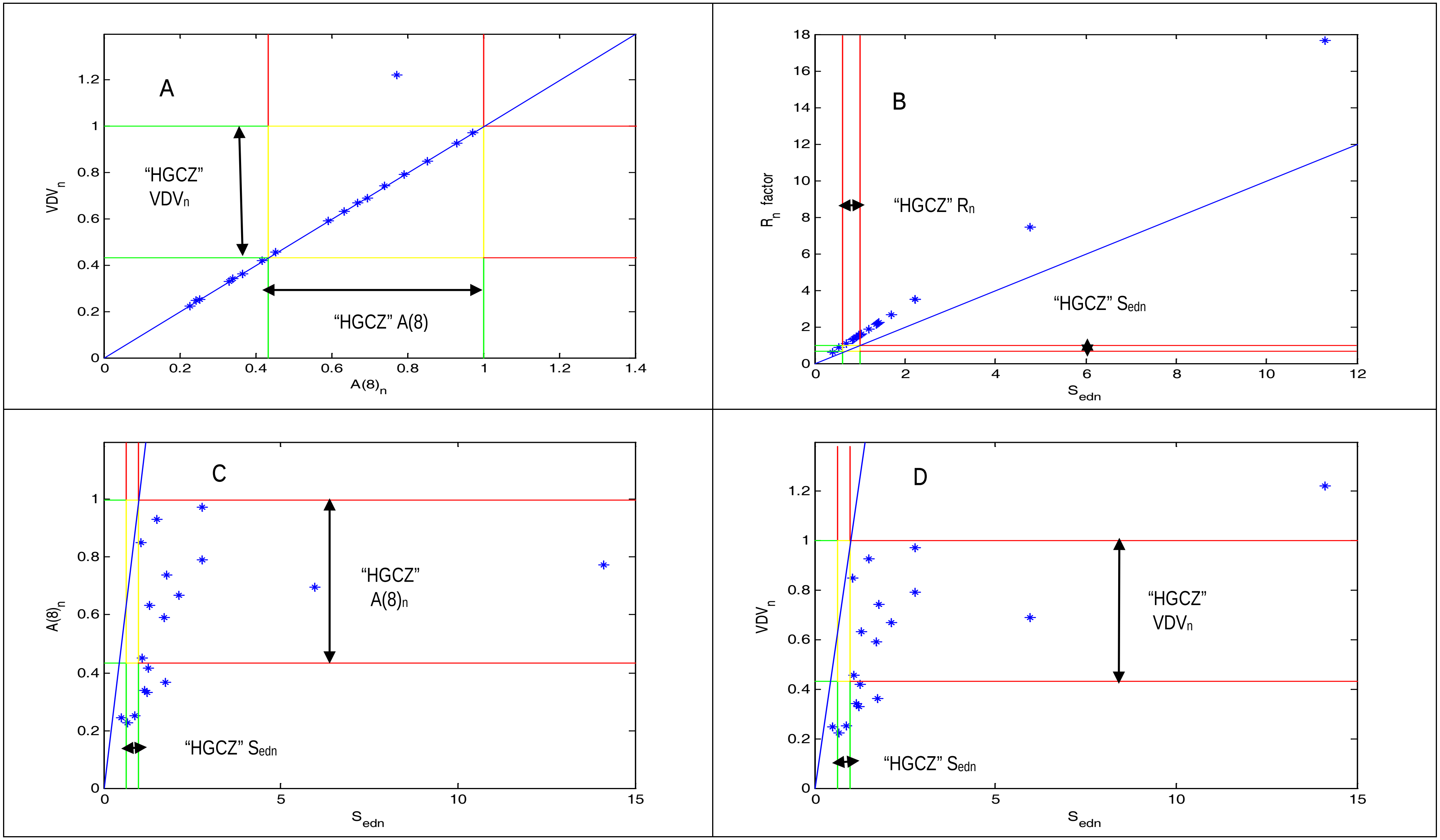


Figure 5.39: **Relationship between health predicted by (a) VDV$_n$ versus A(8)$_n$ values, (b) R$_n$ factor versus S$_{edn}$ values, (c) A(8)$_n$ versus S$_{edn}$ values and (d) VDV$_n$ versus S$_{edn}$ values for the other equipment. The associated HGCZ are also indicated in the figures.**

6. Conclusions and recommendations

6.1 Conclusions

Two methods have been used to evaluate the whole-body vibration on a wide range of equipment in an open cast mine. There are two main parameters for each of the standards. The ISO 2631-1 (1997) standard bases evaluation on the parameters A(8) and VDV, whereas the new ISO 2631-5 (2004) standard methodology uses the parameters S_{ed} and R.

The trends in each of the parameters of the ISO 2631-1 (1997) and ISO 2631-5 (2004) standard methodologies corresponding to each of the standards were monitored using various scenarios obtained by varying the signal characteristics of the simulated sinusoidal signal data and compared against each other. The S_{ed} and VDV parameters were plotted on the x- and y-axes respectively. There was approximate proportional correlation between the two parameters (VDV and S_{ed}) with varying degrees of slope for each scenario. The graphs with plotted values above the unity slope line and slope greater than 1 corresponded to signals with low or no shock content meaning that VDV predicts risk; whereas the graphs with plotted values below the unity slope line and slope less than 1 corresponded to high shock content meaning that S_{ed} predicts risk.

Experimental data was obtained from the mine on different set of machineries. The parameters of interest from ISO 2631-1 (1997) and ISO 2631-5 (2004) standard methodologies were computed and tabulated for each set of machinery for further analysis. The parameters (VDV and S_{ed}) corresponding to the two standard methodologies were compared to see if the same trend obtained from the numerically obtained sinusoidal signals could be validated. It was found that there was a rough proportional correlation with a slope less than 1 between the VDV and S_{ed} parameters corresponding to signals of high shock content thereby validating the numerical findings.

6.2 Recommendations

Various epidemiological studies have been carried out on the ISO 2631-1 (1997) with respect to normal vibration with no shock (WRMS) or low shock (VDV) content which has led to exposure action and limit values been determined and being generally accepted for these two parameters respectively. However, few or no extensive epidemiological studies have been carried using the new methodology in South Africa. It is therefore recommended that more epidemiological studies be done to determine the generally acceptable exposure action and exposure limit values with respect to shocks in the S_{ed} and R factor parameters for the new ISO 2631-5 (2004) standard methodology. In addition, the old data for the previous epidemiological studies could be reinterpreted in terms of the new standard.

In the meantime, caution should be taking when using the new ISO 2631-5 (2004) standard methodology in evaluating vibration measurements. It is suggested that the new standard be used along with the established ISO 2631-1 (1997) standard methodology.

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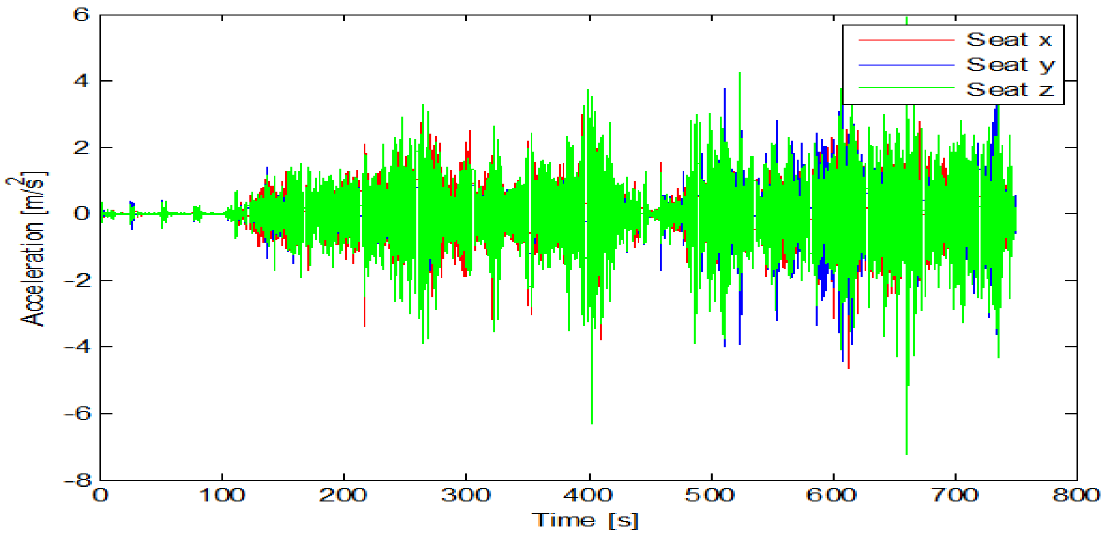
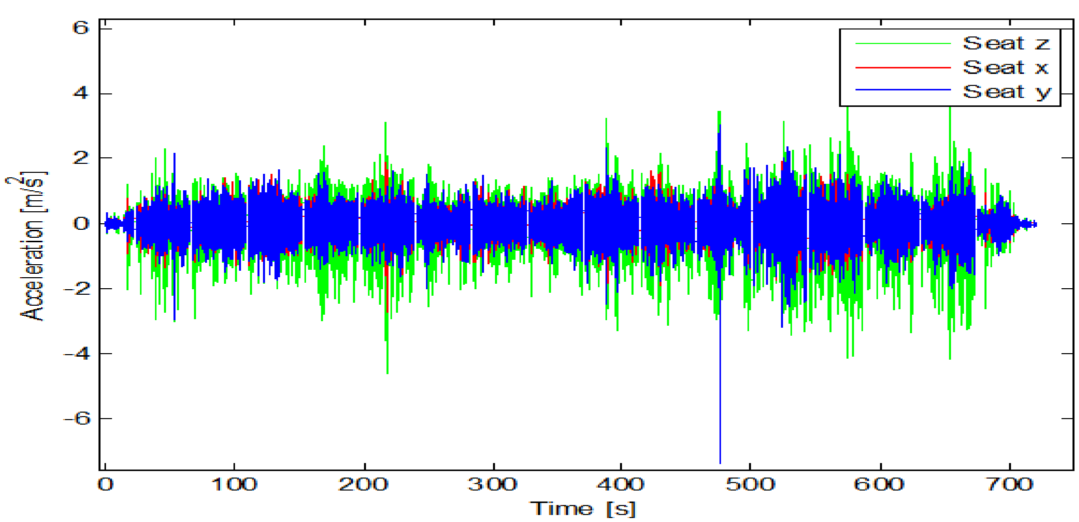
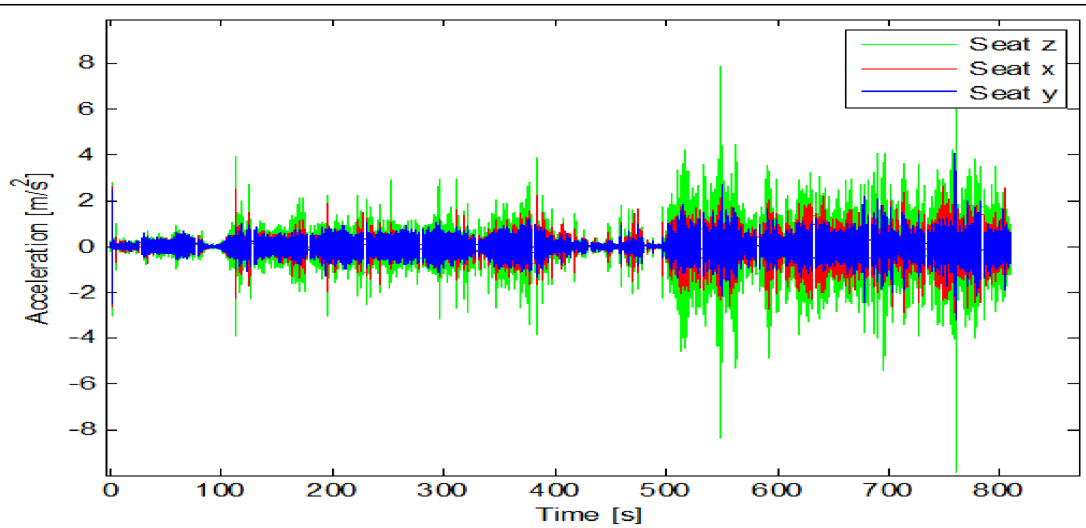
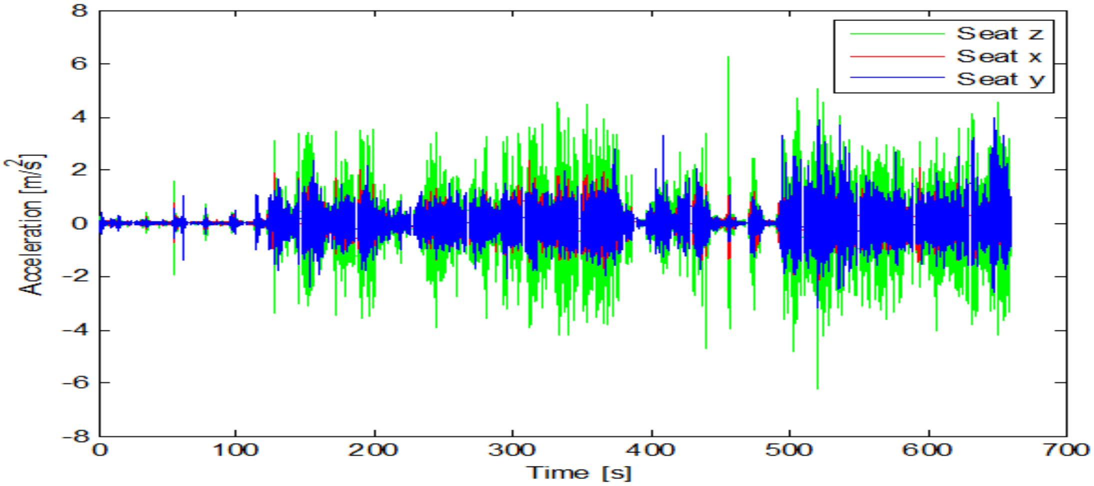
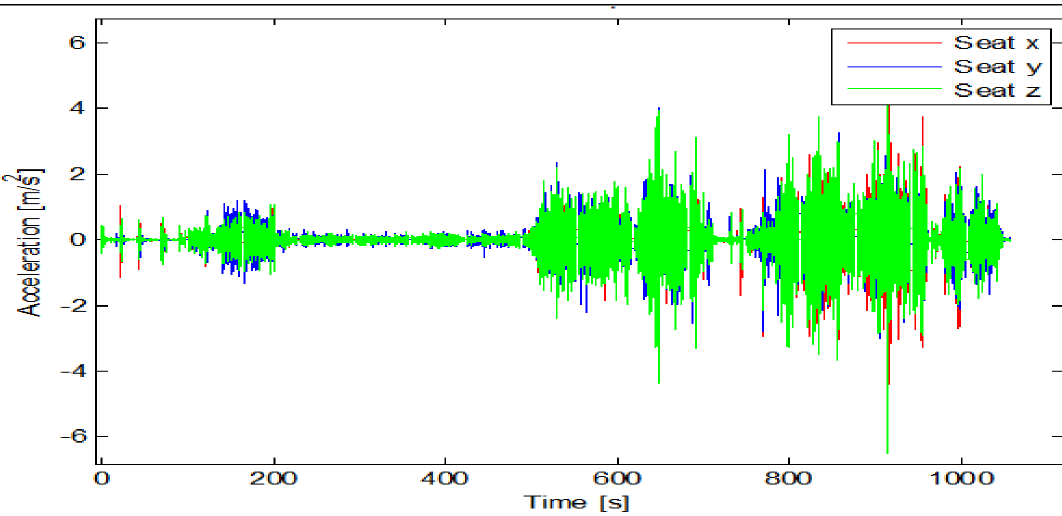
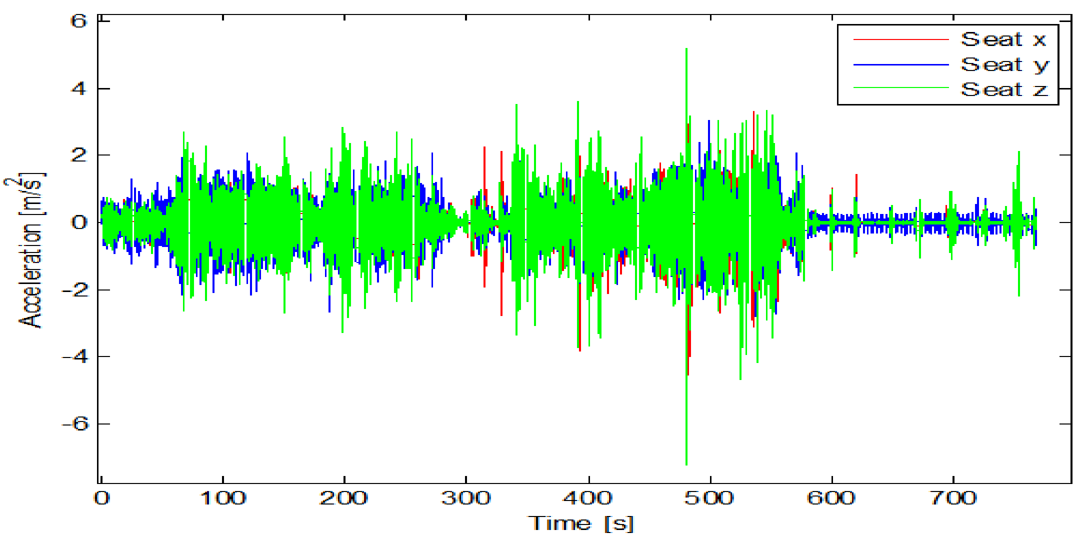
Appendices

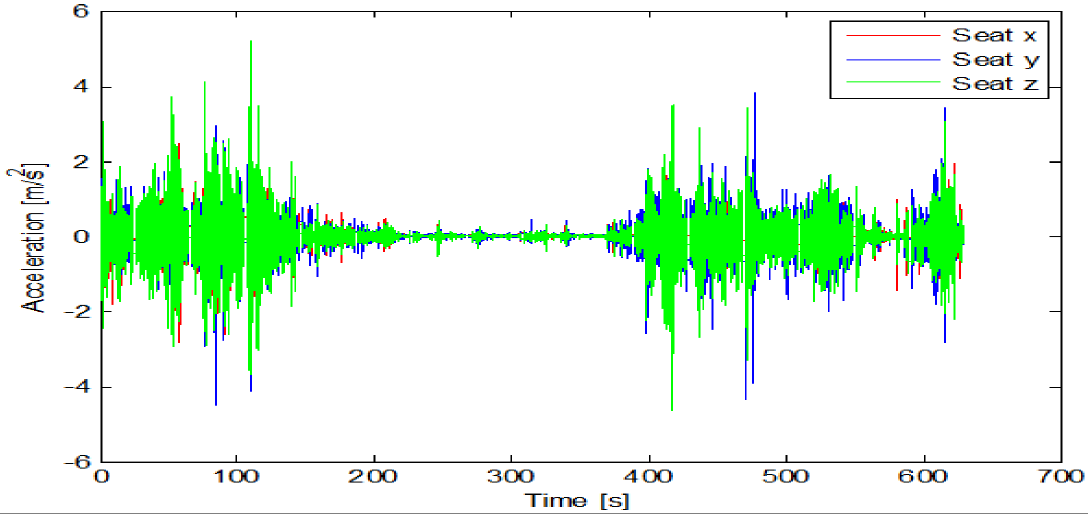
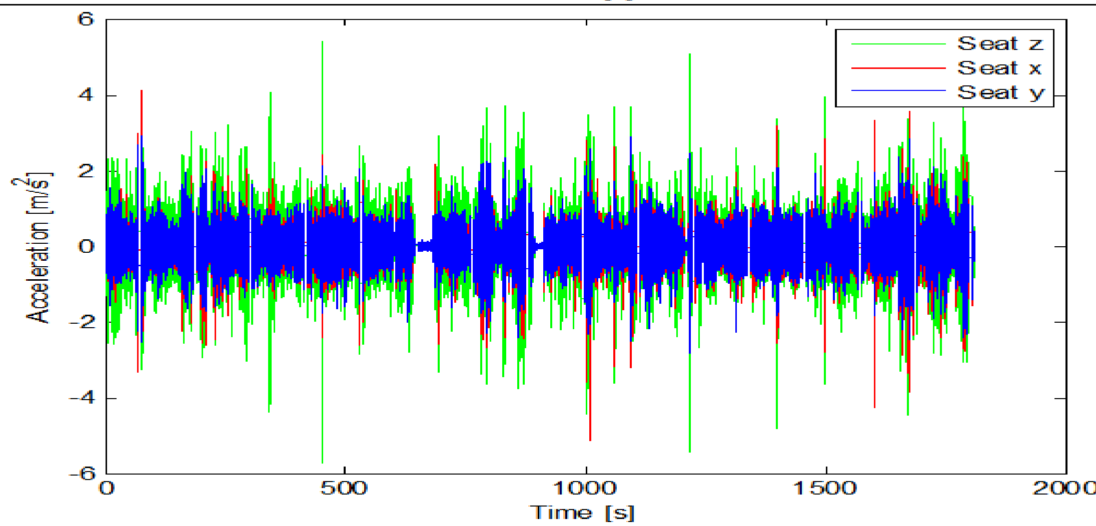
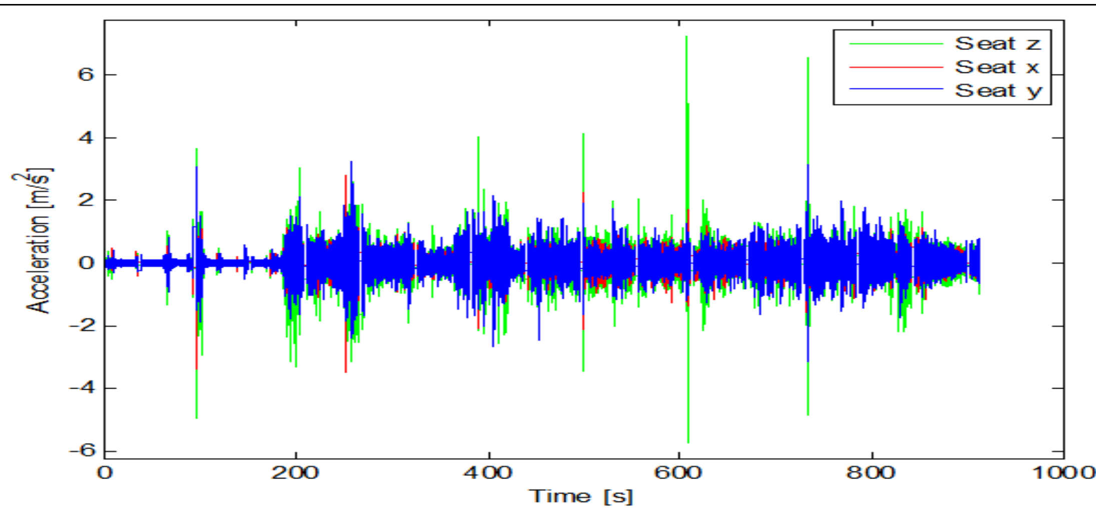
Appendices A-J:

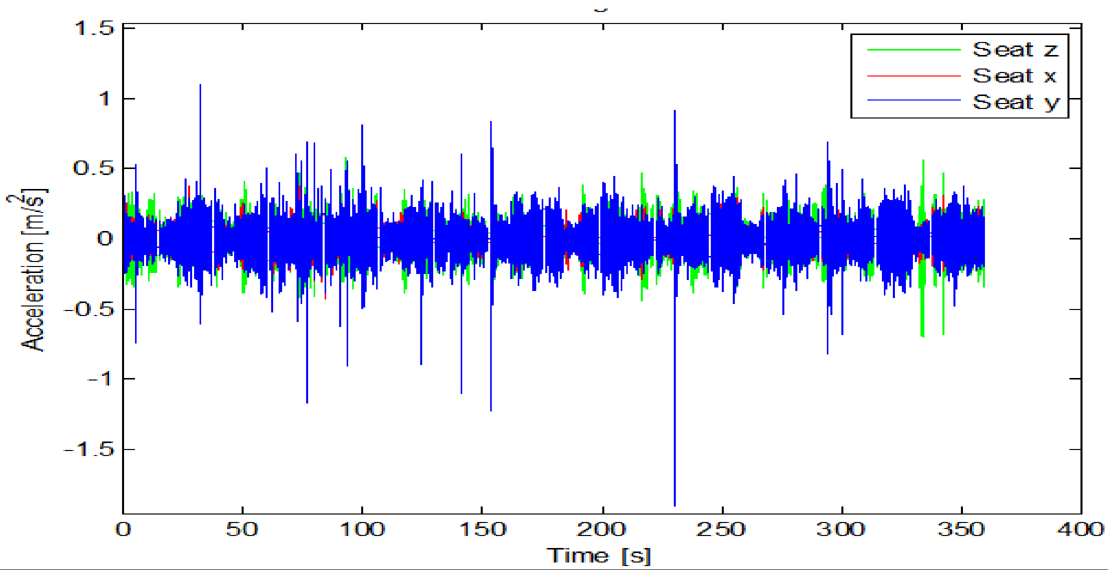
UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Appendix A

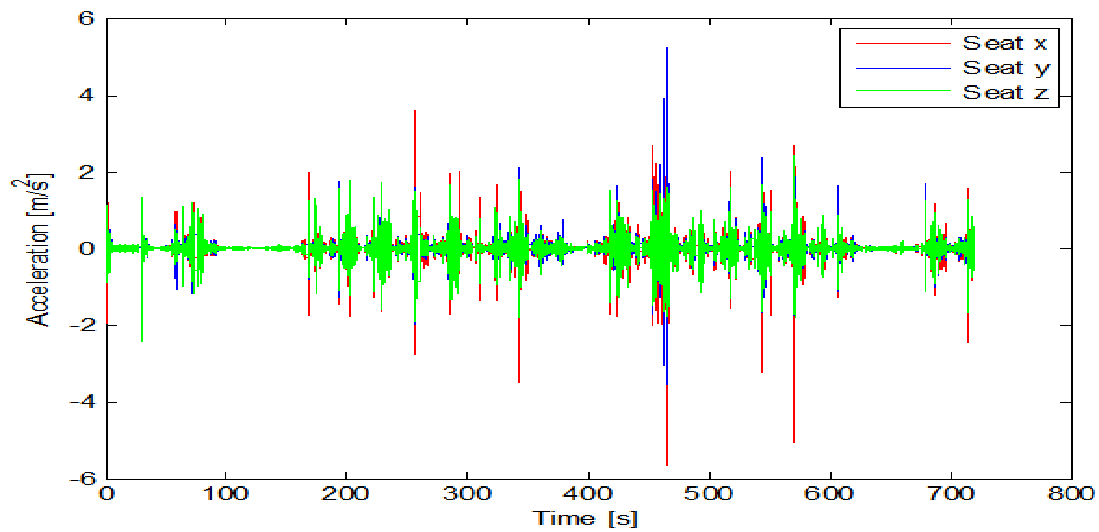
	Weighted acceleration for x, y & z according to ISO 2631-1 (1997)
A1	
A2	
A3	

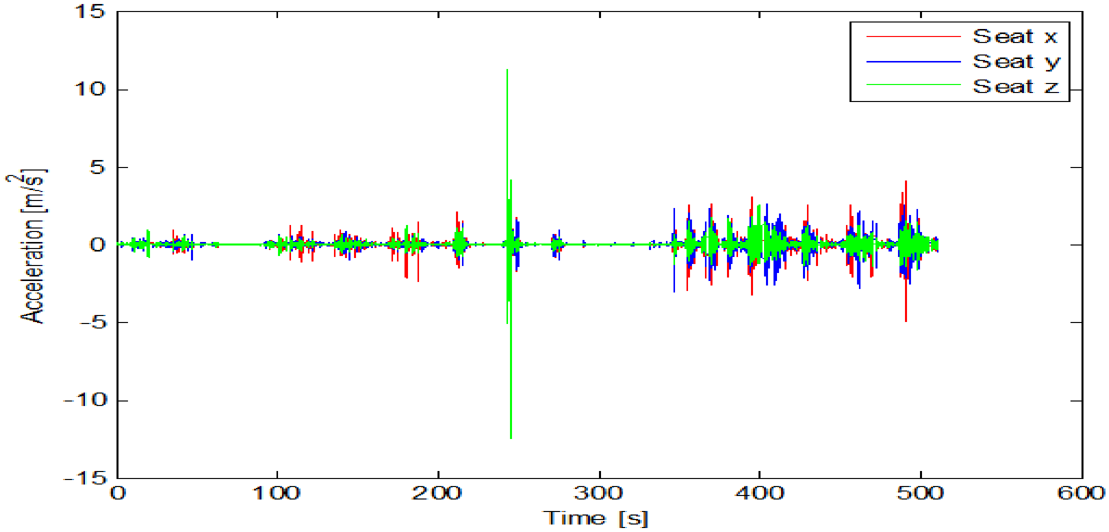
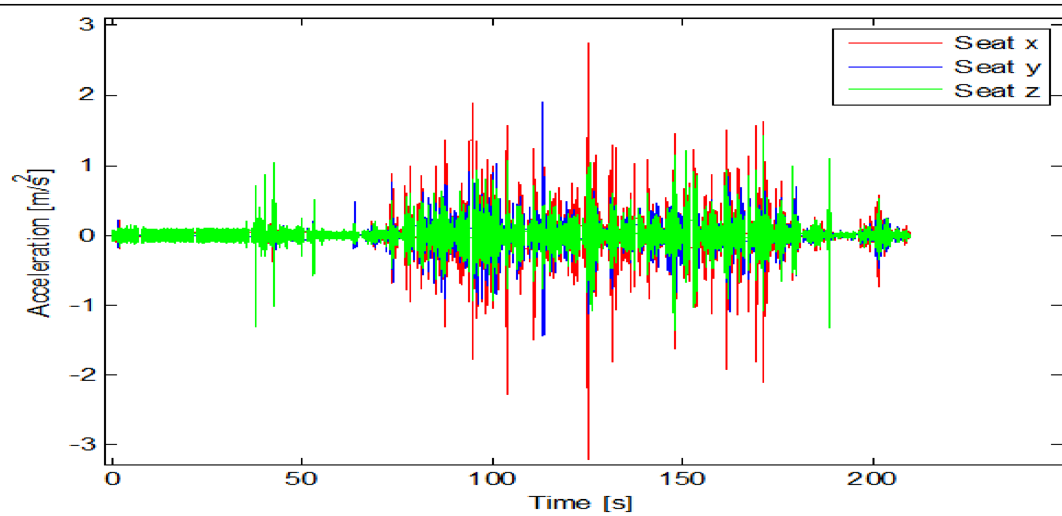
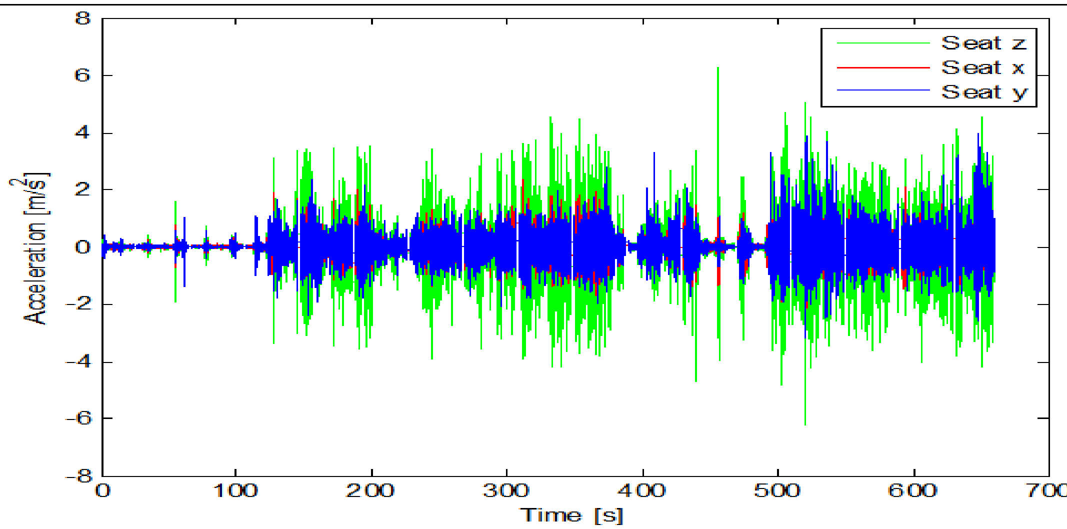
	Weighted acceleration for x, y & z according to ISO 2631-1 (1997)
A4	
A5	
A6	

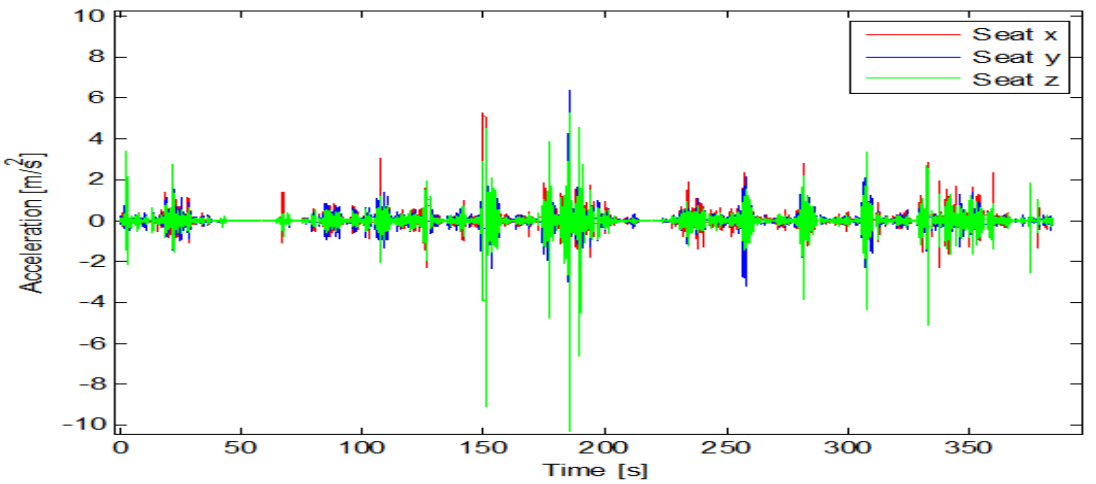
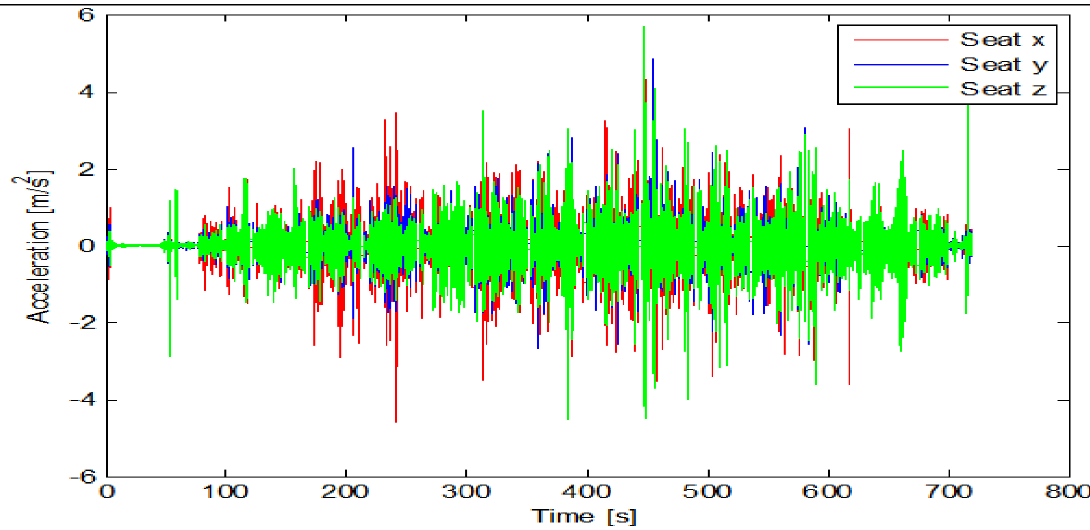
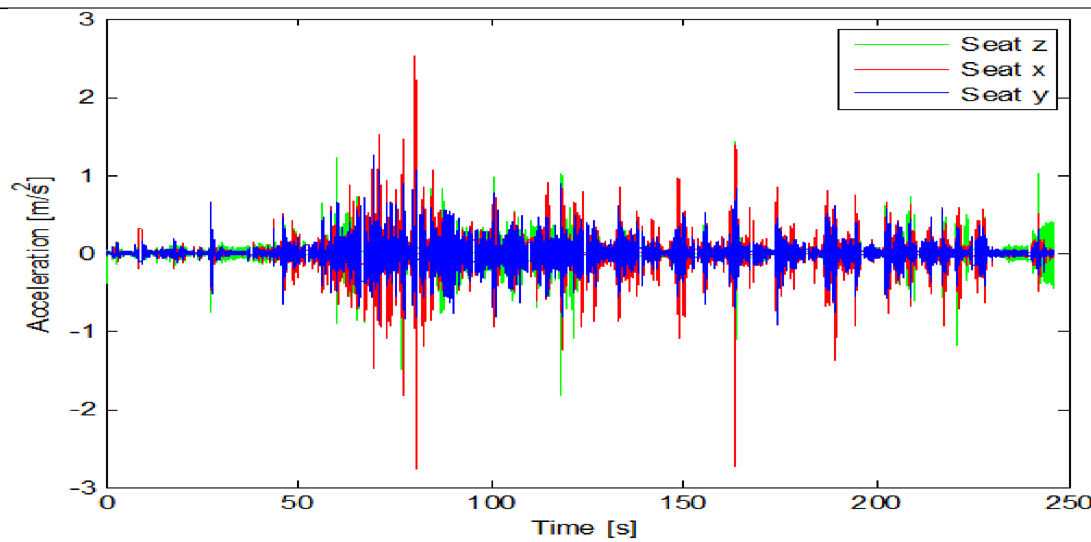
	Weighted acceleration for x, y & z according to ISO 2631-1 (1997)
A7	
A8	
A9	

	Weighted acceleration for x, y & z according to ISO 2631-1 (1997)
A10	

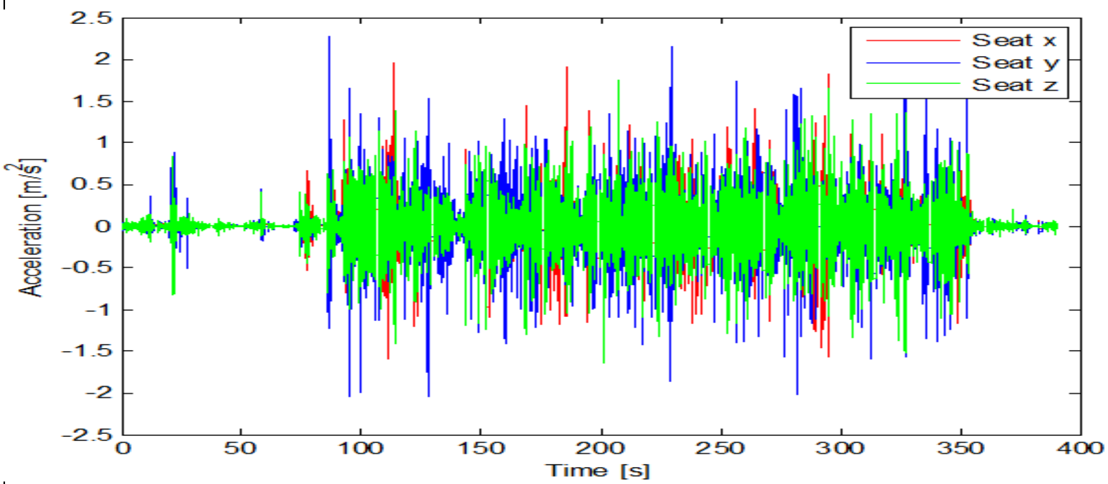
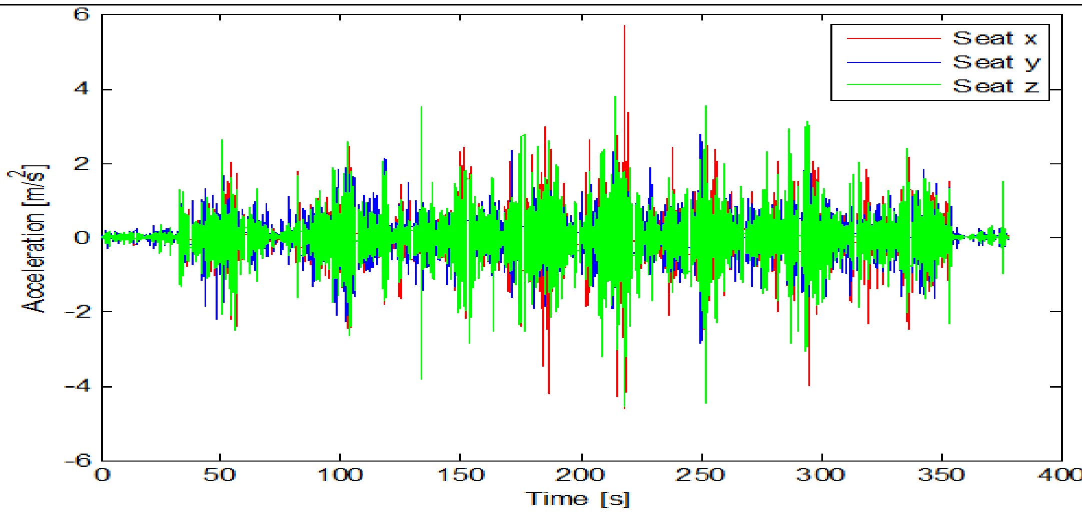
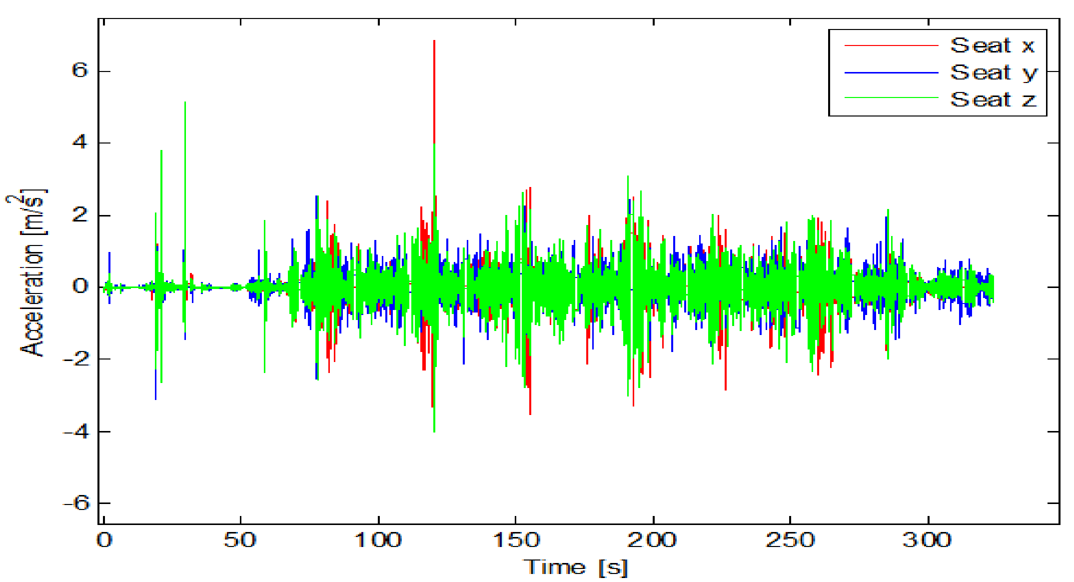
Appendix B

	Weighted acceleration for x, y & z according to ISO 2631-1 (1997)
B1	

	Weighted acceleration for x, y & z according to ISO 2631-1 (1997)
B2	
B3	
B4	

	Weighted acceleration for x, y & z according to ISO 2631-1 (1997)
B5	
B6	
B7	

Appendix C

	Weighted acceleration for x, y & z according to ISO 2631-1 (1997)
C1	
C2	
C3	

Appendix D

<table>
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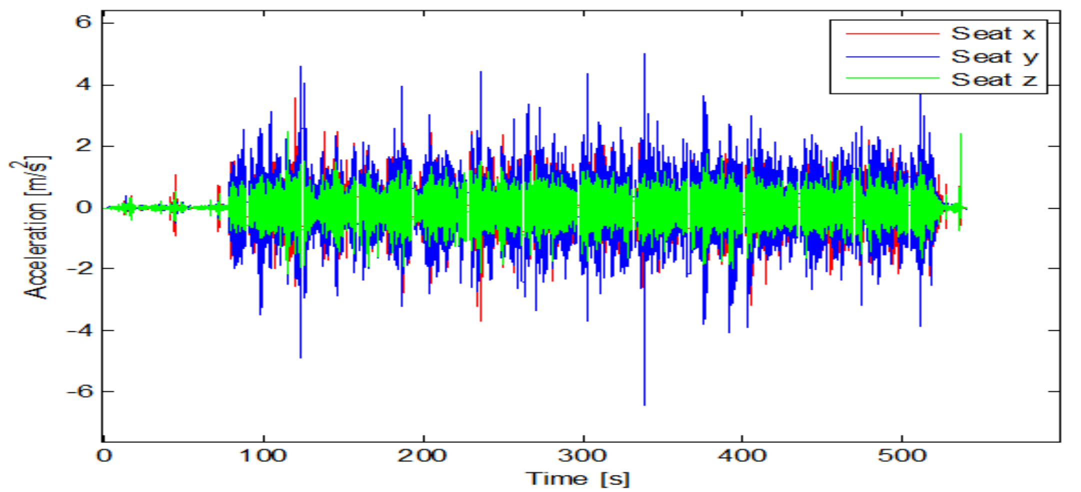
<tr><td>D1</td><td>



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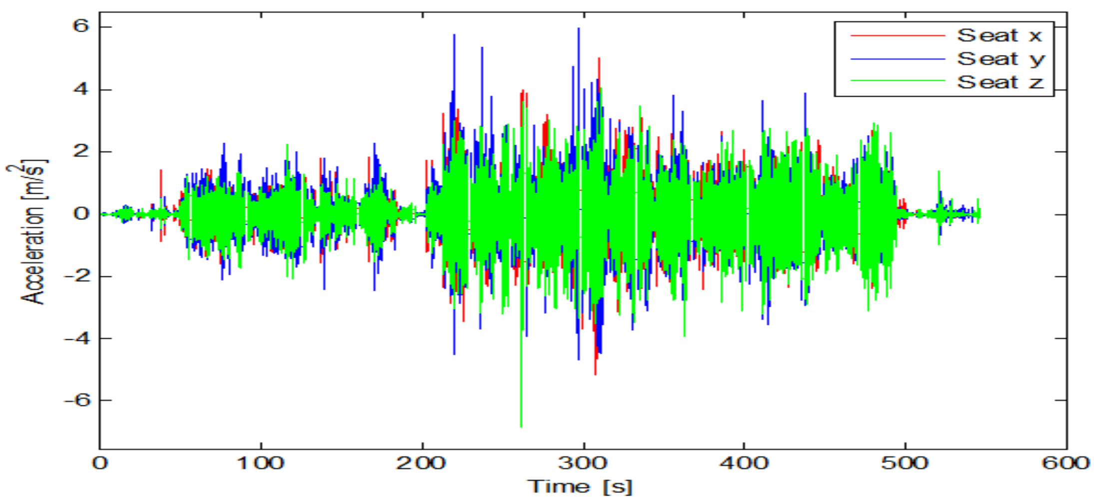

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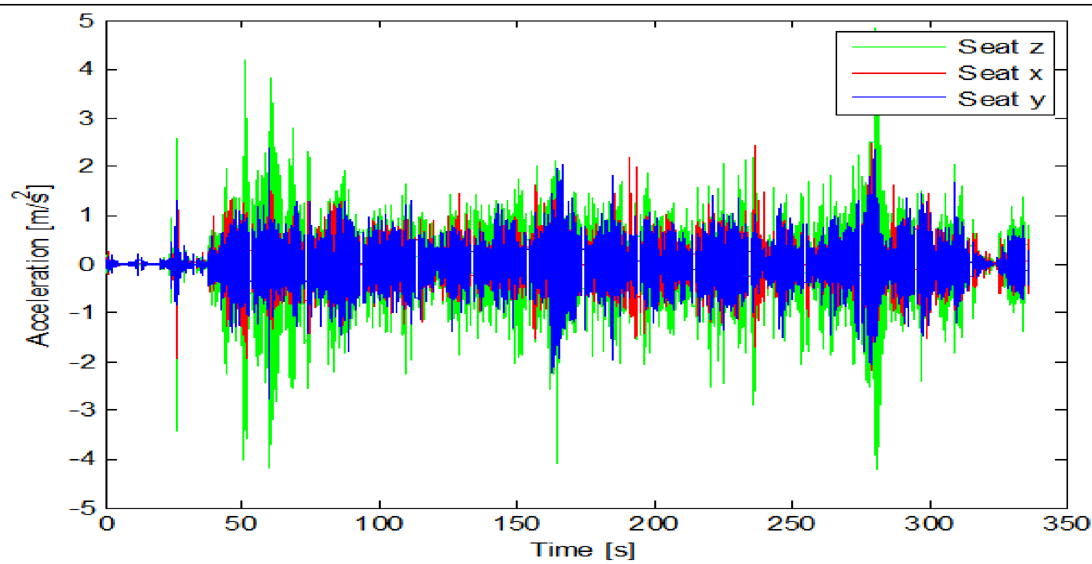

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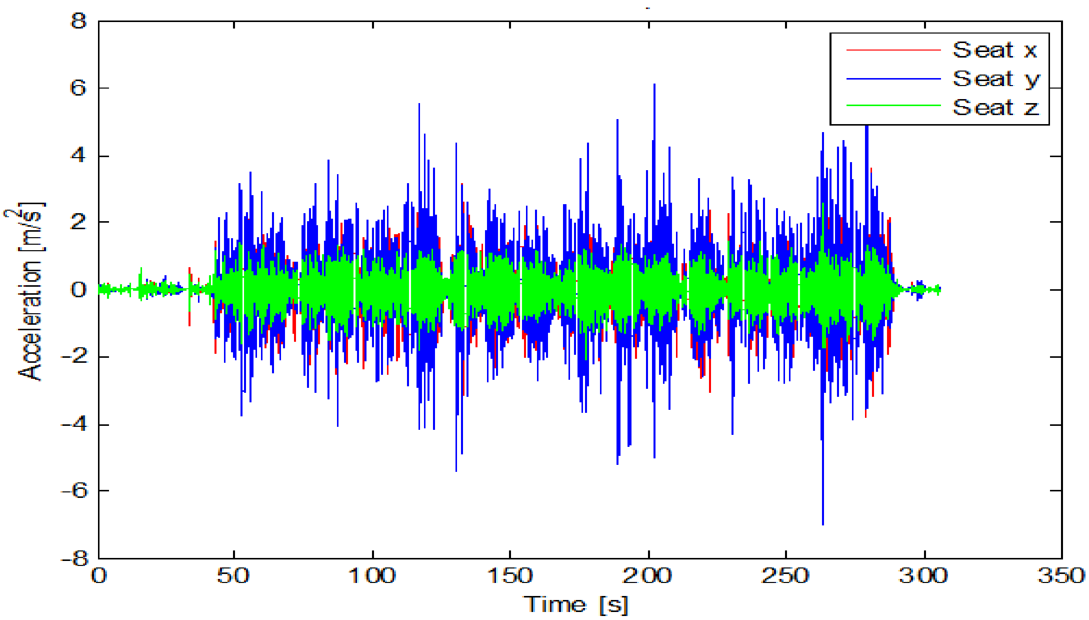
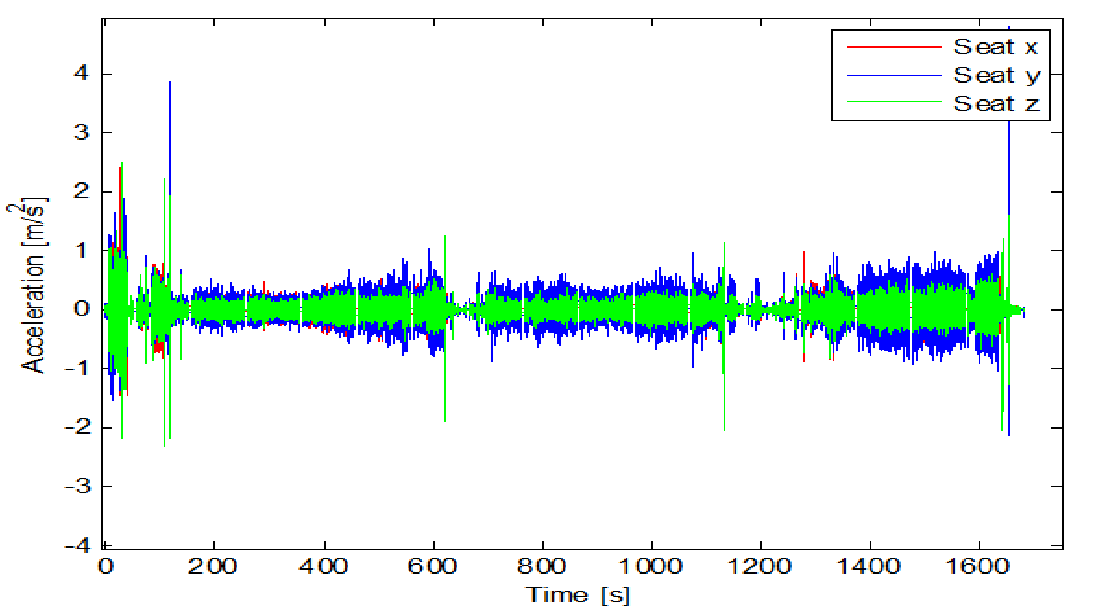
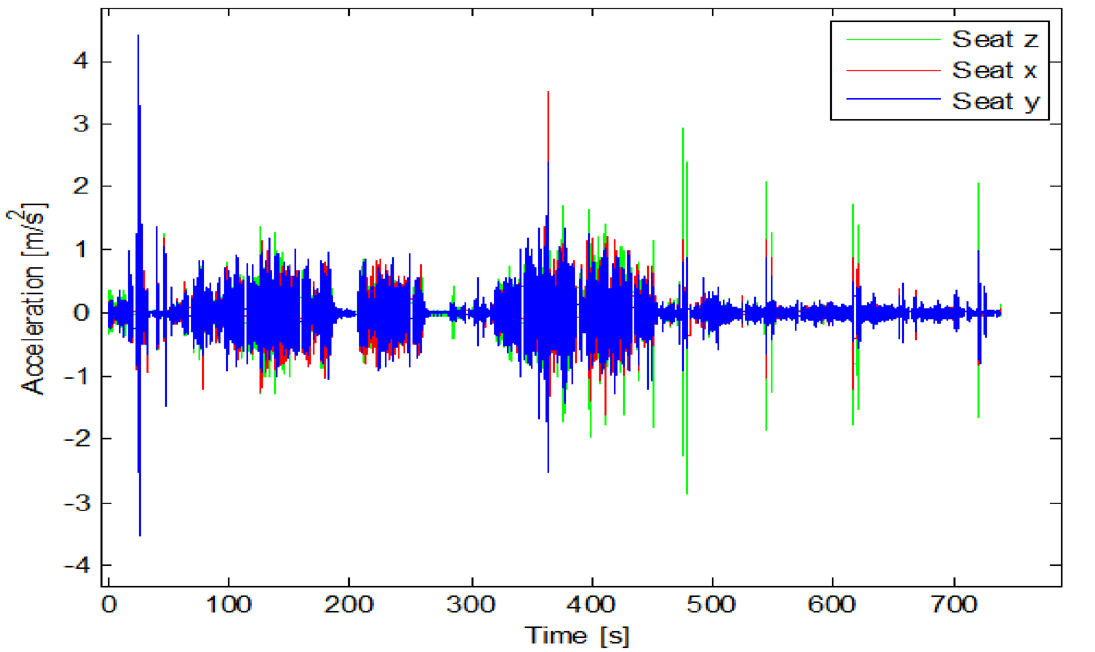
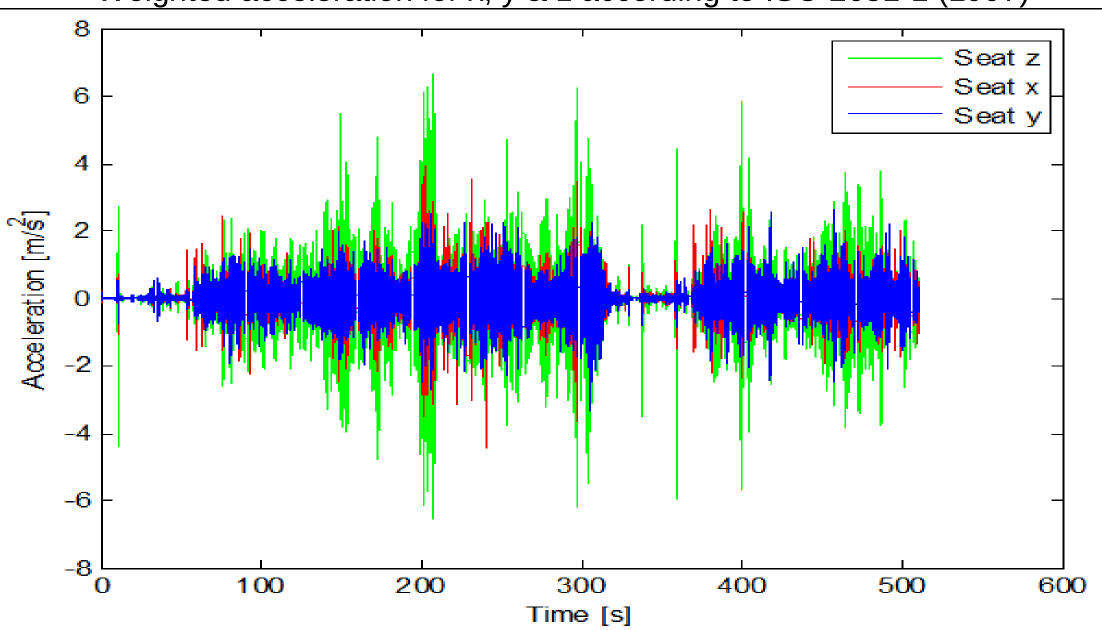
	Weighted acceleration for x, y & z according to ISO 2631-1 (1997)
D4	

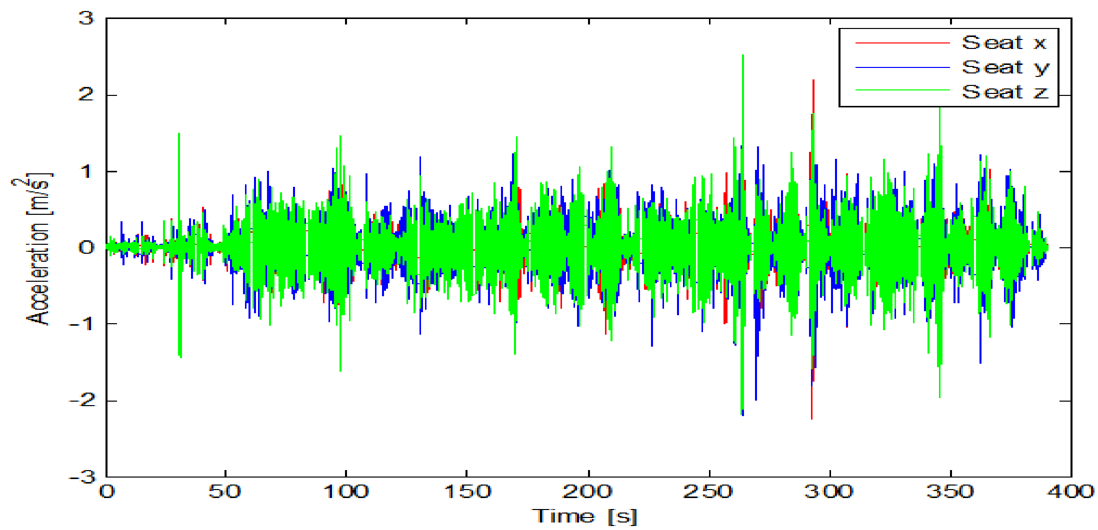
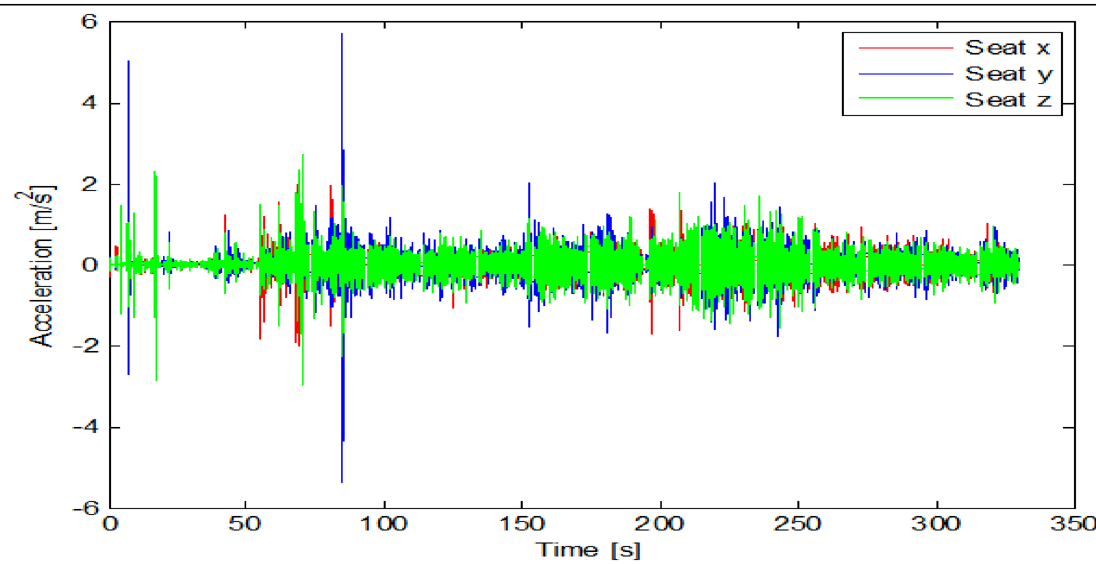
Appendix E

	Weighted acceleration for x, y & z according to ISO 2631-1 (1997)
E1	

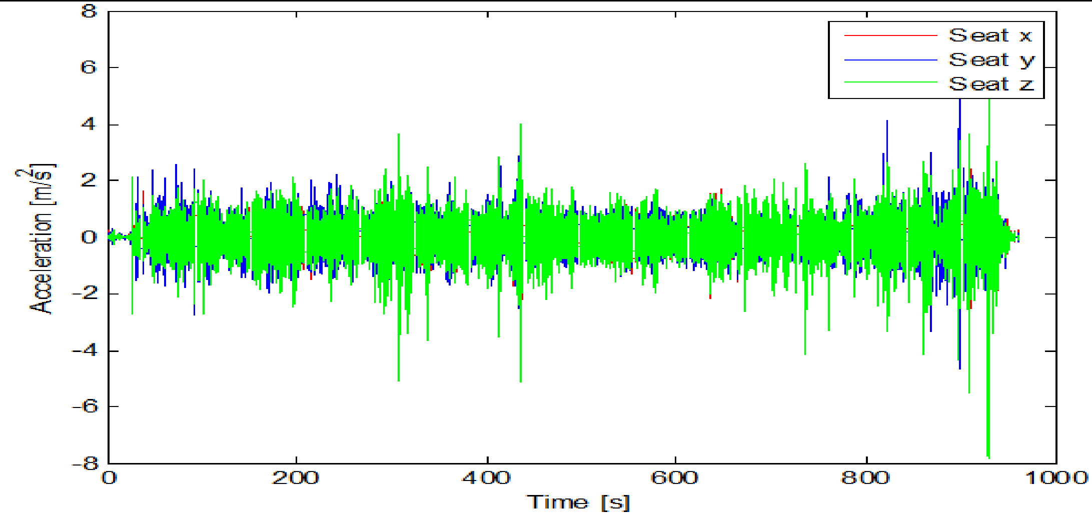
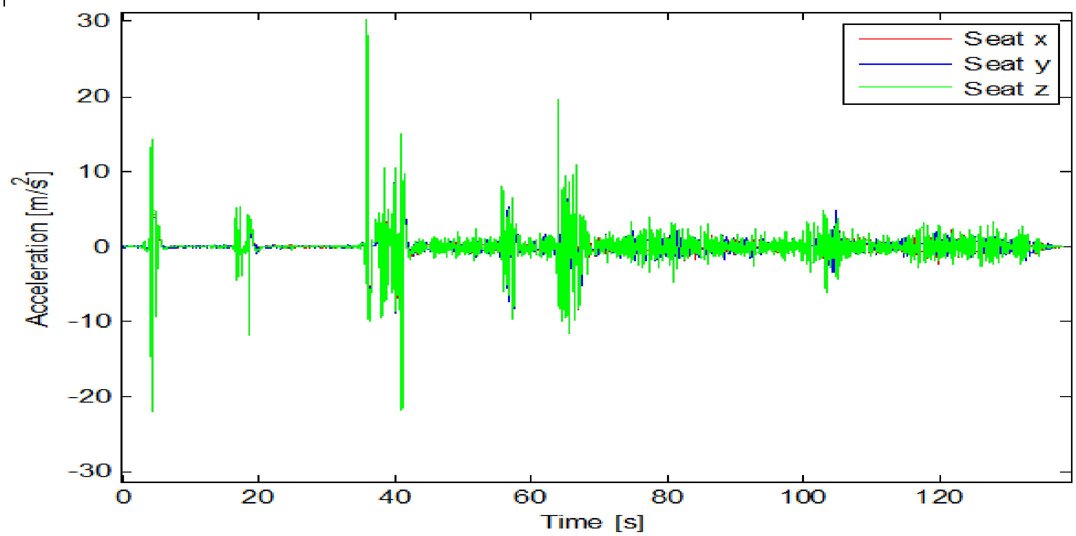
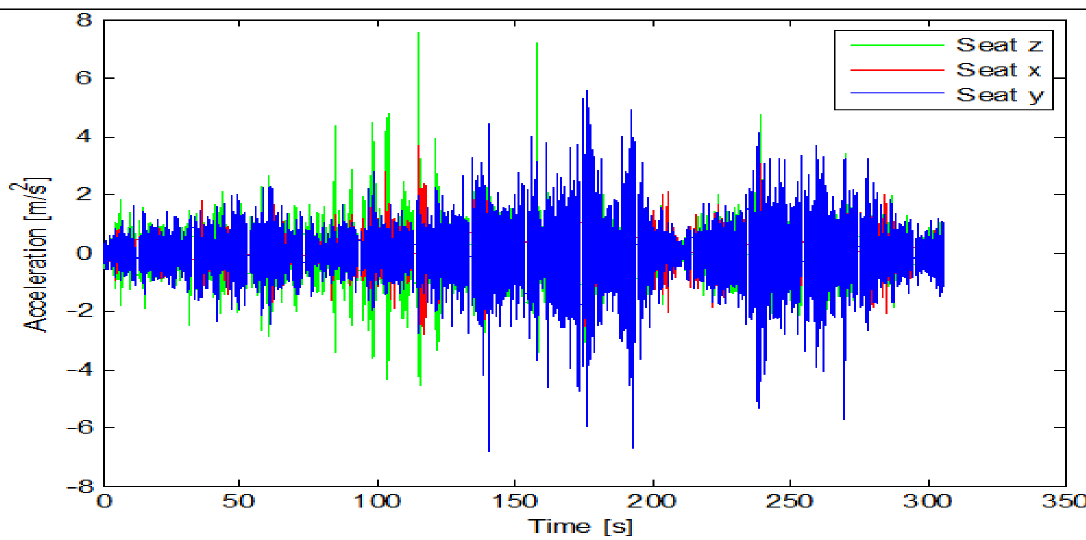
	Weighted acceleration for x, y & z according to ISO 2631-1 (1997)
E2	

Appendix F

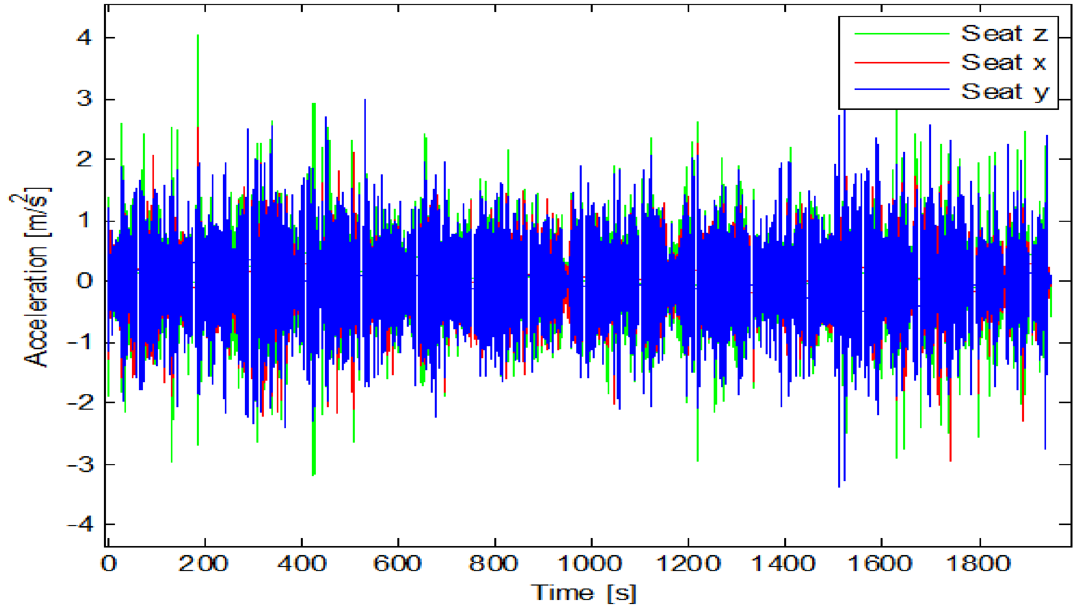
	Weighted acceleration for x, y & z according to ISO 2631-1 (1997)
F1	

	Weighted acceleration for x, y & z according to ISO 2631-1 (1997)
F2	
F3	

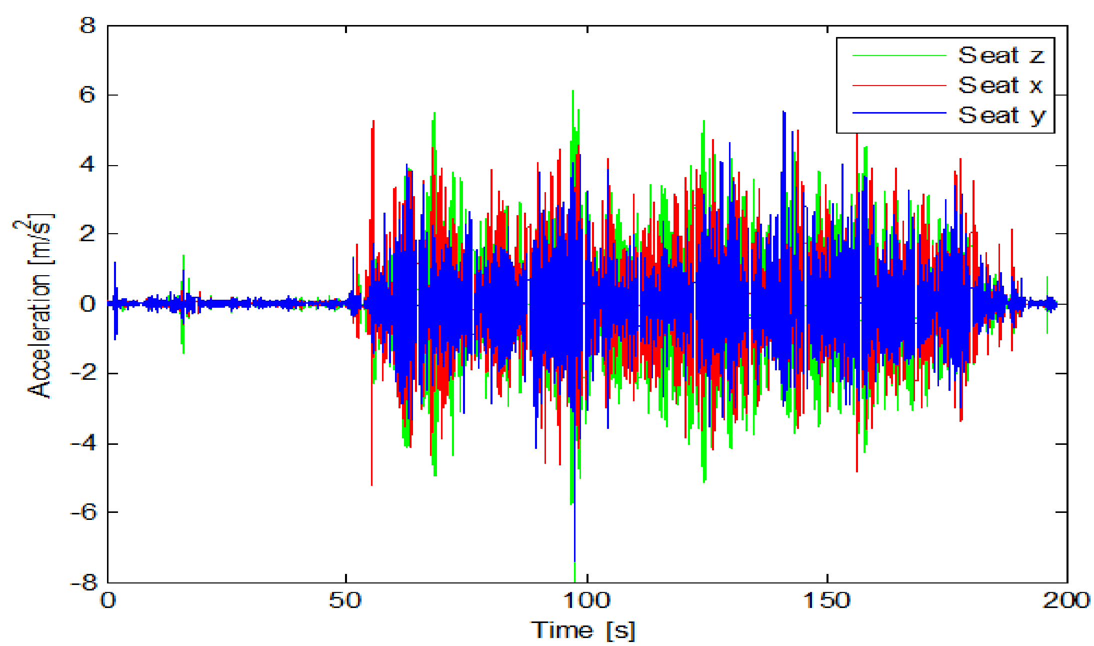
Appendix G

	Weighted acceleration for x, y & z according to ISO 2631-1 (1997)
G1	
G2	
G3	

Appendix H

	Weighted acceleration for x, y & z according to ISO 2631-1 (1997)
H1	

Appendix I

	Weighted acceleration for x, y & z according to ISO 2631-1 (1997)
I1	

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Appendix J: Whole-body vibration questionnaire

Basic data:			
Date:		Time:	
Mine:		Section:	
Section supervisor's name:		Phone no.:	

Operator's information:			
Name:			
Employer:			
Mass:		Height:	

Machine information:		
Machine make and type:		
Model:		
P.I.N:		
Tyre size:		Tyre pressure:
Track length:		Track height:
Suspension:		
Seat suspension:		

WBV instrumentation (description):		
Seat:	Tri-axial seat pad accelerometers	S/N:
Floor:	ICP industrial accelerometers	S/N:
Svantek:	Version 958	S/N: 15112

Site operation(description):				
Operational comments:				
Operator questionnaire:				
How bad are the following factors in your place of work? Key: 1-No problem 2- Acceptable/Fine; 3- Big problem				
Temperature	How warm or cold is it at work? If hot, then you will sweat a lot.	1	2	3
Vibration	Vibration is shaking that you feel when you touch the equipment or sit on it.	1	2	3
Which equipment do you use most of the time?				
At what time do you usually get on the equipment?				
At what time do you usually get off the equipment?				

How long is your break in total?			
Did you suffer from regular back pain? (Yes/No)			
If Yes, How long does the back pain last?			
What is the primary body orientation? (Sitting, standing, lying etc.)			
What material is under the point of contact? (Steel, foam, etc.)			
Seat Make:		Seat Model No.:	
What percentage of working time is the person in actual contact with vibrating equipment?(Time in Actual Contact/Total work time)			

Photographs:		
Description	*Time Taken*	*Reference*
Front view with number on vehicle		
Side view of whole vehicle		
Side view of whole vehicle (background)		
Side view of whole vehicle with Operator		

Calibration Date:	

Measurement Details:							
Time: Start	*Time: End (Stop)*	*Data File*	*WAV File*	*RMS*			

Time (Hrs: Mins)	Time (Hrs: Mins)	Activity: comments