Exposure of earth moving equipment operators to vibration and noise at an opencast coal mine

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Author’s Contribution

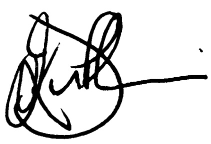
This study was conducted by a team of researchers each with specific contributions as shown in Table 1.

Table 1: Research team.

Name	Contribution
Me. M Groenewald	Student. • Execution of vibration and noise measurements at the opencast mine. • Literature study, analysis and interpretation of results.
Prof. J.L. du Plessis	Supervisor. • Assisted in all planning and execution of the study. • Review of the mini-dissertation with regard to the literature overview, analysis and interpretation of results.
Me. A. Franken.	Co-Supervisor. • Review of the mini-dissertation with regard to the literature overview, analysis and interpretation of results.

Statement from the supervisors that confirms each individual’s role in the study:

I declare that I have approved the article and that my role in the study as indicated above is representative of my actual contribution and that I hereby give my consent that it may be published as part of Mandi Groenewald’s M.Sc. (Occupational Hygiene) mini-dissertation.



Prof. J.L du Plessis	Me. A. Franken	Me. M. Groenewald
Supervisor	Co-Supervisor	Co-Supervisor

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List of abbreviations

ACTH	Adrenocorticotropic hormone
CRH	Corticotrophin releasing hormone
CHPD	Custom made hearing protection device
dB	Decibel
dB(A)	Decibel with A-weighting applied
DME	Department of Minerals and Energy
EME	Earth moving equipment
EU	European Union
HAV	Hand arm vibration
HLD	Haul-load dump
Hz	Hertz
HGCZ	Health Guidance Caution Zone
HPD	Hearing protection device
ISO	International Organization for Standardization
kHz	Kilo-Hertz
LBP	Lower back pain
LHD	Load-haul-dump truck
L_{eq}	Equivalent sound level
MHSA	South African Mine Health and Safety Act (1996)
m/s^2	meters per second, per second (acceleration)
NIHL	Noise-induced hearing loss
NIOSH	The National Institute for Occupational Safety and Health
NRR	Noise reduction rating
OEL	Occupational exposure limit
PPE	Personal protective equipment
r.m.s	Root mean square
ROS	Reactive oxygen species
SANS	South African National Standard
SD	Standard deviation
SLM	Sound level meter
TTS	Temporary threshold shift
TWA	Time-weighted average

USA	United States of America
VDV	Vibration dose value
WBV	Whole-body vibration

Abstract

The phrase “miner” is comparatively non-specific as mining is seen as a multi-disciplinary industry that includes several diverse professions and trades (Donoghue, 2004). One of the functions within mining is the operation of earth moving equipment (EME) such as haul trucks, dozers, excavators and graders. EME are generally used to shift large amounts of earth, dig foundations and landscape areas.

In this study whole-body vibration (WBV) and noise exposure of earth moving equipment (EME) operators were assessed, at an opencast coalmine in South Africa. The aim was to evaluate and quantify the levels of exposure in different EME types, as well as to compare old with new EME, in order to estimate if machine hours contribute to higher noise and vibration levels. WBV and noise levels of the Production and Rehabilitation operations were compared, to determine whether different activities led to different exposures.

Internationally accepted standardised methods, ISO 2631-1 for WBV and SANS 10083:2012 for noise were followed and correctly calibrated instrumentation was used. WBV measurements were conducted with a tri-axial seat pad accelerometer (SVAN 958) and personal noise dosimeters (Casella 35 X) were used for noise measurements. Measurements were taken over a period of four months.

With regards to the European Union (EU) limit (1.15 m/s^2) and the EU action limit (0.5 m/s^2) it was noted that operators of EME within the Production operation were not exposed to WBV levels above the EU limit, but 77% of these operators were exposed to WBV levels above the EU action limit. It was also evident that 45% of operators’ vibration exposure levels were within the Health Guidance Caution Zone (HGCZ) of 0.45 – 0.90 m/s^2. Within the Rehabilitation operation, 9% of operators were exposed to WBV levels above the EU limit and 55% above the EU action limit. Furthermore 50% was within the HGCZ. With regards to the noise Occupational exposure limit (OEL) of 85 dB(A) as stated by the Mine Health and Safety Regulations (MHSR) it was noted that 27% of operators within the Production operation were exposed to noise levels above the limit and for operators within the Rehabilitation operation 14% were reported to be exposed at or above the limit. Statistically significant difference in noise exposure was found between the Production operation and Rehabilitation operation. Results indicated that the majority of EME operators were exposed to high noise levels, in some cases exceeding the 85 dB(A) OEL. A significant positive correlation was found between noise exposure levels and machine hours. Thus higher noise levels were observed as machine operating hours increased.

It was found that operators were exposed predominantly to vibration and noise levels below the limits. However the Dozer group within the Production and Rehabilitation operations in some cases exceeded the vibration and noise legal limit. High exposure levels within the Dozer group can be attributed to the fact that these EME types mostly perform activities in uneven areas and the tracks on which these Dozers move also contribute to higher vibration levels due to a lack of a suspension. Controls should be implemented as far as is reasonably practicable to ensure that operators are not exposed above recommended or permissible levels for each hazard. Continuous improvement of the maintenance plan for all EME and regularly grading and maintaining travelling ways are some of the controls that will contribute to lower vibration and noise levels. Operators exposed to high noise levels should use hearing protective devices as an early on preventative measure to reduce noise exposure levels.

Keywords: whole-body vibration, noise, earth moving equipment operators, opencast mining.

Opsomming

Die term “myner” is relatief nie-spesifiek, want mynbou word gesien as ‘n multi-dissiplinêre bedryf, wat verskeie uiteenlopende professies en ambagte insluit. (Donogue, 2004). Een van die hooffunksies in die mynbedryf is die bestuur van swaervoertuie soos vervoertrokke, stootskrapers, laaigrawe en padskrapers. Hierdie tipe swaarvoetuie word hoofsaaklik gebruik om groot hoeveelhede grond te vervoer, landskap en fondasies te grou.

In hierdie studie is heelliggaamvibrasie en geraasblootstelling van mynvoertuig-operateurs op ‘n oopgroefsteenkoolmyn in Suid-Afrika ondersoek. Die doel van die studie was om vibrasie- en geraasblootstellingsvlakke in verskillende tipes mynvoertuie te evalueer en te kwantifiseer. Blootstellingsvlakke van ou mynvoertuie is ook vergelyk met die van nuwer mynvoertuie om sodoende te bepaal of faktore soos masjien ure blootstellingsvlakke beinvloed. Heelliggaamvibrasie en geraasblootstelling van die Produksie afdeling en Rehabilitasie afdeling is ook met mekaar vergelyk om te bepaal of daar ‘n verskil voorkom in blootstellingsvlakke.

Internasionaal aanvaarde gestandariseerde metodes, ISO 2631-1 vir heelliggaamvibrasie en Suid-Afrikaanse Nasionale Standaard (SANS 10083:2012) vir geraas asook korrek gekalibreerde instrumentasie is gebruik. Metings is oor ‘n tydperk van vier maande geneem.

Met betrekking tot die Europese Unie (EU) limiet (1.15 m/s^2) en die EU aksie vlak (0.5 m/s^2) het resultate getoon dat operateurs in die Produksie afdeling nie blootgestel is aan vlakke bo die EU limiet nie, maar 77% van hierdie operateurs was blootgestel aan heelliggaam-vibrasie vlakke bo die EU aksie vlak. Dit was ook duidelik dat 45% van die operateurs se vibrasie vlakke binne die Gesondheidsriglyn waarskuwingssone (“Health Guidance Caution Zone”, HGCZ) van 0.45 – 0.90 m/s^2 val. In die Rehabilitasie afdeling was 9% van die operateurs blootgestel aan heelliggam-vibrasie vlakke bo die EU limiet en 55% bo die EU aksie vlak. ‘n Verdere 50% van die operateurs was blootgestel an vlakke binne die HGCZ.

Met betrekking tot die beroepsblootstellingsdrempel (BBD) van 85 dB(A) soos deur die MHSR gestippuleer, was daar opgemerk dat 27% van die operateurs in die Produksie afdeling blootgestel word aan geraas vlakke bo en by die drempel en 14% van die operateurs binne die Rehabilitasie afdeling was ook blootgestel aan geraas vlakke bo die limiet. Resultate het aangedui dat die meerderheid van die swaarvoertuig-operateurs blootgestel was aan hoë geraasvlakke, in sommige gevalle bo die 85 dB(A) drempel 'n Positiewe korrelasie is gevind tussen geraasvlakke en masjienure. Dus soos wat die masjienure toeneem, so sal geraas vlakke ook toeneem.

Operateurs is hoofsaaklik blootgestel aan vibrasie en geraas vlakke onder die blootstellingsdrempel Maar die stootskraper groep binne die Produksie afdeling asook die Rehabilitasie afdeling het in sommige gevalle die wetlike drempel vir vibrasie en geraas oorskry. Hierdie hoë blootstellingvlakke binne die stootskraper groep kan toegeskryf word aan die feit dat hierdie swaarvoertuig tipes meestal aktiwiteite uitvoer in ongelyke gebiede en die spore waarop hierdie stootskrapers beweeg dra ook by tot hoër geraas- envibrasie vlakke as gevolg van 'n gebrek aan skokbrekers.

Beheermaatreëls moet sover dit redelikerwys uitvoerbaar is geïmplementeer word om sodoende te verseker dat operateurs nie bo die toelaatbare vlakke blootgestel word nie. Deurlopende verbetering van die instandhoudingsplan vir alle mynvoertuie asook die instandhouding van die mynpaaie is van die beheermaatreëls wat sal bydra in die verlaging van vibrasie- en geraasblootstelling. Operateurs wat blootgestel word aan hoë geraasvlakke moet gebruik maak van gehoorbeskerming as 'n vroeë voorkomende maatreël om geraasblootstellingsvlakke te verlaag.

Sleutelwoorde: heelliggaamvibrasie, geraas, grondverskuiwing, oopgroef mynbou, grondverskywings masjiene.

Preface

This mini-dissertation is written in the article format. In order to ensure uniformity, the reference style of the entire mini-dissertation was written according to the guidelines for publication in the journal, Annals of Occupational Hygiene. The journal requires in text references in the form of surnames and dates, while the list of references should be set in Vancouver style.

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Chapter 1: General Introduction

1.1 Introduction

South African mining companies are considered to be world leaders in mining and key players in this global industry (Kaplan, 2011). Mining is one of the most physically demanding occupations with significant health challenges for workers. However, national and international legislation requires that an employer should provide and sustain a work environment which is safe and without any health risks.

Mining is a diverse industry with many occupations (Donoghue, 2004). One of these is the operation of mining vehicles such as earth moving equipment (EME) which include haul trucks, excavators, bulldozers, front-end-loaders and graders. EME are usually used to shift large amounts of earth, dig foundations and landscape areas. In many cases EME operators work shifts in excess of ten hours, increasing the possibility for exposure to hazards specific to their occupation (Eger *et al*., 2006). Operators of EME are not only exposed to dust, but also to other hazards such as noise and whole-body vibration (WBV) (Eger *et al*., 2006). Groothoff (2012) claimed that noise and vibration are closely linked due to the fact that, the physics of vibration and noise are similar in that they are both transmitted as waves through a medium. As a result exposure to noise is normally linked to vibration exposure. While the specific health related effects of noise exposure are different to those arising from exposure to vibration, they are both of importance and can manifest after a long period of latency (Groothoff, 2012). The prevalence of noise and the effects thereof on the health and safety of miners have been extensively studied in the mining and related industries. Mechanical vibration on the other hand, has received far less attention, even though an increase in numbers of WBV exposures is being observed in mobile equipment (Van Niekerk *et al.,* 2000).

Vibration exposure to the human body is complex, as the human body is exposed to various frequencies in different directions (Sayed *et al.,* 2012). Various definitions have been given for WBV. Rozali *et al.* (2009), Hagberg *et al.* (2006) and Uchikune (2002) defines WBV as mechanical oscillations, with a frequency range between 0.01 to 50 Hz, transferred by a vibration source through the human body via contact either by sitting or standing on the vibrating source. WBV levels transmitted to drivers/operators of equipment and vehicles in the mining industry have been associated with health and safety risks (Gunaselvam and van Niekerk, 2005). Acute health effects of WBV include headaches, increased heart rate, loss of balance and a decreased ability to process information (Smith and Leggat, 2005). The most general complaint from exposed individuals is that of lower back pain, some health effects may even lead to permanent disabilities such as spinal, gastro-intestinal and muscoskeletal disorders (Gunaselvam and van Niekerk, 2005).

Various international standards have been developed which govern the way in which human vibration should be measured and reported, as well as provide indication of health risks involved. In this regard International Organisation for Standardisation 2631-1 is well known (ISO, 1997). European Parliament legislation (EU Directive 2002/44/EC, 2002) stipulates minimum standards for health and safety of workers exposed to either hand-arm vibration (HAV) or WBV. This directive mandates a WBV exposure limit of 1.15 m/s^2, and an action level of 0.45 m/s^2 for an equivalent eight-hour exposure period.

Previous research done by Eger *et al.* (2006) on mining vehicles in Ontario Canada, found vibration to be above the levels recommended by the ISO's Health Guidance Caution Zone (HGCZ) on haul trucks, bulldozers and graders, but found levels of whole-body vibration on jumbo drills and pit drills to be below recommended levels. It was also found that vibration levels were above the recommended HGCZ for smaller haul-load dump trucks (HLD), while larger trucks were within these recommended levels. Earlier studies done by Village *et al.* (1989) found similar exposures in their study on HLD used underground. In a study done by Mayton *et al.* (2012), a comparison was made between two groups of haulage trucks – four older trucks and two newer trucks. They found that the newer trucks and associated seats exposed operators to lower levels of WBV compared to that of older trucks.

Noise, is common to all mining commodities and is present in all activities including to operators of EME (McBride, 2004). Controlling noise exposure has proven to be difficult, and noise-induced hearing loss (NIHL) remains one of the most common risks in the mining industry (Dekker *et al*., 2011). NIHL is a result from irreversible damage to the delicate hearing mechanisms of the inner ear and is seen as the most serious health effect following noise exposure (Nelson *et al*., 2005). According to McBride (2004) there is no uncertainty that most miners are exposed to noise levels above an 8 hour L_{aeq} of 85 dB(A) and some may even be exposed to a peak of 140 dB(A). The National Institute for Occupational Safety and Health (NIOSH) estimates show that in the USA 80% of miners work in an environment where the occupational exposure limit (OEL) time-weighted average occupational exposure limit (TWA-OEL) is above 85 dB(A) and that 25% of these are exposed to a TWA noise level that is above 90 dB(A) (NIOSH, 2003). Furthermore, information available regarding noise exposure levels for South African miners indicate that more than 90% of work is done in areas which exceeds the legislated OEL of 85 dB(A) (Edward *et al*., 2011).

Spencer-Kovalchik (2007) found that noise levels linked with heavy construction equipment can range between 80 to 120 dB(A) with bulldozers, road graders and haul trucks being responsible for the highest levels. In the workplace, excessive noise exposure can limit workers' ability to communicate and hear warning signals, thus excessive noise exposure has an impact on worker safety and productivity (Edward *et al*., 2011). Noise may also contribute to many adverse health effects, including elevated blood pressure, tinnitus, reduced performance, sleeping abnormalities, annoyance and stress, and temporary hearing threshold shift (Nelson *et al*., 2005). Apart from these health effects, another occupational health hazard emerging is low frequency noise (LFN). Excessive exposure to LFN was found to cause extra-aural effects in the form of vibroacoustic disease (VAD) which emphasize the link between noise and vibration (Castelo Branco and Alves-Pereira, 2007).

A study done by Bealko (2008) assessed noise levels within the cabins of different haul trucks. Various trucks were included such as new trucks, old trucks and old trucks with cabins that were refurbished due to many hours of use. In new trucks no significant noise levels were found but in both categories of old trucks an average level exceeding 85 dB(A) was found.

International and national research on noise and vibration in mining vehicles is limited to a few studies (Donoghue, 2004; Kittusamy and Buchholz, 2004; McBride, 2004; Edward *et al.,* 2011). Vibration is one of the last identified and most misunderstood of all occupational hazards with reasonably limited research carried out compared to other hazards, particularly in South Africa. It is often complex and costly to control, and particularly in developing countries where there are numerous other, more visible occupational hazards that exist and are given a higher priority. There is currently limited information indicating WBV exposure levels conducted over an eight-hour exposure period; most of the available data are based on measurements which were taken for thirty minutes to an hour (Southon, 2010).

This study will provide additional information regarding quantifying WBV and noise exposures on mining vehicles in particular EME at an opencast coal mine in South-Africa.

1.2 Aims and Objectives

The aim of this study is to evaluate and quantify Earth Moving Equipment (EME) operators' whole-body vibration and noise exposure at an opencast coal mine in South Africa.

This study endeavors to accomplish the following objectives:

- To assess WBV exposure of EME operators, based on the ISO 2631-1(1997) standard and their personal noise exposure based on the SANS 10083:2012 standard in an open cast mine;
- Critically evaluate WBV and noise results, comparing results obtained with applicable national and international standards;
- To assess and compare old with new EME, in order to investigate if a correlation exists between machine hours and noise and vibration levels.

1.3 Hypothesis

ISO 2631-1 sets a Health Guidance Caution zone between 0.45 m/s^2 r.m.s and 0.90 m/s^2 r.m.s while EU Directive 2002/44/EC sets a limit of 1.15 m/s^2 r.m.s for whole body vibration. SANS 10083:2012 and the Regulation under the South African Mine Health and Safety act 1996 (Act 29 of 1996), states that an 8 hour noise/sound level of 85 dB(A) should not be exceeded. It is therefore hypothesised that EME operators at a South African opencast coal mine are exposed to levels of WBV that exceed advised levels set out in ISO 2631-1 and EU Directive 2002/44/EC; and personal noise exposure that exceed the legal limit as stated by South African legislation and standards.

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Chapter 2: Literature Review

2.1 Introduction

The phrase “miner” is comparatively non-specific as mining is seen as a multi-disciplinary industry that includes several diverse professions and trades (Donoghue, 2004). Operating of mining vehicles such as articulated dump trucks (ADT), graders, excavators, loaders and dozers is one of these professions (Donoghue 2004). In this profession, operators usually work shifts that exceed ten hours, thus a higher possibility for exposure to hazards, specific to their occupation may occur (Eger *et al.,* 2006). Mining remains a key industrial segment in many parts of the world and although significant improvements has been made in controlling occupational hazards such as noise induced hearing loss, respiratory disease and ergonomics, there still remains room for supplementary risk reduction (Donoghue, 2004).

One of the ubiquitous hazards for earth moving equipment (EME) operators is WBV associated with poorly maintained roads and vehicles contributing to the predicament. Noise on the other hand, is also commonly experienced in the mining environment, generated by diverse mining activities such as drilling, blasting and cutting (Donogue, 2004). Exposure to vibration is usually linked with exposure to noise, as noise originate from a vibrating source and have comparable physics as they are both transmitted as waves through a medium. While the specific health related effects of noise exposure are different to those arising from exposure to vibration, they are both of importance and can manifest after a long period of latency (Groothoff, 2012).

Going forward the literature study will focus predominantly on WBV and noise, their health effects, exposure sources and control of these exposures respectively.

2.2 Vibration

Mining consist of many activities such as intensive and continuous usage of EME that may result in the significant exposure of operators to shock and vibration, over prolonged shifts. As a result, prolonged exposure to vibration may lead to discomfort, interference with activities and impaired health (Griffin, 1990). To understand the complexity and variety of these health effects on the human body it is suggested to define human vibration as either WBV or hand-arm vibration (HAV). WBV refers to mechanical oscillations with frequencies ranging from 0.01 to 50 Hz, which are transmitted through the whole body by a vibration source through contact by the buttocks or feet (Unchikune, 2004; Hagberg *et al*., 2005; Smith and Leggat, 2005), whereas hand-arm vibration, is vibration exposure where the transmission is from the tool via the hand, into the arm (Griffin, 2012). For this study, focus will be mainly on WBV exposure, therefore HAV will be excluded from literature research.

2.2.1 Biomechanics of vibration

The human body is seen as a multifaceted mechanical structure which does not react to vibration in a similar manner as a rigid mass. Different body parts in the human body have comparative motions between them, but will differ in direction and frequency of the applied vibration (Griffin, 2001). According to Griffin (1990), the human body's reaction to vibration depends primarily on the magnitude, frequency and direction of the vibration signal.

Velocity (m/s^1), acceleration (m/s^2) and displacement (m) are used to quantify vibration magnitude, expressed as a root mean square value (m/s^2 r.m.s.). Rms relates to the vibration energy and thus indicates the vibration injury potential (Bovenzi and Hulshof, 2007). For standing and seated persons there are three orthogonal axes of WBV namely: forward and backwards movement (x-axis), lateral movement (y-axis) and vertical movement (z-axis) (Mansfield and Maeda, 2007). Workers who are exposed to WBV experience simultaneous motion in all three directions (Mansfield and Maeda, 2007).

Smith and Leggat (2005) stated that all objects have a frequency at which they naturally vibrate and when this happens the term "resonant frequency" is used. When the resonant frequency is reached the vibration amplitude will increase. Resonance frequencies will differ depending on the direction (i.e., axis) of vibration, posture of body, and where on the body the vibration measurement is taken (Griffin, 2001). The human body does not have a single resonant frequency because various parts of the body have different physical characteristics, due to the different composition of bone and tissue structures and tends to vibrate at different frequencies (Smith and Leggat, 2005). According to Smith and Leggat (2005) vertical vibration of the human body has a resonant frequency that ranges between 4 and 8 Hz. ISO 2631-1 (1997) state that the frequency which affects the body with regard to health, comfort, and perception, is between 0.5 – 80 Hz, but under the health section, a note states that frequencies below 1 Hz have no effect on health and can thus be ignored. Furthermore the resonant frequencies for seated persons' spinal cord are between 4 and 7 Hz, and 4.5 Hz specifically for the lower back.

Smith and Leggat (2005) also stated that the physical process between the human body and vibrating energy transfer can be divided into two segments. First, vibration energy will be transferred from the vibrating source to the human body and then primarily stored in the muscle tendons. In a second phase, a lower level of energy will be transferred back to the vibration source, because of energy dissipation. Vertical vibration transmission to the spine is lower when in a seated position than when compared to a standing position (Smith and Leggat, 2005). A rocking motion of the pelvis rotation will increase when a person is in a seated position when exposed to vibration, and will enhance vibration transmitted to the spine, increasing disc degeneration (the height of the spinal disc reduces gradually) (Wilder, 1993). Critical points along the spine have been identified where the human body naturally pivots. Within these regions; including the joints between the seventh cervical vertebra (C7) and first thoracic vertebra (T1), the twelfth thoracic vertebra (T12) and first lumbar vertebra (L1), physiological damage tend to occur. The link between the fifth lumbar (L5) and the sacrum can also be affected (Smith and Leggat, 2005).

2.2.2 Occupational WBV sources

Industries where operators of EME are exposed to potential harmful levels of WBV can be categorized as agriculture, construction, transportation, aviation, operators of mobile equipment, including transport vehicles, heavy industrial vehicles and mining vehicles, (Smith and Leggat 2005; Eger *et al*., 2006).

In a study by Mandal *et al*. (2006) 18 heavy EME in three opencast mines where measured, the fleet was comprised of dozers, dumpers and shovels. They found that 13 of the 18 earth moving machines had vibration levels higher than the safe limits for four hours of operation in a day, as stated by ISO 2631-1 (1997) standard. The vibration levels for the dumpers and dozers indicated a potential health risk but the vibration levels of the shovels were within safe limits. Berenzan *et al*. (2004) found that forceful driving patterns, on both rough and poorly maintained roads as well as pit floors, along with the intermittent bumps and poorly placed load will add to extreme high vibration levels.

A study conducted on surface haulage trucks with a loading capacity of 240 to 350 tons, reported vibration levels higher than the recommended HGCZ levels (Kumar, 2004). Cann *et al*. (2003) conducted a study on different types of construction vehicles in residential, corporate, and public work projects. Vehicles found to have vibration levels above the recommended HGCZ were loaders, dump trucks, graders and dozers.

Van Niekerk *et al.* (2000) made the first attempt to determine the effect of vibration exposure in the South African mining industry. Their research scope included vibration measurements for tools, machinery and vehicles. WBV data, in accordance with ISO 2631-1 (1997), was obtained from several mines. Earth moving equipment was the group with the highest vibration levels of above 1m/s^2. A further study conducted by Mdlazi (2009) focused on the impact of WBV in day to day activities at mining operations in South Africa. Results showed that a number of vehicles and equipment, exposed operators to vibration levels above the European limit and that vibration exposure levels have to be managed to reduce the risk of injury.

It is evident from the literature that vehicle drivers and EME operators are the primary groups in the occupational world that are exposed to WBV.

2.2.3 Quantifying WBV

WBV exposure is calculated using daily exposure which can be defined in two ways. Firstly it can be defined as an equivalent continuous r.m.s. acceleration over an eight hour period or secondly as vibration dose value (VDV).

Vibration which is measured by an accelerometer should be measured according to the coordinate system (x-axes, y-axes, z-axes). WBV should be measured on the surface between the body and the seat interface by placing the accelerometer on the seat pad (ISO 2631-1, 1997). The vibration evaluation, according to ISO 2631-1 (1997), includes measurement of the frequency-weighted root-mean-square (r.m.s) acceleration for all three axes, expressed in m/s^2. Regardless of how WBV is expressed, the axis with the highest vibration level is used to determine exposure (Griffin, 2004).

A fourth-power time dependency is used to determine the VDV as an alternative measure of vibration exposure. The VDV is the accumulation of vibration severity over the exposure period from the shortest possible shock to a full day of vibration; it increases with measurement time, expressed in $m/s^{1.75}$. VDV measures give a better indication of the risks from vibration including shocks (Griffin, 1998).

2.2.4 Factors which influence vibration measurements

According to the European Committee Standardization, EN 14253 (2003), the uncertainty of vibration exposure evaluation is dependent on many factors, including:

- instrument / calibration uncertainty;
- accuracy of source data (e.g. manufacturer's emission data);
- variation of machine operators (e.g. experience, driving speeds or styles);
- ability of the worker to reproduce typical work during measurements;
- repeatability of the work task; and
- environmental factors (e.g. rain, wind, temperature).

An uncertainty value calculated when vibration magnitude and exposure time are measured, can be either 20% above or 40% below the true value. The uncertainty in the evaluation of daily exposures are higher where either vibration magnitude or exposure time is estimated, based on information received from the worker (exposure time) or manufacturer (magnitude) (EN 14253: 2003).

A study done by Pinto and Stacchini (2006) focused on evaluating the contributions of different factors to the uncertainty of daily WBV measurements. Calculations of all measurement uncertainties were made in accordance with the ISO publication "Guide to the Expression of Uncertainty in Measurement". Factors influencing the field measurements were divided into categories, namely: the operators, vehicles, handling of transducers and working cycles. In the category, a number of operators operated a single vehicle, where they focused on different work methods, differences in anthropometric characteristics and posture. In the vehicle category, focus was on the changes in conditions as well as the characteristics of vehicles. Vehicles that performed similar tasks were operated by one operator in the same working cycle. Lastly, the working cycle category, primarily concentrated on the changes occurring on the surface which vehicles was travelling on, within a typical working cycle.

The results of the study concluded that the two factors with the most significant uncertainty components were changes in the characteristics of machines and the different working cycles. A range of 14% < p < 32% for overall percentage uncertainty was reported. According to the authors, failure to account for all the factors which affect vibration, would lead to an inaccurate assessment of the daily eight hour vibration exposure. To summarise, when determining daily eight hour exposures the use of different measurement equipment and different operators contribute least to the uncertainty of a measurement, but on the other hand, characteristics of machines and working cycles contribute substantially to uncertainty (Pinto and Stacchini, 2006).

2.2.5 Health effects of WBV

WBV exposure will lead to physiological as well as pathological health effects (Griffen *et al*., 1990). According to Smith and Leggat (2005) the physiological effects of WBV depend on many variables, namely the magnitude, frequency, direction and duration of vibration, distribution of the motion within the body, and body posture. Smith and Leggat (2005) and Sayed *et al*. (2012) describes the acute effects of WBV exposure as abdominal pain, a general feeling of discomfort, headaches, chest pain, loss of equilibrium (balance), blurred vision, muscle contractions with decreased performance in precise manipulation tasks, shortness of breath, and an influence on speech. The above mentioned effects subside when the vibration source is removed, and is therefore not seen as a major area of concern, but on the other hand, chronic WBV exposure has the capacity to cause long term physiological changes particularly in the spine (Sayed *et al*., 2012). Lower back pain (LBP) is the most common result of WBV exposure and categorised as a musculoskeletal disorder (Smith and Leggat, 2005). Other chronic effects are primarily spine injuries such as disc displacement, degenerative spinal changes, lumbar scoliosis, intervertebral disc disease, degenerative disorders of the spine and herniated discs (Sayed *et al*., 2012). In the following section the focus will be mainly on LBP and other specific health effects.

2.2.5.1 Lower back pain (LBP)

Rozali *et al*. (2009) defined LBP as back pain or discomfort in the back region between the twelfth rib and gluteal folds, with or without a scorching pain down one or both legs, lasting one day or longer. There is a correlation between occupations with exposure to

WBV and LBP (Rehn *et al.,* 2005). A variety of epidemiological studies on LBP among occupational drivers and the link with WBV exposure in high vibration vehicles have been published for agricultural tractors, rally cars, helicopters, forklift trucks, railroad locomotives, buses as well as military vehicles (Beevis and Forshow, 1986; Kumar *et al*., 1999; Mansfield and Marshall, 2001; Hoy *et al*., 2005; Johanning *et al*., 2006; Okunribido *et al*., 2007). Regardless of this association, there is still not enough confirmation to outline an exposure response relationship linking exposure to WBV with LBP disorders (Rehn *et al*., 2005), but taking into account that back problems are reported more by occupational drivers than by any other occupational group (Battié *et al*., 2002), it can be deduced that prolonged exposure to WBV will lead to LBP. LBP is a multifactor problem that includes both work-related and non-work related factors, such as poor posture, age and weight. Factors that can contribute or may possibly even cause LBP in an occupational environment consist of work-related risk factors such as prolonged sitting, lifting, driving speed, seat suspension and type of vehicle as well as individual characteristics such as age and BMI; and psychosocial factors such as work satisfaction (Seidel, 1993; Wilder, 1993; Burdorf and Sorock 1997; NIOSH, 1997; Dunn and Croft, 2004; Mirtz and Greene, 2005; Palmer *et al*., 2003;).

A variety of physiological structures such as bone, muscle, ligament, joints and intervertebral discs could all play a part in contributing to LBP (Kolber and Zepeda, 2006). WBV causes an acceleration of the human body with associated forces acting on the spine; further dynamic internal forces arise from the muscle reaction with intermittent increased and decreased activity of the lower back muscles. Relaxation of the lower back muscles will cause instability in the spine or exert very high forces on the spine. Not only lower back pain but posture and muscle fatigue also contributes to the reaction effect of WBV. Important variables such as postural muscle activity and body mass distribution are affected by gravity. Prolonged seated flexed torso posture (leaning forward) or extended (leaning backwards) can have radically diverse effects on force components in the lumbar spine. A combination of static and dynamic internal forces contributes to the internal load that causes the strain of spinal structures. The severity of the strain depends on the strength as well as the ability of the spinal structure to recuperate from repetitive load (Seidel, 1993). Even though the exact cause for LBP is not always known, there is significant evidence implying that the injured intervertebral discs are a major source of pain (Kolber and Zepeda, 2006).

When exposed to vibration the annular fibers in the spine will be stressed and this could cause increased pressure, finally leading to a failed or herniated spinal disc which protrudes. Thus the resulting pressure on the spinal nerve causes LBP (Smith and Leggat, 2005).

Experimental studies have found that resonance frequencies of the spinal column and some other parts of the body lie between 1 and 10 Hz, which is in the range of dominant frequencies found in occupational vehicles (Paddan and Griffen, 2002). Rozali *et al*. (2009) conducted a cross sectional study among armoured military vehicles drivers in the two largest mechanised battalions with the objective to establish the prevalence of LBP, its association with WBV and other linked factors. A total of 159 respondents participated in this study and 102 (64.2%) of them were subjected to WBV measurements. A total of 117 participants complained of LBP. The occurrence of LBP among wheel-armoured vehicle drivers was lower than that of to tracked armoured vehicle drivers. The aim of a study conducted by Hagberg *et al.* (2006) was to describe the relationship between WBV and musculoskeletal pain, as well as to see whether ergonomic factors (frequent bending and material handling) were confounding to the relationship. It was found that these ergonomic factors played a more important role in causing LBP, than WBV. Nonetheless, WBV is a cause for other musculoskeletal pain in the neck, shoulder/arm and hand segment. Excessive and prolonged WBV exposure will lead to back muscle being fatigued and discs are compressed, the spine is thus under immense strain and will not be able to sustain large loads. Therefore the risk increases for LBP to occur (Pope *et al*., 1998). In a study done by Okunribido *et al*. (2006), it was found that a combined effect of WBV, bad posture and material handling was the main contributor to LBP compared to when individuals were exposed to only one of these factors.

From the literature it seems that many studies completed in the past years have found that WBV is a significant risk factor in causing LBP. However the most recent studies seem to indicate that WBV is not the primary factor causing LBP, but rather serves as one of the multiple contributing factors (Hagberg *et al.,* 2006*;* Okunribido *et al*., 2006; Rozali *et al.,* 2009).

2.2.5.2 Other effects

Motion sickness is caused by low-frequency vibration. An epidemiological study of long term exposure to WBV was done by Seidel and Griffin (2000) and results showed that prolonged WBV exposure led to an elevated risk to health, primarily in the neck and shoulder area.

A study done by Ishitake *et al*. (1998) found a high frequency of gastrointestinal disorders which have been observed in workers exposed to WBV. Findings in this study proposed that short term exposure to WBV can suppress gastric motility by decreasing contractile activity. This suppression is likely to cause gastric disorders such as gastric neurosis and nonulcerative dyspepsia.

El-Said *et al*. (2009) conducted a study regarding the biochemical changes among workers who are exposed to vibration. The study included a total of 165 workers (104 exposed to vibration and 61 as a comparison group). Hematological parameters, a coagulation profile, a lipid profile, liver and cardiac enzymes, trace elements and urinary catecholamine were studied among exposed and control subjects. Significant fluctuations in the levels of tested biochemical parameters were observed among workers exposed to WBV, some parameters increased whilst others decreased. To mention a few, focussing on the lipid profile it was observed that there was a increase in low density lipoprotein (LDL) cholesterol and a decrease in high-density lipoprotein (HDL) cholesterol was observed.

Limited research has been conducted regarding the relationship between vibration exposure and myocardial infarction, but studies have been published indicating vibration exposure as a possible risk for ischemic heart disease (Björ *et al*., 2008). In a case-control study they found that an increased risk of acute myocardial infarction is associated with high vibration exposures. However, it was stated that the occupations assessed included other risk factors such as noise, which could not be separated from vibration, which also has been found to have cardiovascular effects (Björ *et al*., 2008).

2.2.6 Control of vibration exposure

Vibration exposure is complex and needs to be managed to minimise the risk of injury. Certain engineering and administrative control measures are available to reduce vibration exposure (Paschold *et al.,* 2011).

Engineering control measures can be divided into three categories.

1. Limiting vibration at its source taking into account factors such as terrain/area, maintenance and loading of vehicles.
2. Vehicle suspension, cab suspension, seat suspension and tires which all form part of crucial suspension points in order to reduce the transmission of vibration to operator.
3. Optimising operators' posture through improving cab ergonomics such as seat profile (Donati, 2002)

Vibration that is primarily caused by bumpy terrain and rough roads can firstly be reduced by implementing a good road maintenance plan but also by the selection of appropriate tyres and shock absorbers on the vehicle and by provision of suspension cabs (Paschold *et al.,* 2011).

While big machines use tracks, most off-road vehicles make use of pneumatic tires, the use of solid tires are the exceptions. Factors such as cost, stability, rolling resistance and grip should all be kept in mind when tires are selected. It is stated that in terms of vibration reduction and control, large tires cannot compare to a suspension system. Even on reasonably smooth surface roads vibration build up occurs, thus tires would need to absorb five to ten times more vibration energy in order to improve their suspension ability. The ideal tires will have a higher rolling resistance, will be softer and larger, but will have a decreased life span (Donati, 2002). For that particular reason, little can be done on tires to improve vibration attenuation.

Kittusamy and Buchholz (2004) made certain suggestions to control vibration exposure on heavy vehicle operators. These included that a seat design should not only take comfort but vibration transmissibility into account. Seats should also specifically damp vibration in the frequency range of 1-8 Hz. Lastly reduction in speed and good maintenance of heavy vehicles could reduce vibration. Paddan and Griffin (2002) conducted a study and found a broad series of vibration magnitudes on different vehicles when measured. This led to the assumption that proper selection of vehicles and operating conditions could decrease vibration exposure for vehicle operators.

A combination of engineering and administrative controls can thus be used to reduce vibration exposure; these include redesigning machine structures/cabin, work procedures as well as operator training. A literature study by Tiemessen *et al*. (2007) concluded that; (i) a successful intervention program that reduce exposure should combine technical (e.g. seat suspension) and behavioural factors (e.g. driving speed) and (ii) to reduce the occurrence of LBP in drivers exposed to WBV. It is important to identify, develop and execute intervention programs as well as evaluate their efficacy or effectiveness. Only one study done by Hulshof *et al*. (2006) was identified, who developed an all-inclusive occupational health and safety intervention program, aiming to decrease the musculoskeletal complaints by reducing WBV exposure. The results of this study was promising, even though a trend but not a significant reduction in WBV exposure was found ($p = 0.06$).

2.2.7 Guidelines and standards

There are currently no South African standards regulating exposure to WBV and there is no defined occupational exposure limit for vibration for vehicle operators. The South African Bureau of Standards (SABS) has adopted ISO 2631-1 (1997) as SANS 2631-1 as the standard for measuring whole-body vibration in this country.

ISO 2631-1(1997), Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration, specifies a guideline for dangerous levels of vibration exposure relating to health effects. This can be found in Annex B of the standard.

Table 2.1: Summary of vibration exposure Action Level and Limit level (ISO 2631-1, 1997 and EU Directive 2002/44/EC).

Values	**RMS**	**VDV**
EAV (Action Value)	0.5 m/s^2	9.1 $m/s^{1.75}$
ELV (Limit Value)	1.15 m/s^2	21.0 $m/s^{1.75}$

The EU Directive 2002/44/EC is another standard used in Europe. It specifies "daily action exposure levels" and "daily exposure limits" above which the employer must take necessary technical, administrative and medical measures to protect the workforce. It describes these limits in terms of two separate units namely A(8) which is the daily acceleration value normalised over an eight hour period and VDV which is the Vibration Dose Value. The action level for WBV is given as 0.5 m/s^2 r.m.s. and 9.1 $m/s^{1.75}$. The exposure limit is given as 1.15 m/s^2 r.m.s. and 21 $m/s^{1.75}$.

Table 2.2: Permissible 8 – hour and 12- hour average vibration exposure. (ISO 2631-1, 1997).

Exposure Duration	**Likely health risk**	**Caution Zone**	**Comfort level**
8 - hours	0.8 m/s^2	0.5 m/s^2	0.315 m/s^2
12 - hours	0.7 m/s^2	0.4 m/s^2	0.315 m/s^2

2.3 Noise

Concha-Barrientos *et al*. (2004) made the statement in their study that there is no difference between sound and noise, as sound is a sensory insight and noise relates to unwanted sound. By definition, noise means any sound that could adversely affect health (MHSR,2002). In all human activities a part thereof consist of noise, if assessing the effect of noise on human well-being it is characterised either as occupational noise (noise in the workplace), or as environmental noise (e.g traffic, playground, music) (Concha-Barrientos *et al.,* 2004).

Across different commodities particularly in mining, excessive exposure to noise levels causes hearing loss; this has been found to be a worldwide problem (McBride, 2004; Kurmis and Apps, 2007). In 2004, McBride stated that NIOSH (National Institute of Occupational Safety and Health) estimates shows that 80% of US (United States) miners are exposed to noise levels exceeding the time-weighted average (TWA) of 85 db(A) and that 25% of these are even exposed to TWA noise levels above 90 dB(A). In 2010 estimates reported by NIOSH showed that 30 million workers are exposed to excessive noise levels that cause irreversible hearing loss (Martinez, 2012). In 2013 the WHO reported that 360 million people have been identified with hearing loss, which is over 5% of the world's population (WHO, 2013). The Department of Mineral

Resources states that currently in South Africa a total of 1600 cases of NIHL are reported yearly (Booyens, 2013).

2.3.1 Biomechanics of noise

Sound exists in a broad range of frequencies (Leventhall, 2003), where the human ear distinguish sound within the 20 Hz to 20 kHz frequency range. Frequencies between 1kHz and 10kHz are easier perceived by the human ear (Alves-Pereira and Castelo Branco, 2000). Frequency (or ‘pitch’) and intensity (‘loudness’) are both important factors used to describe and understand sound (Cherimisinoff, 1996). Frequency of sound can be defined as the rate of oscillation of air particles formed by a noise source, measured as cycles per second, called hertz (Hz) (Cherimisinoff, 1996). Intensity of sound can be defined as the amount of energy that vibrating particles deliver to the receptors (Cherimisinoff, 1996).

Thus, sound is the end result of a noise source setting a medium, normally air, into vibration, where the ears are the receptors (Guyton and Hall, 2006). The human ear is divided into three different sections, the outer ear, the middle ear, and the inner ear. The outer ear acts much like a channel, collecting the sound waves and transfers it via a passage (ear canal) that's about 3 cm long, ending at the tympanic membrane (eardrum). The thin tympanic membrane separates the outer ear from the middle ear, which vibrates when sound waves reaches it. The middle ear consists of a set of three small bones, called the hammer, anvil and stirrup. They transfer the sound wave (vibration) from the tympanic membrane to the inner ear. The cochlea is a liquid filled tube curled up and is shaped like a shell, about 3 cm in length and roughly 2 mm in diameter, and is divided along its length by the basilar membrane. It also consists of a set of sensory hair cells which convert these vibrations into nerve impulses, where the brain interprets these impulses into sound.

Loudness of sound is determined in three ways; (i) as sound increases, the amplitude of vibration of the basilar membrane and hair cells will amplify, thus the nerve endings of the hair cells will excite more rapidly; (ii) when vibration amplitude is increased, impulses will be transmitted through a wider range of nerve fibers because more hair cells are stimulated which are located on the outer edge of the resonating part of the basilar membrane; (iii) the basilar membrane should first reach a high intensity then only will the outer hair cells be stimulated, which conveys the message to the nerve system that the sound is loud (Guyton and Hall, 2010).

2.3.2 Health effects of noise

2.3.2.1 Noise induced hearing loss

Many definitions have been given for noise induced hearing loss (NIHL). It is mainly caused by extreme or prolonged exposure to noise that manifest over a number of years and result in bilateral and symmetrical impairment of hearing (McBride, 2004). Numerous factors such as age, exposure to various sources of noise and length of time exposed to noise all contribute to hearing loss (McBride, 2001). Edward *et al.* (2011) conducted a study which focused on the noise exposure profile of South African mines. They found that the mean noise exposure of miners ranged between 63.9 to 113.5 dB(A), thus an estimate of 73.2 % of workers are exposed to noise levels higher than the legislated OEL of 85 dB(A).

Exposure to intense noise or to prolonged loud noises, damages the hair cells. If damage exceeds the cells ability to repair themself, they die, leading to noise-induced hearing loss (Bohne *et al.,* 2007). Kurmis (2007) states that a person with NIHL loses the ability to hear sound between 4 kHz – 6 kHz, within this frequency range most of the human speech is present, therefore leading to the inability to understand and discriminate speech.

Within the cochlea, the organ of Corti is located on the basilar membrane, containing both the inner and outer hair cells (Guyton and Hall, 2006). Excessive exposure to noise increases the Ca^{2+} concentration within the hair cells. Increased Ca^{2+} levels in turn have different effect/consequences namely, activation of Ca^{2+} - regulated enzymes and mitochondrial Ca^{2+} overload. Ca^{2+} overload leads to cytotoxity and trigger cell death pathways (Hu and Zheng, 2008). Different modes of cell death have been identified, namely active and passive cell death (Hu and Zheng, 2008). Apoptosis, requires a constant energy supply, this is an active mode of cell death. Passive mode cell death is primarily due to early disintegration of cells, this is called necrosis. Apoptosis are the primary cell death pathway leading to cochlear lesions (Hu and Zheng, 2008).

Production of free radicals is another important factor which contributes to NIHL. Noise exposure causes production of free radicals within the inner ear by increasing cell metabolism. These free radicals are produced by cell mitochondria. Free radicals can be defined as molecules with one or more unpaired electrons and includes reactive oxygen species known as ROS. As much as they are important for normal cellular function, an overload of these molecules will damage the cellular lipids, proteins and DNA. Free radicals caused by excessive noise can be neutralised with a variety of antioxidant agents, including glutathione (primary cellular antioxidant) (Le Prell *et al.,* 2007).

Excessive exposure to high noise levels is not limited to permanent hearing loss only, but shorter exposures may cause temporary threshold shifts (TTS). The mechanism of the human auditory is extremely tolerant to abuse and consist of many ways to protect it from damage when exposed to very loud sounds. One of these is to decrease sensitivity, this will lead to an upwards threshold shift in hearing. Hearing will subsequently recover within hours or days depending on how loud the noise have been and exposure is not repeated (Ross, 2007). Horie (2002) makes the statement that TTS can be used as future predictor for noise-induced hearing loss.

2.3.2.2 Stress and cardiovascular effects of noise

Studies have been published which assessed the relationship between community noise and cardiovascular disease (Porter, 1998; Babisch, 2000; Passchier-Vermeer and Passchier, 2000). Prolonged environmental noise exposure leads to higher stress hormone regulation as well as, increasing endogenous risk factors of ischemic heart diseases (IHD). Thus, a higher risk of myocardial infarction is likely to occur (Ising and Kruppa, 2004). Babisch *et al.* (2003) studied the association between annoyance and disturbances due to road traffic noise and the incidence of ischemic heart disease in 3950 middle aged men. They concluded that there is a strong relationship between noise annoyance and health outcomes such as high incidence of IHD.

Noise exposure leads to the release of stress hormones which are linked to certain physiological effects such as cardiovascular disease. The hypothesis associating noise and stress are well studied and understood in that noise activates the sympathetic-adrenal-medullar axis and pituitary-adrenal-cortical axis. Thus after acute and chronic noise exposure a change in the stress hormones, cortisol, epinephrine and norepinephrine are observed (Babisch, 2002).

The effects of chronically high levels of cortisol include; (i) stress ulcers, (ii) immuno suppression, reduced circulation of basophilic and eosinophilic granulocytes and leukocytes, (iii) catabolic effects such as protein breakdown in muscles, (iv) anti-anabolic effects such reduction in muscle protein synthesis, (v) diabetogenic effects such as inhibition of glucose use and transport (vi) hypertonic effects such as increased renal sodium retention and increased sensitivity of adreno receptors of vasomotors (vii) adipose tissue metabolism, a higher level of fatty acids in blood increased by lypolysis triglycerides and thus a risk for arteriosclerosis (Spreng, 2000).

Hormones such as, cortisol, epinephrine and norepinephrine are known as neurotransmitters. These stress hormones form part of a positive-negative feedback system which affects blood pressure, blood lipids, blood clotting, blood glucose and heart activity (Babisch, 2003).

It may be concluded that the risk of cardiovascular disease may increases as a result of prolonged noise exposure.

2.3.2.3 Other effects

Exposure to noise also affects workers in non-auditory ways, this include behavioral effects and safety (Steenkamp, 2003). Palmer *et al*. (2001) stated that excessive noise leads to an increased effort to hear and has a ‘domino effect’ of increased frustration, stress and fatigue. Morris (2006) observed that interference in thought processing and task execution occurred when exposed to noise.

Increased listening effort and higher concentration levels are needed when workers are constantly exposed to noise in a working environment. Constant noise exposure leads to higher levels of irritability, nervousness and disturbance in sleep patterns, which then in turn again result in decreased concentration (Morris, 2006).

Excessive noise is thus negatively linked to safety due to the fact that it distracts the workers attention and ability to concentrate and also drowns out the sound of alarm signals or warning shouts and malfunctioning machines (Dineen, 2001).

Apart from these effects, another occupational health hazard emerging is low frequency noise (LFN). Excessive exposure to LFN was found to cause extra-aural effects in the form of Vibroacoustic disease (VAD) (Castelo Branco and Alves-Pereira, 2004). VAD causes abnormal proliferation of extra-cellular matrices, defined as a noise-induced whole body, systemic pathology (Castelo Branco and Alves-Pereira, 2004). Cardiac infarction, cancer, stroke, epilepsy and rage reaction are some of the health effects that may occur after years of exposure. Currently no legislation concerning LFN is available and research done on low frequency noise is limited.

2.3.3 Occupational noise sources

People are daily exposed to a wide range of noise caused by occupational and non-occupational activities, such as transportation and leisure (Diaz, 2006). In mining, miners are not only exposed to loud noise levels but also to continuous noise (Sensogut, 2007). Typical mining noise sources include pneumatic drills, extracting equipment, diesel powered haulage equipment, blasting, cutting, materials handling, ventilation, crushing conveying and ore processing (Donoghue, 2004; McBride, 2004; Edward *et al*., 2011).

Watts and Stait (2008) conducted a study on vehicles producing excessive noise and/or vibration. They found that vehicle body rattle noise is likely to be the cause of most excessive noise exposure. Another relative cause of high noise levels is exhaust noise. The exhaust system of older machines usually produce higher noise levels than new machines, thus the age of the vehicle is an important factor. They also stated that air turbulence has an indirect effect on noise production, as loose covers and securing straps vibrate and flap, causing noise across a wide range of frequencies.

A study done by Spencer and Kovalchik (2007) assessed high noise levels in operators of heavy construction equipment. They reported noise levels between 95 and 99 dB(A) for bulldozers, 80-82 dB(A) for haul trucks equipped with air conditioning and 90-92 dB(A) without. Factors such as radios and open windows contribute to increased sound levels within a cab. Excavators and front-end loaders had the lowest noise levels, 76 - 78 dB(A) and 76 - 80 dB(A), respectively.

A study done by Kisku *et al.* (2002) monitored noise sources from equipment to help assess what the impact of bauxite mine noise has on employees. They found that the highest noise levels was from rock breakers which ranged between 87.3 dB(A) to 99.6 dB(A) and dozers with noise levels between 82.4 dB(A) to 87.3 dB(A).

Sixty to seventy percent of workers in the Spanish construction industry are exposed to noise levels above the recommended limit of 85 dB(A). Machines were utilised in high risk areas while sound measurements was taken. According to these findings high noise levels are a significant problem in sectors such as construction and manufacturing (Férnandez *et al*., 2008).

2.3.4 Control of noise exposure

Controlling noise exposure is a legal responsibility but will also contribute to a safer and healthier workplace, which leads to a decrease in absenteeism, accidents and enhance performance; this is also financially beneficial to a company (Fernández *et al.,* 2008). Many companies simply issue PPE (Personal Protective Equipment), even though legislation requires companies to use hearing conservation measures and engineering tools available to reduce noise levels (Bruce and Wood, 2003).

2.3.4.1 Engineering control

According to Nelson (2005) the use of engineering controls can reduce noise at its source and will minimise the NIHL burden. The use of vibration isolation mountings, reduction of external vibration parts, operator's sound proof booths, sound absorptive material in high noise areas are all first-level noise control measures (Standard, 2002).

The European Agency for Safety and Health at work (2005) compiled a list of engineering control measures considering equipment and workplace maintenance in order to reduce noise exposure;

- Rotational use or replacement of machines/tools
    - Use of belt drives rather than noisy gears
    - Use electrical tools rather than pneumatic tools.
- Isolation of the source
    - Use dampening materials such as air springs, rubber linings or elastomeric supports.
- Reduction at the source
    - Use barriers and enclosures
    - Exhausts silencer or mufflers
    - Reduce impact and cutting speed

- Maintenance
    - Preventive maintenance as parts becomes worn.

Noise control at the design stage is costly (Bies and Hansen, 2009). It is easier to design noise control measures into new machines than to apply it to already existing machines (Standard, 2002). In a study conducted by McBride (2004) it was stated that "buying quiet" along with a good maintenance plan focused on noise sources, would lower noise levels in the mining environment effectively. In some cases the only practical method for noise control is to make use of a barrier or enclosure.

2.3.4.2 Administrative control

One way of administrative noise control is the rotation of workers from noisy areas (Standard, 2002). Scheduling machine operating times in order to minimise operator exposure, is another form of administrative control that can mitigate noise exposure.

2.3.4.3 Personal protective equipment

Hearing protection is effective in redusing exposure to noise, but should be considered as a last resort (Steenkamp, 2003). Hearing protection can be divided into two basic categories namely; (i) ear muffs, which cover the ear and (ii) ear plugs, which are inserted into the ear canal. These types of hearing protection come in a variety of forms and degrees of protection. According to McBride (2004), in high noise areas, ear muffs may be the best protection but ear plugs perform better due to the fact that they are not as easily removed.

In a study conducted by Kurmis and Apps (2007), results showed that 98% of workers knew that hearing protection devices (HPD) should be worn but only 50% of workers complied with hearing protection usage. A reason for non-compliance was primarily discomfort experienced when HPD was used (Kurmis and Apps, 2007). Factors such as sound control, ventilation, physical fit, speech discrimination and level of isolation, all influence comfort (Steenkamp, 2003).

Custom made hearing protection devices (CHPD's) are better regarded by mining workers than "one size fits all" HPD's, due to the fact that CHPDs are custom made which increases comfort levels, sound control, ventilation etc. (Steenkamp, 2003). These factors all contributed to the fact that CHPD were observed to be worn more and thus effectively protect an individual hearing which leads to a safer work environment (Steenkamp, 2003).

2.3.5 Quantifying noise

Noise can be described in terms of intensity (loudness) and frequency (pitch) (Cherimisinoff, 1996). A logarithmic scale is used for measuring sound intensity in units called decibels (dB) (Franz, 2007). Noise exposure measurements are expressed as dB(A), a scale weighted toward sounds at higher frequencies, to which the human ear is more sensitive and for compliance with the Mine Health and Safety act (MHSA) and SANS 10093: 2012, that specify permissible noise exposures in terms of a time-weighted average sound level or daily noise dose (Franz, 2007). Based on the logarithmic scale, a 3-dB increase in sound pressure level (SPL) represents a doubling of the sound intensity. Thus, four hours of noise exposure at 88 dB(A) is considered to provide the same noise dose as eight hours at 85 dB(A) (Laventall, 2003).

2.3.6 Guidelines and standards

The Regulations under the South African Mine Health and Safety Act 1996 (Act 29 of 1996), The Regulation of NIHL under the Occupational Health and Safety act 1993 (Act 83 of 1993) and the South African National Standard (SANS 10083:2012) reports an OEL of 85 dB(A) for an 8 hour shift.

In 2003, the mining sector set two targets to eliminate noise-induced hearing loss, namely;

- no deterioration in hearing greater than 10% amongst occupationally exposed individuals after December 2008

- the total noise emitted by any equipment to not exceed 110 dB(A) at any location in that workplace, by December 2013 (DMR, 2003)

2.4 Summary

It is apparent from previous research that operators of EME are exposed to occupational hazards such as noise and vibration. Exposure levels above the legal limits were predominantly reported, which in turn leads to many adverse health effects. Consequently there should be more focus on implementing preventative measures to reduce exposures significantly.

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Chapter 3: Article

The Results and Discussion section in this chapter is presented separately, and also note that tables and figures are not placed at the end as described, in order to ensure fluency for examination.

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8. **Survey design.** Sampling surveys should be planned using modern statistical principles so that the quality of the data is good enough to justify the inferences and conclusions drawn.

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Article

Exposure of earth moving equipment operators to vibration and noise at an opencast coal mine

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Abstract

Objectives: Whole-body vibration (WBV) and noise exposure of earth moving equipment (EME) operators were assessed at an opencast coalmine in South Africa. The aim was to evaluate and quantify the levels of exposure in different EME types, as well as to compare old with new EME, in order to estimate if machine hours contribute to higher noise and vibration levels. WBV and noise levels of the Production and Rehabilitation operations were compared, to determine whether differences in exposure levels occur.

Methods: International accepted methods, ISO 2631-1 for WBV and SANS 10083:2012 for noise were followed and correctly calibrated instrumentation were used. WBV measurements were conducted with a tri-axial seat pad accelerometer (SVAN 958) and personal noise dosimeters (Casella 35 X) were used for noise measurements. Measurements were taken over a period of four months.

Results: With regards to the EU limit (1.15m/s^2) and the EU action limit (0.5 m/s^2) it was noted that operators of EME within the Production operation were not exposed to WBV levels above the EU limit, but 77% of these operators were exposed to WBV levels above the EU action limit. It was also evident that 45% of operators' vibration levels were within Health Guidance Caution Zone (HGCZ) of 0.45 – 0.90 m/s^2. Within the Rehabilitation operation, 9% of operators were exposed to WBV levels above the EU limit and 55% above the European action limit. Furthermore 50% was within the HGCZ. With regards to the Occupational exposure limit (OEL) of 85 dB(A) as stated by the South African National Standard (SANS 10083:2012) it was noted that 27% of operators within the Production operation were exposed to noise levels above the limit and for operators within the Rehabilitation operation 14% were reported to be above the limit. Statistically significant difference was found between the Production operation and Rehabilitation operation noise levels. Results indicated that the majority of EME operators were exposed to high noise levels, in some cases exceeding the 85 dB(A) limit. A significant positive correlation was found between noise exposure levels and machine hours. Thus higher noise levels were observed as machine operating hours increased.

Conclusion: It was found that operators were exposed predominantly to vibration and noise levels below the limits. However the Dozer group within the Production and Rehabilitation operations had in some cases exceeded the vibration and noise legal

limit. High exposure levels within the Dozer group can be attributed to the fact that these EME types mostly perform activities in uneven areas and the tracks on which these Dozers move also contribute to higher vibration levels due to a lack of shock absorbers. Controls should be implemented as far as is reasonably practicable to ensure that operators are not exposed above recommended or permissible levels for each hazard. Continuous improvement of the maintenance plan for all EME and regularly grading and maintaining travelling ways are some of the controls that will contribute to lower vibration and noise levels.

3.1 Introduction

Mining companies in South Africa are known to be world leaders in mining and key players in this global industry (Kaplan, 2011). Mining consist of many different trades and professions (Donoghue, 2004). One of the functions within mining is operating of earth moving equipment (EME) such as haul trucks, dozers, excavators and graders. EME are generally used to shift large amounts of earth, dig foundations and landscape areas. Within the Production operation EME operators will mostly perform activities which include exposing coal (drilling, blasting and dozing) and extraction of coal (dozing, loading and dumping). Whereas within the Rehabilitation operation, EME operators will perform activities such as loading, dumping and levelling of discard and topsoil materials. These workers usually work extended shifts of ten hours or longer, which increases their exposure to hazards. Operators of EME are predominantly exposed to hazards such as whole body vibration (WBV) and noise (Eger *et al*., 2006). Noise and vibration are closely linked due to the fact that their physics are similar in that they are both transmitted as waves through a medium. While the specific health related effect caused by noise and vibration differ, they are both of importance and their effect can manifest after a long period of latency (Groothoff, 2012). The occurrence of noise and the related health and safety effects have been extensively studied in the mining and related industries. Even though an increase in numbers of WBV exposure in mobile equipment has been observed, still far less attention has been given to WBV in relation to noise (Van Niekerk *et al.,* 2000).

WBV can be defined as mechanical oscillations which are transmitted through the whole body by a vibration source through contact by the buttocks or feet and have a frequency range from 0.01 Hz to 50 Hz (Uchikune, 2002; Hagberg *et al.,* 2006; Rozali *et al.,* 2009).

Thousands of workers in the EME operating sector are exposed daily to WBV (Seidel, 1993). Effects such as interference with activities, impaired health and discomfort are mostly experienced by operators when exposed to vibration (Griffen, 1990). Hagberg *et al.* (2006) stated that there is a strong association between WBV exposure and increased risk of lower back pain (LBP), spinal degeneration and sciatic pain. It is evident from previous studies that high levels of WBV exposure are experienced in the mining and construction sector (Cann *et al.,* 2003; Kumar 2004; Aya and Heyns, 2011). Factors which contribute to WBV are vehicle activity, engine vibration and rough roads. (McPhee *et al.,* 2009). Another key factor which also contributes to significant vibration exposure is the frequent and intensive usage of EME over prolonged periods (Griffen, 1990).

There are currently no South African legislation regulating exposure to WBV. The South African Bureau of Standard (SABS) has adopted ISO 2631-1 (1997) as SANS 2631-1 as the standard which govern the way in which human vibration should be measured and reported, as well as provide indication of health risks involved. Another international standard used is the European Parliament legislation (EU Directive 2002/44/EC, 2002) which stipulates minimum standards for health and safety of workers exposed to WBV. This directive mandates a WBV exposure limit of 1.15 m/s^2, and an action level of 0.5 m/s^2 for an equivalent eight-hour exposure period.

Aya and Heyns (2011) conducted a study on a wide range of mining equipment, such as dozers, excavators and dump trucks at a South African opencast mine. The results obtained showed that 95% of vibration levels were below the European exposure limit value of 1.15 m/s^2, but 50% of vibration measurements were above the European exposure action limit value of 0.5 m/s^2. Similar results were obtained from other studies supporting the fact that action should be taken to reduce vibration levels (Cann *et al.,* 2003; Kumar, 2004).

Noise is a common hazard present in all commodities and daily activities; including operators of EME (McBride, 2004). Excessive exposure to noise has an impact on the safety and productivity of operators, as noise limits the operator's ability to communicate and hear warning signals (Edward *et al.,* 2011). Noise also has an impact on health such as, elevated blood pressure, tinnitus, sleeping abnormalities, annoyance and stress and temporary hearing threshold shift (Nelson *et al*., 2005). Noise induced hearing loss (NIHL) is the most common health risk caused by extreme or prolonged exposure to noise that manifest over a number of years (McBride, 2004). NIHL is preventable but a high prevalence of NIHL is still reported (Booyens, 2013). According to the Department of Mineral Resources, in South Africa there is an estimated of 1600 NIHL cases reported yearly (Booyens, 2013). Two targets were set in 2003 for the mining sector to eliminate NIHL, namely (i) no deterioration in hearing greater than 10% amongst occupationally exposed individuals after December 2008 and (ii) the total noise emitted by any equipment to not exceed 110 dB (A) at any location in that workplace, by December 2013 (DMR, 2003).

The Regulations under the South African Mine Health and Safety Act 1996 (Act 29 of 1996), NIHL Regulations under the Occupational Health and Safety act 1993 (Act 85 of 1993) and the South African National Standard (SANS 10083:2012) reports a OEL of 85 dB(A) for an 8 hour shift.

In a study conducted by Spencer and Kovalchik (2007), they reported noise levels of EME to range between 80 to 120 dB(A), with dozers, graders and haul trucks being responsible for the highest levels. Bealko (2008) conducted a study assessing noise levels within the cabin of a variety of haul trucks. New and old trucks and old trucks with cabins that were refurbished were included. He reported in both categories of old trucks an average noise level which exceeded the 85 dB(A), but no significant noise levels above 85 dB(A) were found for the new truck category.

Research regarding noise and whole-body vibration exposure on mining equipment is limited. This study will provide additional information regarding WBV and noise exposure on mining vehicles in particular EME at an opencast coal mine in South-Africa. The aim of this study was to evaluate and quantify the levels of exposure of EME operators at a South African opencast coal mine to whole-body vibration and noise, as well as to assess and compare old with new EME, in order to estimate if machine operating hours contribute to higher noise and vibration levels.

3.2 Methodology

3.2.1 Approach

Data for WBV and personal noise exposure were collected simultaneously during normal working operations. Two different fleet sets of vehicles were selected based on availability and participation in certain activities, namely mining (Production) and Rehabilitation, and vehicles of the same kind were grouped together during the study. These groups of EME are representative for the whole fleet for Production and Rehabilitation operations respectively. Vehicles such as busses or LV (Light Vehicles) that were primarily used for transporting of personnel were not included. The different EME groups which were included are different types of dozers, front-end-loaders, dump trucks, excavators, graders, diesel/water-bowsers. From the Production operation, drills were also included and from the Rehabilitation operation, tractor-loader-backhoes.

Table 1: EME types and number of EME included for both vibration and noise measurements.

EME Type	Number of EME	
	Production operation	**Rehabilitation operation**
Pit Viper Drills	2	N/A
Dozers	6	6
Front-end-loaders	2	N/A
Dump Trucks	4	4
Excavators	2	4
Graders	2	2
Water Bowser	2	2
Diesel Bowser	2	2
TLB	N/A	2

*N/A: Not applicable

3.2.2 Whole-body Vibration Measurements

Vibration measurements were done according to the measuring procedure outlined in ISO 2631-1, Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration – Part 1: General Requirements (1997). A SVAN 958 (SVAN AND DYTRAN, South Africa) (four channel sound & vibration level meter & analyser) whole body vibration monitor (Serial number: 208733925; Calibration date: 5-6 December 2012) with a whole body accelerometer pad was used to measure whole body vibration levels. Acceleration levels were measured on the operator seat of the selected EME in three perpendicular directions (x- longitudinal, y- transverse and z- vertical), for a time period of approximately two hours, during a morning shift prior to a fatigue break or approximately two hours after a fatigue break. In accordance with company policy, travelling speed didn't exceed 60 km/h on haul roads and 40 km/h in the pit. No further restrictions were placed on the route to follow or how to operate the EME.

In accordance with the ISO 2631-1, different weightings and multiplying factors were used for different axis, namely: Wd weighting with a multiplying factor of 1.4 was used for both x and y axis and Wk weighting with a multiplying factor of 1 for the y-axis. Analyses of measurements were done using SvanPC+ ver. 1.0.2.1k software and the Health, Safety Environment and Community (HSEC) vibration calculator. Exposures were adjusted to an eight hour equivalent and reported as r.m.s acceleration values (m/s^2).

3.2.3 Noise Measurements

For this study noise measurements were performed according to the SANS 10083:2012: The measurement and assessment of occupational noise for hearing conservation purpose. Casella 35 X (Casella, South Africa), calibrated noise dosimeters were used for monitoring personal noise exposure of operators. Each dosimeter was calibrated using a Casella Cel-110/2 acoustic calibrator prior to measurements. A pre-sample calibration value as well as post-sample calibration values were noted to determine the calibration deviation, if the deviation was above 5%, the sample was rejected. The dosimeters were fastened with a clip to the operator's clothes, on the side of the shirt collar (shoulder) within the hearing zone (close to the ear) and measurements were taken for a full cycle or 7-8 hours. The data obtained from dosimeters $L_{Aeq,8h}$ were adjusted to normalise noise exposure levels for extended work shift according to the Australian/New Zealand standard (AS/NZS 1269.1:2005).

3.2.4 Statistical analysis

WBV and noise data gathered from EME operators for Production and Rehabilitation operations were kept separately because the activities that are predominantly performed by these groups are different as well as the location and route where these activities occurred.

Data was gathered and statistically analysed using Graphpad Prism 5.1 and Statistica© Software v10.0. Basic descriptive statistics were used to determine the arithmetic mean and standard deviations. The statistical significant differences were determined through one-way ANOVA analysis, as well as unpaired t-tests. A value of $r \geq 0.5$ and ≤ 1.0 is indicative of a moderate to perfect correlation respectively. A p-value of ≤ 0.05 indicates a statistically significant difference. Based on a normality test outcome, either a Pearson or Spearman correlation test was performed with a linear regression to determine correlations. Data was illustrated with Graphpad Prism 5.1.

3.3 Results

3.3.1 Vibration

The European Directive 2002/44/EC has been adopted by the employer (mining company) as the method for assessment of WBV exposure. The EU Directive 2002/44/EC states that the axis with the highest acceleration level is used to assess vibration measurements. WBV data will be primarily compared to the limit level of 1.15 m/s^2 and action level of 0.5 m/s^2 as stated by the European Directive 2002/44/EC. But to understand and get a clear picture of the health effects caused by WBV exposure, data will also be compared to the Health Guidance Caution Zone (HGCZ) which ranges between 0.45 m/s^2 and 90 m/s^2 as stated by ISO 2631-1 (1997). WBV levels above the HGCZ are likely to lead to health effects, whereas levels within the parameters indicate a risk of causing health effects and there are no clear health effects for levels below the HGCZ.

The mean frequency weighted r.m.s acceleration values of the three vibration axes of different EME operator groups for both the Production operation and Rehabilitation operation are summarised in Tables 2 and 3, respectively. There was no statistical significant difference ($p > 0.497$) found between WBV levels of the two EME operator groups, i.e. the Production operation and Rehabilitation operation.

Table 2: WBV exposure (mean ± SD) per EME operator group for the Production operation compared to the EU Directive and ISO 2631 -1.

EME Group	n	A(8) equivalent, exposure time in m/s^2			EU Directive	ISO 2631-1 HGGZ
		X	Y	Z		
Drills	2	**0.52 ± 0.02**	**0.52 ± 0.01**	0.22± 0.01	Above action level	Within HGCZ
Dozers	6	1.02 ± 0.04	**1.10 ±0.09**	0.87 ± 0.06	Above action level	Above HGCZ
FEL	2	0.27 ± 0.01	**0.39 ±0.03**	0.23 ±0.01	Below action level	Below HGCZ
Dump Trucks	4	**0.89 ± 0.05**	0.66 ±0.09	0.63 ±0.08	Above action level	Within HGCZ
Excavator	2	0.50 ± 0.04	**0.51 ±0.02**	0.40 ±0.01	Above action level	Within HGCZ
Grader	2	0.52 ± 0.02	**0.55 ±0.01**	0.26 ±0.03	Above action level	Within HGCZ
Water Bowser	2	0.36 ± 0.02	**0.47 ±0.06**	0.33 ±0.04	Below action level	Within HGCZ
Diesel Bowser	2	0.36 ± 0.01	**0.44 ±0.01**	0.29 ±0.01	Below action level	Below HGCZ

Indicated in bold is the highest axis value per vehicle type
European Directive: Action level – 0.5 m/s^2 and Limit level – 1.15 m/s^2
ISO 2631-1: HGCZ range between 0.45 m/s^2 – 0.90 m/s^2

It is clear from Table 2 that there are no mean vibration exposure levels above the EU limit level, but five out of the eight EME groups exposed operators to vibration levels above the EU action levels. It is also indicated that five of the EME operator groups are within the HGCZ and only one operator group (Dozers) was found to be above the HGCZ.

From Figure 1 it can be seen that within the Dozer operator group only one was above the European limit level, and that vibration levels for EME operators were predominantly above the European action level.

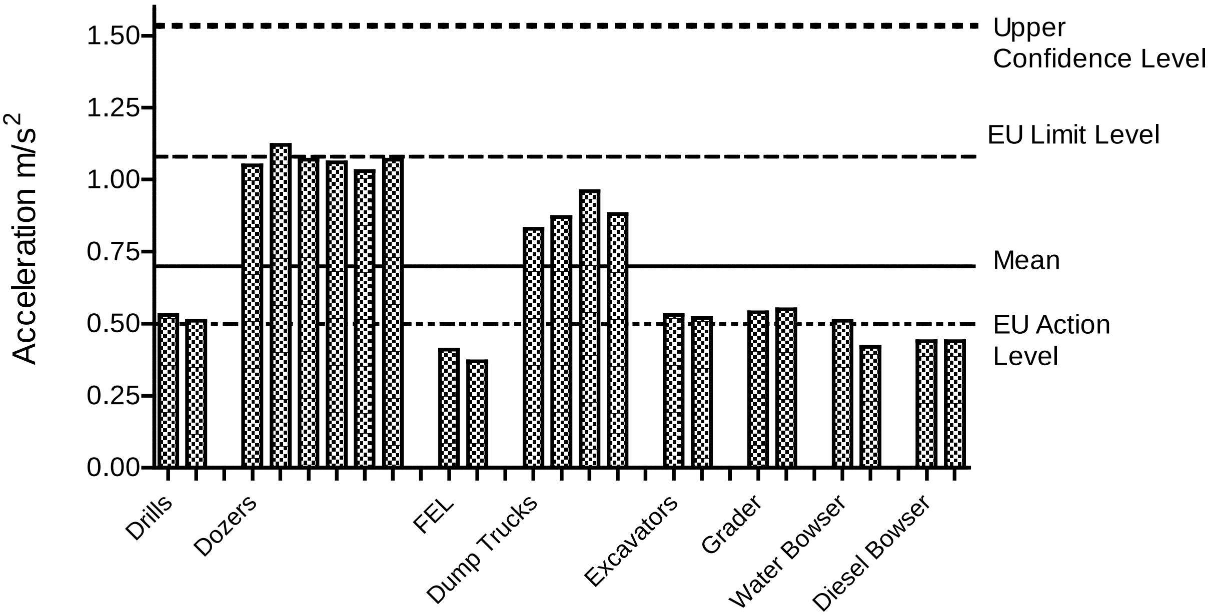

Figure 1: WBV levels of operators of different EME groups within the Production operation.

Table 3 indicates that there are no vibration exposure levels above the EU limit level, but three out of the seven EME operator groups exposed operators to vibration levels above the EU action levels. Four of the EME operator groups were found to be within the HGCZ, with only one group (Dozers) above the HGCZ.

It is evident (Figure 2) that within the dozer group two operators had vibration exposures which were above the European limit level. It is also clear that vibration level for EME operators were predominantly above the European action level.

Table 3: WBV exposure (mean ± SD) per EME operator group for the Rehabilitation operation compared to the EU Directive and ISO 2631 -1.

EME Group	n	A(8) equivalent, exposure time in m/s^2			EU Directive	ISO 2631-1 HGGZ
		X	Y	Z		
TLB	2	0.33 ± 0.06	**0.36 ± 0.04**	**0.36 ± 0.01**	Below action level	Below HGCZ
Dozers	6	0.81 ± 0.09	**0.98 ± 0.23**	0.44 ± 0.05	Above action level	Above HGCZ
Dump Trucks	4	**0.77 ± 0.04**	0.56 ± 0.04	0.50 ± 0.14	Above action level	Within HGCZ
Excavator	4	**0.50 ± 0.02**	0.47 ± 0.07	0.31 ± 0.03	Above action level	Within HGCZ
Grader	2	0.42 ± 0.02	**0.46 ± 0.01**	0.24 ± 0.01	Below action level	Within HGCZ
Water Bowser	2	0.33 ± 0.02	**0.40 ± 0.06**	0.29 ± 0.04	Below action level	Below HGCZ
Diesel Bowser	2	0.30 ± 0.04	**0.39 ± 0.01**	0.25 ± 0.01	Below action level	Below HGCZ

Indicated in bold is the highest axis value per vehicle type
European Directive: Action level – 0.5 m/s^2 and Limit level – 1.15 m/s^2
ISO 2631-1: HGCZ range between 0.45 m/s ^{2} – 0.90 m/s ^{2}

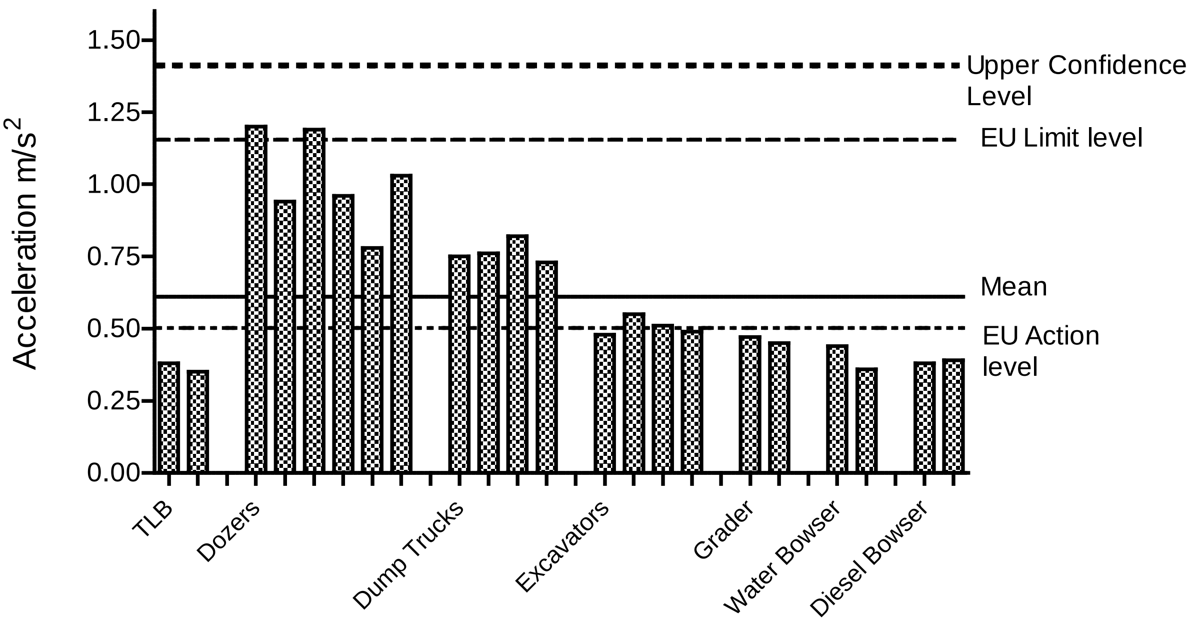

Figure 2: WBV levels of operators of different EME groups within the Rehabilitation operation.

3.3.2 Noise

Tables 4 and 5 summarises the mean A-weighted equivalent sound levels measured per EME operator group for both the Production operation and Rehabilitation operation respectively. To assess the risk of noise exposure to the human ear, an A-weighted scale is used (Franz, 2007). Both the Regulations of the South African Mine Health and Safety (MHSR 2002) and The South African National Standard (SANS 10083:2012) states that a worker should not be exposed to noise levels equal or above the 8 hour exposure rating limit of 85 dB(A). A statistical significant difference ($p \leq 0.001$) was found between noise exposure of the two EME operator groups, Production operation and Rehabilitation operation.

Table 4: L_{Aeq} A-weighting per EME operator group (mean ± SD) for the Production operation, compared to the OEL of 85 dB(A) limit.

EME Group	N	Dosimeter – dB(A) (mean and SD)	Minimum dB(A)	Maximum dB(A)	Regulation of MHSR 85 dB(A)
Drills	2	82.3 ± 1.4	81.3	83.3	Below limit
Dozers	6	**87.6 ± 3.0**	83.7	**90.6**	Above limit
FEL	2	84.2 ± 0.8	82.9	**85.4**	Below limit
Dump Trucks	4	81.6 ± 2.7	77.8	83.8	Below limit
Excavator	2	83.2 ± 1.1	82.4	83.9	Below limit
Grader	2	81.0 ± 2.4	79.3	82.7	Below limit
Water Bowser	2	78.1 ± 0.3	77.9	78.3	Below limit
Diesel Bowser	2	83.9 ± 1.0	83.2	84.6	Below limit

Indicated in bold are noise levels above the 85 dB(A) limit.

In Table 4 it can be seen that only one EME operator group (Dozers) had a mean noise exposure level above the 85 dB(A) noise rating limit. Within the Front-end loader operator group a maximum noise level was found to be above the 85 dB(A) noise rating limit, but the mean noise exposure for that group was below 85 dB(A).

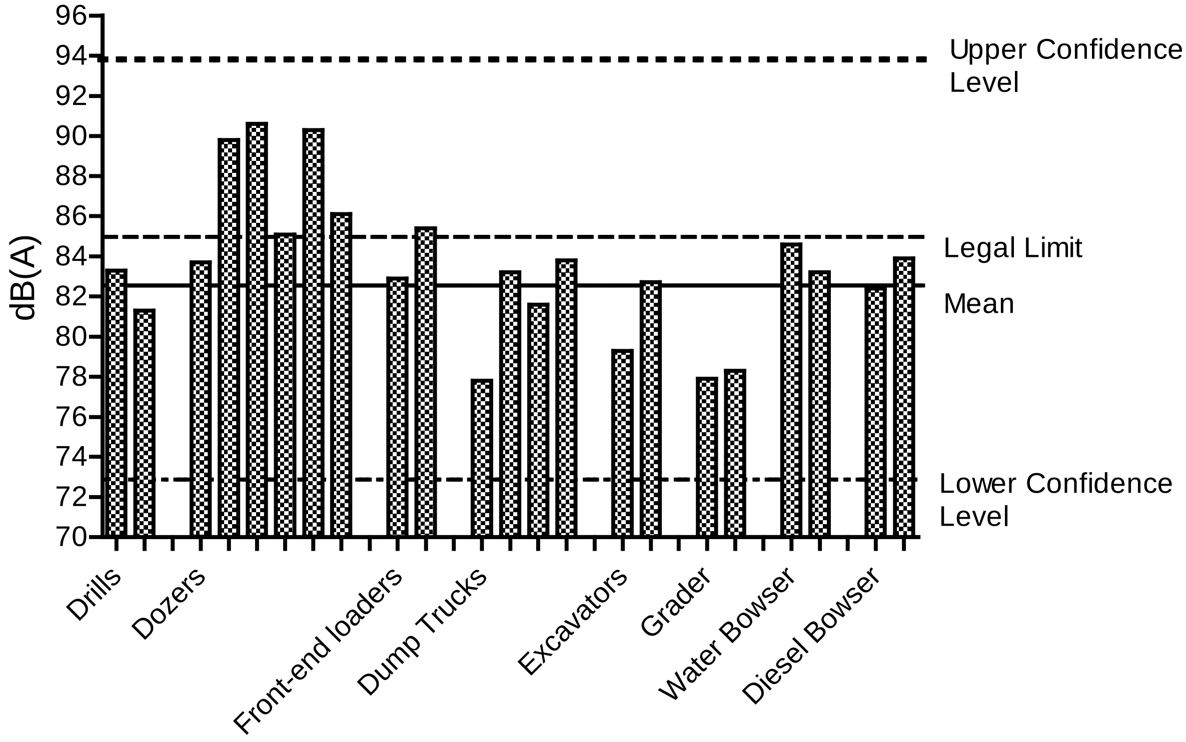

Figure 3: Noise levels of operators of different EME groups within the Production operation.

It can be seen from Figure 3 that operators noise exposures are mainly below the legal limit except for the Dozer operator group where five of the six operators' noise exposure were found to be above the 85 dB(A) noise rating limit. It was also noted that within the Front-end loader and Water bowser groups only one operator was exposed to noise levels above 85 dB(A), respectively.

Table 5: L_{Aeq} A-weighting per EME operator group (mean ± SD) for the Rehabilitation operation, compared to the Regulation of MHSA 85 dB(A) limit.

Vehicle Type	N	Dosimeter – dB(A) (mean and SD)	Minimum	Maximum	Regulation of MHSA 85 dB(A)
TLB	2	81.8 ± 1.3	80.8	82.7	Below limit
Dozers	6	82.7 ± 3.0	79.3	**86.5**	Below limit
Dump Trucks	4	78.0 ± 3.3	74	81.8	Below limit
Excavator	4	81.5 ± 3.0	79.4	84.6	Below limit
Grader	2	82.2 ± 0.3	82	83.6	Below limit
Water Bowser	2	84.5 ± 2.1	83	82.4	Below limit
Diesel Bowser	2	83.3 ± 2.3	79.9	**86**	Below limit

Indicated in bold are noise levels above the 85 dB(A) limit.

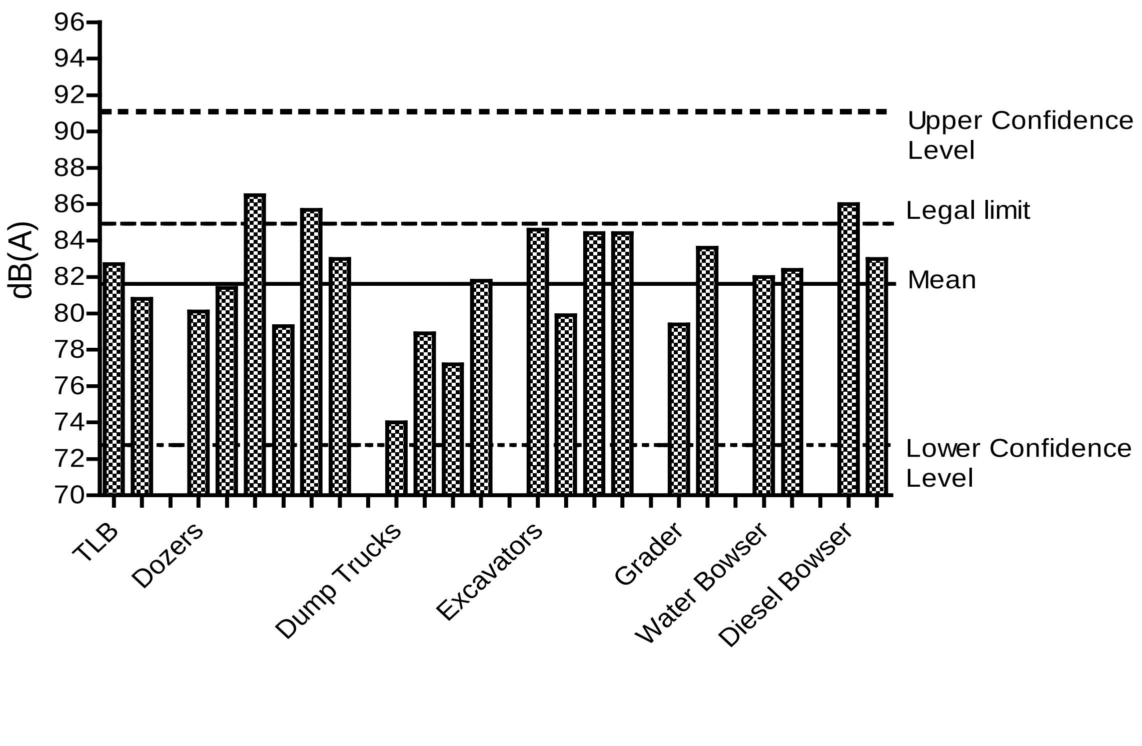

Figure 4: Noise levels of operators of different EME groups within the Rehabilitation operation.

It was noted (Table 5) that there was no mean noise exposures above the permissible 85 dB(A) noise rating limit for all operator groups within the Rehabilitation operation. However, it should be noted that within two EME operator groups (Dozers and Diesel bowsers) the maximum noise value were found to be above 85 dB(A).

Figure 4 also indicates that the majority of noise measurements were below the noise rating level of 85 dB(A) with only three measurements above the noise limit. Within the Dozer group two operators had noise levels above the noise limit and for the Diesel bowser group only one operator was over exposed.

3.3.3 Correlations

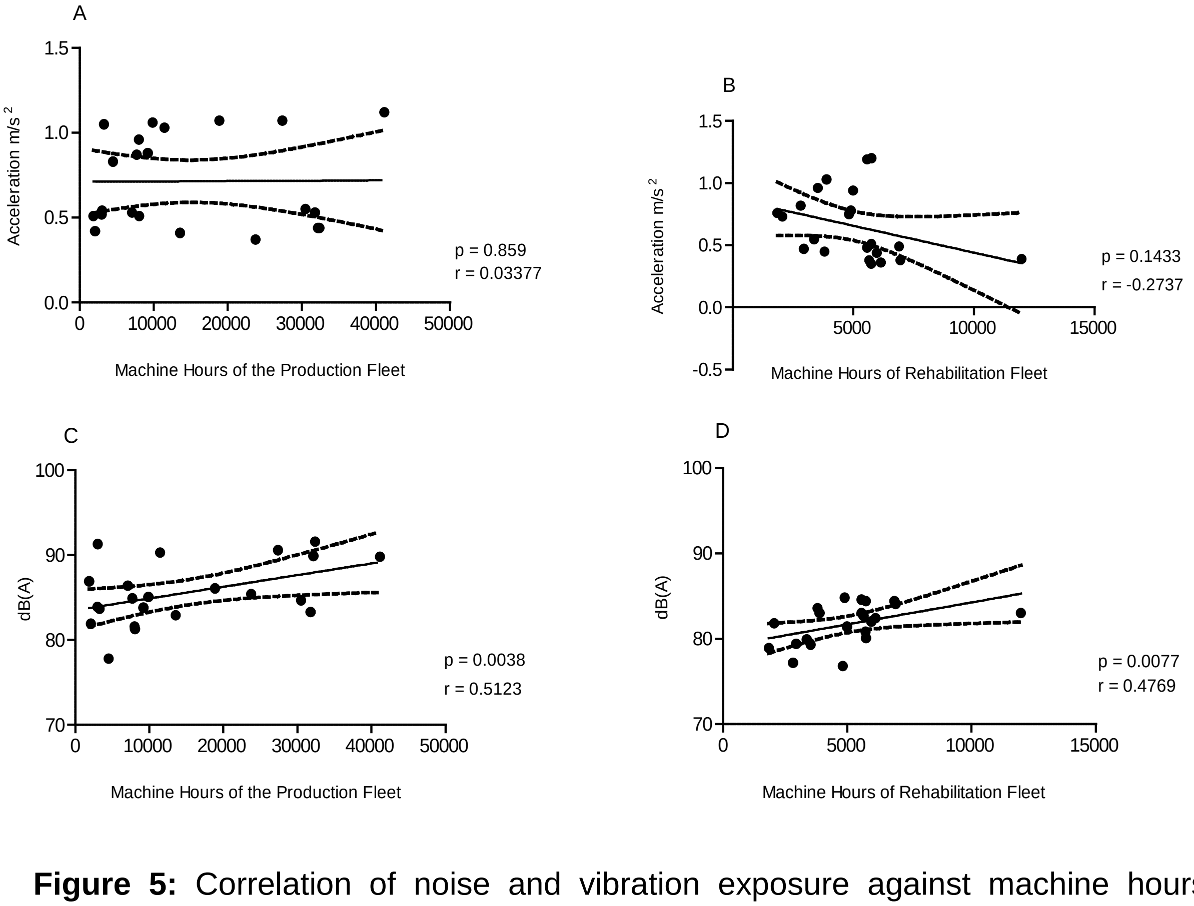

Figure 5: Correlation of noise and vibration exposure against machine hours. For vibration (A & B), Spearman correlations were performed and for noise (C & D) Pearson correlations. Linear Regression lines (solid line) and 95% confidence levels (dotted lines) are indicated.

Correlation coefficients were calculated to determine the relationship between operators' vibration exposure levels and machine hours as well as operators' noise exposure levels and machine hours for both the Production operation and Rehabilitation operation. The results are represented in Figure 3. The r-value is an indication of the strength of the correlation ($r \geq 0.5$) where a negative correlation indicates a relationship between a variable that increases as the other decreases, for a positive correlation both variables will increase together, while the p-value indicates whether the difference was statistically significant ($p \leq 0.05$).

WBV experienced in the Production operation and Rehabilitation operation (Figure A & B) were not statistically significant but for the Production operation a positive correlation ($r = 0.033$) was noted, while for the Rehabilitation operation a negative correlation was noted ($r = -0.273$). Noise exposures of the Production operation and Rehabilitation operation (Figure C & D) share statistically significant positive correlations between operators' noise exposure and machine hours. This trend corresponds with the linear relationship indicated by the linear regression line, where an increase in machine hours corresponds with an increase in operators' exposure to noise.

3.4 Discussion.

A study done by Eger *et al*. (2006) have shown that operators of EME such as dozers, graders and dump trucks were exposed to WBV levels above the ISO 2631-1 HGCZ, but drill operators were exposed to WBV levels within these levels. With regards to the EU limit (1.15 m/s^2) and the EU action limit (0.5 m/s^2) it is noted that for operators within the Production operation no data points are beyond the EU limit, but 77% of operators in this sample group were reported to be above the EU action limit. It was also recorded that 45% of operators' vibration levels were found to be within HGCZ. For operators within the Rehabilitation operation, 9% were found to be above the EU limit and 55% above the European action limit. Furthermore 50% of operators WBV exposure was within the Health Guidance Caution Zone (HGCZ) of 0.45 – 0.90 m/s^2. It is thus evident that operators within the Production operation are more likely to be exposed to WBV levels above the EU action limit than operators within the Rehabilitation operation. This may be due to the operators performing different activities in different areas. Activities which include exposing coal (drilling, blasting and dozing) and extraction of coal (loading and dumping) are mostly performed by EME operators within the Production operation. Whereas EME operators will perform activities such as loading, dumping and levelling of discard and topsoil materials within the Rehabilitation operation.

In terms of the EU Directive 2002/44/EC, only some of the Dozer operators within the Production operation and Rehabilitation operation were exposed to levels above the European limit level of 1.15 m/s^2. The dozers' high vibration levels seemed to originate from factors such as rough terrain on which these machines operate on a daily basis. Tracks on which these dozers move also contribute to higher vibration levels due to a lack of shock absorbers. Measurements were taken while the dozers were performing either, rehabilitation or production activities, such as pushing discarded material into the void or leveling of top soil. Eight-hour equivalent acceleration levels were observed to be high for both the x- (forward and backwards movement) and y-axes (lateral movement), but the y-axes mostly showed very high acceleration levels close or above the EU limit. Dozers performing rehabilitation activities had the lowest eight hour equivalent acceleration mean level of 0.983 m/s^2 in the y-axis where production activities reported a mean level of 1.10 m/s^2 in the y-axis. It is thus evident that the x-axis and y-axis reported overall the highest vibration levels, indicating that the movements caused by operating of EME, manifest mostly in these vibration directions. Regardless of these high levels, operators were observed to be comfortable while working. Machine maintenance was also observed to be up to standard as there were no damaged or broken seat suspensions reported.

The results found in this study are similar to literature which reports vibration levels capable of causing health effects. Aya and Heyns (2011) found that 95% of vibration levels in an opencast mine in South Africa were below the exposure limit value of 1.15 m/s^2, but 50% of vibration measurements were above the exposure action limit value of 0.5 m/s^2. A study done by Eger *et al*. (2006) reported mean r.m.s levels of 0.28 m/s^2 and 0.37 m/s^2 for dump trucks and a mean r.m.s level of 1.96 m/s^2 for dozers. Although the present study reported vibration levels at an opencast mine in South Africa to be lower; it is important to note that both studies found that dozers were the group exposing operators to vibration levels above the European Union limit level of 1.15m/s^2. Similar results were also obtained from a study done by Kumar (2004) who reported vibration levels to be above the recommended HGCZ for dump trucks. Results found in the current study confirm previous literature with regards to EME operators being exposed to WBV levels which may have a significant effect on their health. Acute health effects related to WBV exposure include headaches, increased heart rate, loss of balance and a decreased ability for information processing (Smith and Leggat, 2005).

Statistical analysis indicated that there was no significant correlation between vibration exposure and machine hours for both Production and Rehabilitation operations. This was unexpected; since the assumption was made that vibration exposure will increase as EME operating hours increase, but due to the fact that there may be a variety of other confounding factors that could have influenced vibration values, such as the area/surface where machines operate and operator experience.

With regards to the eight hour noise rating level of 85 dB(A) as stated by the Regulations under the Mine Health and Safety Act 1996 (Act 29, 1996) and South African National Standard (SANS 10083:2012) it was noted that 27% of operators within the Production operation were exposed to noise levels above the limit and for operators within the Rehabilitation operation, 14% were reported to be above the limit. Measurements obtained from operator noise exposure within the Production operation were found to be statistically higher from that of operators' noise exposure within the Rehabilitation operation. Thus from comparison to the legal limits it is evident that noise levels for the Production operation is slightly higher than the noise exposure reported in the Rehabilitation operation. This could be due to the fact that only the Production operation vehicles are equipped with FM radios which contribute to higher noise levels. In terms of the eight hour noise rating limit of 85 dB(A) it was noted that only the operators from the Dozer group within the Production operation was exposed to levels above the limit level. The operators' high noise levels may be due to the fact that this EME group perform activities such as pushing discard, coal or shale materials which lead to high engine revolutions. Other factors such as track noise while tramming, reverse alarms, two-way and FM radio all contribute to these high noise levels experienced.

It was also noted that higher noise levels were experienced in older EME (more machine hours) than in newer EME indicated by the correlations (Figure 3. C & D). A linear regression indicated the relationship between two variables, a positive linear regression line for both the Production operation and Rehabilitation operation was noted therefore noise exposure levels of operators will increase as the EME hours increase. From the regression it was calculated that operators' noise levels will exceed 85 dB(A) when EME reaches 19 345 working hours for the Production operation and 13 460 working hours for the Rehabilitation operation.

Spencer and Kovalchik (2007) reported noise levels measured with dosimeters for operators of heavy vehicles to be between 95 to 99 dB(A) for dozers, 80 to 82 dB(A) for haul trucks, 97 dB(A) for a road grader, 76-78 dB(A) for excavators and 76-80 dB(A) for front-end-loaders. A study done by Kisku *et al.* (2002) monitored noise sources from equipment and found that the highest noise levels for EME was from dozers with noise levels between 82.4 dB(A) and 87.3 dB(A). Noise exposure levels reported for the current study differed from that found in literature, operators' overall noise exposure for both the Production operation and Rehabilitation operation were found to be lower. This may be due to the fact that preventative measures have been put introduced to reduce noise exposure such as enclosed cabins, equipped with heating ventilation air-conditioner (HVAC) systems and daily EME inspections to ensure no rattles or loose safety flaps. Furthermore operators' noise exposures within the Rehabilitation operation were also found to be predominantly lower compared to the operators within the Production operation. Noise levels for operators of EME within the Production operation was between 83.7 and 90.6 dB(A) for dozers, 77.8 and 83.8 for dump trucks, 79.9 and 82.7 for graders and 82.4 and 83.9 for excavators. From the above it can be concluded that noise exposures are predominantly below the 8 hour permissible noise level of 85 dB(A). Noise exposures above the 85 dB(A) will most likely lead to certain health effects such as Noise Induced Hearing Loss (NIHL). Apart from NIHL many other adverse health effects, including elevated blood pressure, tinnitus, reduced performance, sleeping abnormalities, annoyance and stress, and temporary hearing threshold shift (Nelson *et al*,. 2005).

Results of this study indicated that the WBV and noise exposures of EME operators were found to be lower than previous levels reported in literature (Kumar 2004; Eger *et al*., 2006; Spencer and Kovalchik, 2007; Aya and Heyns, 2011). Using the average exposure measurements per EME group a hierarchy was constructed for vibration and noise. In future the hierarchy can be used to prioritise and determine where (what EME group) focus should be aimed at, in order to reduce exposure to vibration and noise. Table 6 A & B indicates the EME groups that should take preference when reducing noise and vibration exposure.

Table 6A: Vibration hierarchy

EME GROUP
1. Dozers
2. Dump Truck
3. Grader
4. Excavator
5. Drills
6. Diesel Bowser
7. TLB
8. Water Bowser
9. FEL

Table 6B: Noise hierarchy

EME GROUP
1. Dozers
2. Diesel Bowsers
3. Excavators
4. Graders
5. Drills
6. Dump Truck
7. FEL
8. TLB
9. Water Bowser

3.5 Conclusion

This study quantified vibration and noise exposures of EME operators at an opencast coal mine within two operations, namely Production and Rehabilitation. With regards to the EU limit (1.15 m/s^2) and the EU action limit (0.5 m/s^2) it was noted that operators of EME within the Production operation were not exposed to WBV levels above the EU limit, but 77% of theses operators were exposed to WBV levels above the EU action limit. It was also recorded that 45% of operators' vibration levels was within Health Guidance Caution Zone (HGCZ) of 0.45 – 0.90 m/s^2. Within the Rehabilitation operation, 9% of operators were exposed to WBV levels above the EU limit and 55% above the European action limit; furthermore 50% was within the HGCZ. It is important to note that within the dozer group three samples were above the European legal limit of 1.15 m/s^2. To summarise, operators of different EME's within the two operations were exposed to WBV levels that present a moderate probability for causing adverse health effects.

With regards to the 8 hour OEL of 85 dB(A) as stated by Regulations under the MHSA and The South African National Standard (SANS 10083:2012) it is noted that 27% of EME operators within the Production operation were exposed to noise level above the limit and for EME operators within the Rehabilitation operation, 14% of operators were reported to be above the limit. Thus the majority of EME operators were exposed to noise levels below the 85 dB(A), except for the operators of dozers' whom exceeding the 85 dB(A) limit.

High vibration and noise levels within the Dozer group can be attributed to the fact that these EME types mostly perform activities in uneven areas and the tracks on which these Dozers move.

Statistical analysis indicated that a positive statistical significant correlation was found between machine hours and operators' noise exposure within Production operation and Rehabilitation operation. It was calculated that operators' noise levels will exceed 85 dB(A) when EME reaches 19 345 working hours for the Production operation and 13 460 working hours for the Rehabilitation operation. An EME hierarchy for both vibration and noise were constructed which should be used to prioritise and determine where focus should be aimed at, in order to further reduce exposure. Following the hierarchy for both vibration and noise, it is clear that the Dozer group are at the top of the priority list, where action should be taken to reduce vibration and noise exposures of EME operators.

A wide range of solutions are available for reducing vibration and noise exposure. Ideally these solutions should follow the hierarchy of control (engineering control, administrative control and lastly personal protective equipment (PPE), starting with control at the source. The first control measure would be to ensure continuous improvement of vehicle maintenance, with focus predominantly on seat and machine suspensions, tyre pressures if applicable and any machine body rattles. It is recommended that all travelling ways need to be regularly graded, maintained and rubble or debris removed according to the mines specific operating procedures.

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Chapter 4: Concluding Chapter

4.1 Conclusions and Recommendations

This study quantified operators of earth moving equipment's exposures to whole-body vibration (WBV) and noise. The study focused on two main groups namely, the Production operation and Rehabilitation operation, since activities performed by these groups are different which could influence the results. Within the Production operation EME operators mostly perform activities which include exposing coal (drilling, blasting and dozing) and extraction of coal (dozing, loading and dumping). Whereas within the Rehabilitation operation, EME operators will perform activities such as loading, dumping and levelling of discard and topsoil materials.

Initial field measurements when compared to the European Directive 22/44/EC indicated that operators of EME for both the Production operation and Rehabilitation operation were predominantly exposed to vibration levels above the European action level of 0.5 m/s^2, but within the dozer group three samples were above the European legal limit of 1.15 m/s^2. Maximum exposure within the Dozer group and Front-en loader group were found to be above 85 dB(A). High vibration and noise levels within the Dozer group can be attributed to the fact that these EME types mostly perform activities in uneven areas and the tracks on which these Dozers move also contribute to higher vibration and noise levels due to a lack of shock absorbers

Higher noise levels were experienced in older EME compared to newer EME, this was confirmed by statistical analysis which indicated a positive correlation between machine hours and operators' noise exposure within the Production operation and the Rehabilitation operation. From the regression it was calculated that operators' noise levels will exceed 85 dB(A) when EME reached approximately 19 000 working hours for the Production operation and 13 000 working hours for the Rehabilitation operation.

An EME hierarchy for both vibration and noise were obtained and should be used to prioritise and determine which EME group focus should be granted to, in order to reduce exposures. Following the hierarchy for both vibration and noise, it is clear that the dozer group is at the top of the priority list, where action should be taken to reduce vibration and noise exposures of EME operators.

The aim and objectives of this study were to evaluate and quantify the levels of exposure in different EME types, as well as to compare old with new EME, in order to estimate if longer machine hours contribute to higher noise and vibration levels. WBV and noise levels of the Production and Rehabilitation operations were compared, to determine if there were differences in exposure levels between the two operations. The objectives of this study were achieved.

In Chapter 1 the hypothesis stated that Earth Moving Equipment (EME) operators at a South African opencast coal mine are exposed to levels of WBV that exceed advised levels set out in ISO 2631-1 and EU Directive 2002/44/EC; and personal noise exposure that exceed the legal limit as stated by South African legislation and standards. The hypothesis of this study was partially accepted, as the majority of the operators were exposed to WBV and noise levels below the legal limits, but within the Dozer group, operators were exposed to WBV and noise levels exceeding these limits.

4.2 Limitations

Limitations identified during this study was that noise levels were measured with only A-weighted scale; as a result it did not give a clear indication of the total noise risk associated with noise exposure of EME operators. Low frequency noise (LFN) was found in other studies to cause extra-aural effects in the form of vibroacoustic disease (VAD). Even a short exposure to infrasound noise can bring on symptoms of strenuousness like drowsiness, irritation, headaches, pressure in the ears, being short of breath and heart action disruptions. When all sound weightings are included a better analysis of the acoustic environment can be made and the total risk associated with noise exposures can be estimated. Only one vibration monitor was available and resources to perform vibration measurements were limited, therefore the time frame for measurement was restricted to two hours.

4.3 Future Studies

Infrasound is sound waves with frequencies below the lower limit of human audibility and operators of EME are exposed to these frequencies. Infrasound waves act on the entire human body. Even a short exposure to infrasound noise can bring on symptoms of strenuousness like drowsiness, irritation, headaches, pressure in the ears, being short of breath and heart action disruptions. Thus for future studies it is suggested to perform noise measurements which include the entire spectrum of sound frequencies, which will contribute in performing better analysis of the acoustic environment and a total risk associated with noise exposures can be estimated. Furthermore frequency analysis could also be performed which will then indicate the frequency bands the sound energy is predominantly located in.

It is also suggested that vibration measurement should be taken for a full shift to identify risk activities which contribute to high vibration levels as well as to observe operators behaviour and technique. A clear and better picture of vibration intervals could then be estimated. More intervention studies on how to reduce WBV exposure of operators by means of changing operators' behavior and operating techniques is needed, because roughness of the terrain or road conditions and the operating technique of the vehicle contribute substantially to vibration exposure. Indicators reflecting the behavioral change should be determined in order to measure the implementation process.

4.4 Recommendations

WBV and noise sources should be controlled, like any other health risk present in a workplace. Control measures should be implemented to reduce WBV and noise exposure. Therefore the following interventions are recommended:

- A continuous improved maintenance plan for all EME should be implemented and maintained with regular service intervals focussing mainly on seat and machine suspensions, tyre pressures if applicable and any machine body rattles.

- Travelling ways need to be regularly graded, maintained and rubble or debris removed according to site specific operating procedures.

- Employers and drivers should be provided with information about the disadvantages and effects of WBV, changing their behaviour towards WBV exposure and WBV related issues. Training on vibration should be used to improve operators' driving techniques and skills, thus when operators are working in rough terrains they will drive to conditions in a way that will not unnecessarily increase vibration exposures.

- If operators were exposed to noise levels at or above 85 dB(A), these operators should be included in a Hearing Conservation Program, with regular follow up measurements.

- It is recommended that if operators are exposed to noise levels at or above 85 dB(A) they should use hearing protective devices as an preventative measure to reduce noise exposure levels. It is recommended that hearing protection with an NRR factor of 26 should be used. A variety of hearing protection such as Sonomax (personally moulded ear protection) or a range of 3M disposable earplugs are available providing the operator with choices.

- A project was already identified during the study to reduce noise exposure through implementing radio-control units which control all FM and 2 way radio volumes.

- Furthermore it is important to have a continuous sampling strategy for both WBV and noise in place, which will effectively monitor changes in exposure levels and also to assess if control measures are effective. The sampling strategies should be based on previous exposures.

There is also a need to implement National Legislation for WBV. A legislative framework is needed in order to implement and enforce limits regarding WBV exposure levels. Legislation will also ensure that the responsibilities, rights and roles of each party (employer and employee) are defined and recognised. The purpose of the legislation is to ensure that the employer will be held responsible to reduce operators' exposures to vibration below safe limits as well as to ensure that operators are not exposed to vibration levels which can lead to adverse health effects.

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