Exposure of vehicle operators to vibration and noise at a Tanzanian opencast goldmine

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Hons. B.Sc.

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Author's Contribution

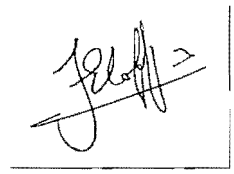
This study was planned and executed by a team of researchers each with specific contributions as shown in Table 1.

Table 1: Research team

Name	Contribution
Mr. B.R. Schmidt	Student. • Sampling of vibration and noise in Tanzania. Literature research, analysis and interpretation of results.
Prof. F.C. Eloff	Supervisor. • Assisted in all planning and execution of the study. • Reviewing of the mini-dissertation with regard to the literature overview, analysis and interpretation of results.
Mr. J.L. du Plessis	Co-Supervisor. • Reviewing of the mini-dissertation with regard to the literature overview, analysis and interpretation of results.
Mr. Jaco van Rensburg	Assistant Supervisor. • Planning of study.

The following is a 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 Brian Schmidt's M.Sc. (Occupational Hygiene) mini-dissertation.



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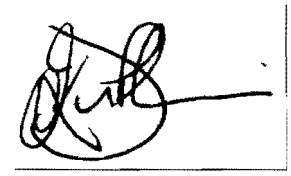

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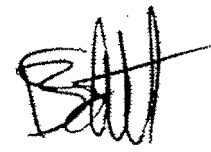

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List of abbreviations

ACTH	Adrenocorticotropic hormone
CRH	Corticotrophin releasing hormone
CHPD	Custom made hearing protection device
dB	Decibel
dB(A)	Decibel with A-weighting applied
dB(C)	Decibel with C-weighting applied
dB(Lin)	Decibel linear (no weighting)
dB(Z)	Decibel with no weighting applied (zero-weighting)
EU	European Union
Hz	Hertz
HGCZ	Health Guidance Caution Zone
HPD	Hearing protection device
ISO	International Organization for Standardization
kHz	Kilo-Hertz
Kph	Kilometres per hour
LBP	Lower back pain
LHD	Load-haul-dump truck
LFN	Low frequency noise
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
PPE	Personal protective equipment
RF	Resonant frequency
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
VDV	Vibration Dose Value
VAD	Vibroacoustic disease
WBV	Whole-body vibration

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Preface

This mini-dissertation was done in article format. In order to ensure uniformity, the reference style of the entire mini-dissertation was done 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.

The Results and Discussion section in Chapter 3 is presented as one, after inspection of recent articles in Annals of Occupational Hygiene. Also note that tables and figures are not placed at the end of the article as prescribed, in order to ensure fluency for examining purposes.

ABSTRACT

In this study the exposure of mining vehicle operators, on an opencast goldmine in Tanzania, to certain hazards specific to their occupation was assessed. The aim was to quantify these levels of exposure in order to estimate the risk of health effects but also to report levels of these hazards that exist on mining vehicles. Three different hazards with different physiological effects were assessed and it included exposure to whole-body vibration, A-weighted noise and low frequency noise. In each case correctly calibrated instrumentation was used and internationally accepted methods were followed. It was found that mining vehicles commonly exposed operators to levels of whole-body vibration within and above the ISO Health Guidance Caution Zone (HGCZ) and above the European action level, which indicates the need for intervention and control. These levels are a cause for concern and will likely lead to health effects. Noise that damages human hearing (A-weighted noise) was present in high levels on mining vehicles, in each case being higher than the permissible exposure limit of 85 dB(A). Thus operators of mining vehicles are exposed to noise levels that will damage their hearing in time. A potential hazard in the occupational world, low frequency noise, was also included in the assessment. Literature indicates that low frequency noise is capable of causing many human health effects and thus levels on mining vehicles were reported in order to give an indication of what levels may be expected in this department of mining. It was found that much of the sound energy measured on vehicles was located in the low frequency range. In the lowest frequency band measured, L_{eq} levels of more than 100 dB(Z) were commonly found. 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. These controls can include good maintenance of vehicles and roads to reduce whole-body vibration, sound proofing of vehicle cabs along with hearing protection devices to protect hearing and further research regarding the exposure and health effects caused by low frequency noise. Following literature indicating the physiological effects of low frequency noise exposure and also the presence thereof in different occupations,

it is concluded that A-weighted noise measurements alone can not be used when quantifying the risk involved in a given acoustical environment.

Keywords: whole-body vibration, noise, low frequency noise, vehicle operators, mining.

OPSOMMING

In hierdie studie is die blootstelling van mynvoertuig-operateurs aan sekere risiko's spesifiek tot hul beroep ondersoek. Die ondersoek is gedoen op 'n oopgroef goudmyn in Tanzanië. Die doel was om die vlakke van blootstelling te kwantifiseer sodat die risiko vir gesondheidseffekte beraam kon word, maar ook om verslag te doen oor die vlakke waarin hierdie risiko's op mynvoertuie voorkom. Drie verskillende risiko's, elkeen met verskillende fisiologiese effekte is ondersoek en dit het heelliggaam-vibrasie, A-beswaarde geraas en laefrekwensie-geraas ingesluit. In elke geval is gebruik gemaak van korrek gekalibreerde instrumentasie en internasionaal aanvaarde metodes is nagevolg. Daar is bevind dat mynvoertuie die operateurs deurgaans blootstel aan vlakke van heelliggaam-vibrasie wat binne of bo die ISO "Health Guidance Caution Zone" (HGCZ) val, asook bo die Europese aksievlak is. Hierdie vlakke sal volgens die standaarde waarskynlik lei tot skadelike gesondheidseffekte. Geraas wat skadelik is vir menslike gehoor (A-beswaarde geraas) was in hoë vlakke teenwoordig in die mynvoertuie en in alle gevalle was die vlak meer as die wetlike limiet van 85 dB(A). Dus was hierdie operateurs van die mynvoertuie blootgestel aan vlakke van geraas wat oor tyd hul gehoor sal beskadig. 'n Potensiële risiko in die beroepswêreld nl. laefrekwensie-geraas is ook ingesluit by die ondersoek. Die literatuur dui daarop dat laefrekwensie-geraas aanleiding kan gee tot verskeie menslike gesondheidseffekte en dus is die vlakke teenwoordig op mynvoertuie gerapporteer om 'n aanduiding te gee van watter vlakke te verwagte is in hierdie area van die mynbedryf. Daar is bevind dat 'n groot deel van die klankenergie wat gemeet is op die voertuie in die lae frekwensiebande teenwoordig was. In die laagste frekwensieband wat gemeet

is, is L_{eq} vlakke van meer as 100 dB(Z) deurgaans gevind. Beheermaatreëls moet toegepas word vir elke risiko sover dit redelik is om te verseker dat operateurs nie blootgestel word bo voorgestelde drempels of die wetlike limiete nie. Hierdie beheermaatreëls kan insluit die instandhouding van voertuie en paaie om heelliggaam-vibrasie te verminder, klankdemping in voertuie se kajuit saam met persoonlike gehoorbeskermingsapparaat en laastens verdere navorsing oor die blootstelling en gesondheidseffekte van laefrekwensie-geraas. Na afleiding van literatuur wat die fisiologiese effekte van laefrekwensie-geraas sowel as die teenwoordigheid daarvan in verskillende beroepe aandui, is daar tot die slotsom gekom dat A-beswaarde geraas metings alleen, nie genoegsaam is wanneer die risiko van 'n betrokke akoestiese omgewing gekwantifiseer word.

Sleutelwoorde: heelliggaam-vibrasie, geraas, laefrekwensie-geraas, mynvoertuig-operateurs, mynbou.

Chapter 1

GENERAL INTRODUCTION

1.1 Introduction

Mining is an ancient occupation that has long been known to be arduous and to cause injury and disease (Donoghue, 2004.) Mining hazards such as accidents and mining dust have overshadowed other hazards such as noise exposure when it comes to causes of mortality and morbidity (McBride, 2004). Yet mining is a diverse industry and many occupations make up what is collectively known as mining (Donoghue, 2004), not least of which is the mining vehicle operator category. Operators of mining vehicles are potentially exposed to certain hazards other than dust and accidents.

Whole-body vibration is one such potential hazard. It is transmitted through the entire body by a vibration source which is in contact with a person either by sitting or standing on it (Smith and Leggat, 2005). Estimates show that up to seven percent of all workers in the USA, Canada and Europe are regularly exposed to whole-body vibration (Palmer et al. 2003). Previous research by Paddan and Griffin (2002) found high levels of vertical whole-body vibration on many types of vehicle including cars, excavators, lift trucks, lorries, armoured vehicles, busses, a helicopter, excavators, mobile cranes, lift trucks and mowers. These measurements were done while the vehicle was operating on the surface normally associated with it, for example measurements on busses were done on roads while mowers were assessed on a grass surface. Eger et al. (2006) assessed whole-body vibration on mining vehicles in Ontario (Canada) and found levels likely to cause health effects on haul trucks, bulldozers and graders. This study also found levels of whole-body vibration on jumbo drills and pit drills to be below recommended levels. It is currently accepted that exposure to whole-body vibration can lead to lower back pain as such a correlation has been found in previous studies (Smith and Leggat, 2005) and it is stated that lower back pain is reported more by occupational drivers than any other occupational group (Battié et al. 2002).

Noise is a widespread problem in all mining sectors (McBride, 2004). In Europe noise-induced hearing loss is considered the most common occupational problem (Fernández et al., 2008) and the National Institute for Occupational Safety and Health (NIOSH) states that overexposure to noise is common in mines in the United States of America (McBride, 2004). Noise has long been known to cause hearing loss (Horie, 2002) and high levels have previously been reported for mining haul trucks (Bealko, 2008) as well as construction vehicles that include bulldozers, haul trucks and graders (Spencer and Kovalchik 2007).

Current literature available on low frequency noise primarily serves to describe what low frequency noise is and what health effects it causes in humans (Alves-Pereira and Castelo Branco, 2007). However, literature on low frequency noise is scarce. Low frequency noise is yet to be recognised as an occupational hazard despite studies indicating a wide range of health effects caused by exposure to low frequency noise (Alves-Pereira and Castelo Branco, 2000). The term Vibroacoustic disease is used to describe the health effects caused by exposure to low frequency noise (Alves-Pereira and Castelo Branco, 2007). It is thus relevant to report levels of this new hazard in different areas of the occupational world and specifically for this study on mining vehicles.

Permissible levels for both whole-body vibration and noise exist. The International Organization for Standardization state levels of whole-body vibration which is likely to lead to health effects (ISO 2631) while an EU Directive (2002/44/EC) reports an action level as well as a limit level. The South African National Standard reports permissible noise levels for an 8 hour shift (SANS 10083:2004). The regulations under the South African Mine Health and Safety Act 1996 (Act 29 of 1996) also states that a level of 85 dB(A) for an 8 hour shift should not be exceeded. This regulation was used in this study due to the lack of similar regulations in Tanzania.

Worldwide, research on whole-body vibration and noise found on mining vehicles is limited, and even totally lacking in the case of low frequency noise. Certainly

no research of such a nature was found to have originated from Africa or even a study in Africa. Thus the present study serves as new information regarding such exposure on mining vehicles operating in Africa. In the absence of relevant regulations, the enforcement thereof and maintenance of vehicles is questionable.

1.2 Aims

The aims of the study were:

- to quantify whole-body vibration and noise, including low frequency noise, on different mining vehicles to which operators, at an opencast goldmine in Tanzania, are exposed during a shift.
- to compare measured sound and vibration levels to relevant standards in order to estimate the relative risk of health effects.

1.3 Hypothesis

ISO 2631 defines a Health Guidance Caution Zone between 0.45 ms^{-2} r.m.s. and 0.90 ms^{-2} r.m.s., while the EU Directive 2002/44/EC states a limit of 1.15 ms^{-2} r.m.s. for whole-body vibration. SANS 10083:2004 defines that an 8 hour noise/sound level of 85 dB(A) should not be exceeded. It is therefore hypothesized that vehicle operators at a Tanzanian goldmine are exposed to levels of whole-body vibration and noise that exceed levels stated by standards.

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Chapter 2

Literature Review

2.1 Whole-Body Vibration

Whole-body vibration (WBV) is the vibration transmitted through the entire body by a vibration source which is in contact with a person either by sitting or standing on it (Smith and Leggat, 2005). It is further defined as mechanical oscillations which are transferred to the body as a whole (Hagberg et al. 2006).

Vibration is becoming an occupational problem particularly in conditions where workers are exposed to the vibration for long periods during their working shifts. Bovenzi and Hulshof (1998) estimate that up to seven percent of all workers in the USA, Canada and Europe are often exposed to whole-body vibration. Whole-body vibration is one of the most common occupational hazards in Britain and it is estimated that up to 8.5 million people are exposed to it every week. This includes 370 000 people with exposures above the proposed action level in the British standard (Palmer et al. 2003).

In mining, workers are also being exposed to potentially harmful levels of vibration that are brought about by increased mechanization and longer shifts. These shifts are in many cases in excess of 10 hours (Eger et al. 2006).

2.1.1 Biomechanics of WBV

The magnitude of vibration is expressed in terms of an average measure of the acceleration, usually the root mean square value (ms^{-2} r.m.s.). The r.m.s. magnitude is related to the vibration energy and thereby gives a measure of the vibration injury potential (Bovenzi and Hulshof, 2007). Vibration occurs in three dimensions which are agreed upon internationally. These are defined as follows: X-axis is forward and backward movement, Y-axis is movement from side to side and Z-axis is movement in a vertical direction (Taylor and Wasserman 1988).

All objects have a speed at which they naturally vibrate. When this happens the term "resonant frequency" is used. The resonant frequency (RF) of an object depends on its physical characteristics. The amplitude of vibration increases when the resonant frequency is reached. The body does not have a single resonant frequency due to the different composition of bone and tissue structures (Smith and Leggat, 2005). Smith and Leggat (2005) state that vertical vibration of the body has a resonant frequency which appears to be between 4 and 8 Hz. According to ISO 1997:2631–1 the frequency which affects the body with regard to health, comfort and perception, is between 0.5-80 Hz. In the standard, under the health section, a note states that frequencies less than 1 Hz have no effect on health and can thus be ignored. Furthermore the resonant frequencies for the spine are between 4 and 7 Hz for seated persons, with a frequency of 4.5 Hz specifically for the lower back.

Smith and Leggat (2005) state that vibration energy flows from the vibration source to the body through a contact point where it is then stored in the muscle tendons. The energy is then transferred back to the vibrating object at a lower level. There is greater vibration transmission to the lower spine in a standing person, than when seated. In the seated position the main problems include bending of the lower spine and a rocking motion (Smith and Leggat, 2005). Because of the body's natural pivots in the spine, there are certain areas where damage due to vibration tends to occur including the joints between C7 and T1 as well as between T12 and L1. The link between L5 and the sacrum can also be affected (Smith and Leggat, 2005).

2.1.2 Occupational WBV sources:

Smith and Leggat (2005) categorized occupations where WBV is prevalent as agriculture, construction, transportation and aviation. Examples given are of vehicle drivers only; including tractor drivers, earth moving and heavy machinery operators, taxi drivers, train drivers, bus drivers and helicopter pilots.

Eger et al. (2006) did a study on the vibration exposure of mining vehicle operators. It was done on vehicles used commonly at Ontario mines (Canada). A variety of mining vehicles were included and on some vibration was found to be above the levels recommended by the ISO 2631-1 health guidance caution zone (HGCZ). Vehicles that were found to be above recommended levels were an underground haulage truck, a bulldozer, a LHD (load-haul-dump truck), a cavo loader, a muck machine and a personnel carrying tractor. A surface grader, a larger load-haul-dump truck, scissor lift truck and locomotive were found to have vibration limits below the HGCZ used. It was also found that vibration levels were higher on the smaller sized haul trucks. The smaller LHD had vibration levels above the recommended HGCZ, while the larger LHD was found to be within these recommended levels. Village et al. (1989) found the same correlation years earlier in their study on LHD underground mining vehicles. The personnel carrying tractor was described by Eger et al. (2006) as being similar to agricultural tractors aside from having a modified bench on the back where material or people could be transported. Potentially harmful vibration exposures were found on these vehicles and were higher than expected, presumably because of rough underground road conditions.

Another study on surface haulage trucks reported vibration levels above the recommended HGCZ levels. This study was done on haulage trucks with a loading capacity of 240 and 350 tons (Kumar, 2004). Cann et al. (2003) studied different types of construction vehicles in corporate, residential and public work projects. Wheel loaders, off-road dump trucks, scrapers and dozers were among the vehicles found to have higher vibration exposures than the recommended HGCZ levels. It is also important to note that these vibration exposures that were classified as potentially dangerous by Cann et al. (2003) were all for vibration in the x-axis.

In a study done by Paddan and Griffin (2002), a variety of vehicles were monitored repeatedly. A survey of 100 vehicles was done including cars, excavators, lift trucks, lorries, armoured vehicles, busses and a helicopter to

name some. Comparisons were made between different vehicle categories as well as between different vehicles in the same category. They found large variations in vibration magnitude between different vehicle categories, but also between different measurements on vehicles in the same category. Thus they concluded that a single vibration measurement on a vehicle is not sufficient to determine vibration on all such vehicles. They interestingly found that the vertical axis (z-axis) had the highest vibration magnitudes on most of the vehicles. This is in contrast with Cann et al. (2003) whose study on construction vehicles found the x-axis to have the highest vibration magnitude. Thus it becomes clear from the literature that vehicle drivers or operators are the primary persons in the occupational world to be exposed to whole-body vibration.

2.1.3 Physiological Effects of WBV

According to Smith and Leggat (2005) the physiological effects of WBV can depend on many variables because the person is not always in direct contact with the source. These could include the type and condition of a seat, the type of shoes being worn and also the person's body posture. Other factors such as vibration magnitude, direction and frequency play an important part in the effects caused by exposure.

Smith and Leggat (2005) describe the acute effects of WBV as headaches, increased heart rate, hyperventilation and loss of balance. Other effects may include increased tension in muscles as the body attempts to dampen vibration. An effect on the ability of workers to perform tasks is also mentioned especially with regard to information processing. Vibration of the retina is said to occur between 20 and 90 Hz and could cause blurred vision. These effects subside when the vibration source is removed and therefore are not a major area of concern.

Chronic WBV exposure has the capacity to cause long term physiological changes. Lower back pain (LBP) is the most common result of WBV exposure and is categorized as a musculo skeletal disorder. Perceived discomfort from vibration exposure is another problem. This problem exists at frequencies of 1-2 Hz and generally increases with exposure time. The posture of an exposed person also affects discomfort (Smith and Leggat 2005).

2.1.3.1 Lower Back Pain (LBP)

Work related lower back pain is one of the most challenging conditions in healthcare. Clear verifiable diagnosis is rarely made concerning the source of the condition, while effective treatment is just as scarce. Some of the main causes of workplace back problems are heavy lifting, work postures that create postural stress and whole-body vibration associated with driving. Back problems are reported more by occupational drivers than by any other occupational group (Battié et al. 2002).

Physiologically there are a variety of structures that have been implicated in causing LBP. Bone, muscle, ligaments, joints and intervertebral discs could all play a part in causing LBP. Although the precise cause for LBP is not always known, there is significant evidence to suggest that the intervertebral discs are a major source of pain (Kolber and Zepeda, 2006). Vibration may cause the annular fibres in the spine to be stressed. This could cause increased pressure, finally leading to a failed or herniated spinal disc which protrudes. The resulting pressure on the spinal nerve could cause LBP (Smith and Leggat 2005).

A spinal disc contains a gelatinous inner nucleus pulposus which has the ability to migrate within an outer annulus fibrosis. The migration will depend on the movement and position of the spine and occurs as a consequence of vertebral pressure on the disc. In this way, when the lumbar spine is in flexion, the nucleus pulposus will migrate to the posterior where the posterior longitudinal

ligament is located. This migration is temporary in the normal disc and returns to its normal position once the spine is in a neutral position. In cases where excessive and repeated movements occur, this displacement might become more permanent. The posterior longitudinal ligament and the posterior part of the annulus fibrosis withstand the migration, but in the lumbar area these structures are weak in comparison to higher regions of the spine. Thus the area is predisposed to migration and permanent displacement of the nucleus pulposus when the lumbar spine is in flexion. Studies showed the opposite effect when the lumbar spine is in extension, its normal position. This is significant because disc herniations are primarily caused by posterior migration of the nucleus pulposus (Kolber and Zepeda, 2006). This clearly showed that bad posture could be a primary cause of disc herniation. The role of vibration then comes into question.

One hypothesis is that WBV exposure during driving has a direct effect on the spinal discs which leads to LBP. This implies degeneration and herniation of the spinal disc. The hypothesis is strengthened by the fact that higher rates of disc herniation in occupational drivers than other occupations were found, while results of animal and in-vitro studies also suggest that WBV could affect the disc (Battié et al. 2002). With this in mind, Battié et al. (2002) also states that significantly higher frequencies of back symptoms and degenerative effects were found in occupational drivers compared to other occupations. However, these findings become uncertain in light of the many uncontrolled confounding factors such as work postures, extended sitting times, lifting and other lifestyle factors which differ among individuals. Battié et al. (2002) finally concludes that back pain associated with driving and WBV most likely does not result from disc degeneration and damage to vertebrae. This is despite substantial exposures. Furthermore it is said that driving does not cause permanent damage to discs and that attention for future research should be directed to other explanations for the presence of back pain in drivers.

Smith and Leggat (2005) state that LBP is the most commonly reported problem for workers exposed to WBV and that the prevalence of LBP can be correlated to

the four occupational categories for high WBV exposures, namely tractor drivers (agriculture), heavy equipment operators (construction), drivers (transportation) and aviation personnel.

A variety of studies show that WBV is associated with an increased risk of LBP, sciatic pain and degenerative effects on the spinal system. In spite of this it is uncertain whether WBV is the single causal factor for LBP or whether it is merely a contributor among other factors such as posture and extended sitting (Hagberg et al. 2006). In a study by Palmer et al. (2003) it was found that lifting was a relatively higher cause of LBP when compared to WBV in British workers. In this study only weak correlations were found for WBV and LBP, while no dose-effect relationship was found. The aim of a study by Hagberg et al. (2006) was to describe the relation between WBV and musculo skeletal pain and also to see whether ergonomic factors (frequent bending and material handling) were confounding to the relationship. It was found that these ergonomic factors are more important in causing LBP, than WBV. The WBV was however a cause of other musculo skeletal pain in the neck, shoulder/arm and hand. A study of the effects of WBV on the musculo skeletal system, excluding the lower back, was suggested. Okunribido et al. (2006) also found that the combined effect of WBV, bad posture and material handling is the main contributor to LBP when compared to an individual exposure to one of the factors, thus strengthening the findings of Hagberg et al. (2006).

According to Pope et al. (1998) it is clear that persons in a seated posture show a characteristic spinal response to vibrational inputs. A prime example of this is the fact that resonant frequencies are very much the same among many different subjects. The main frequency is at 4.5 – 5.5 Hz. This resonance occurs because of the biological systems between L3 and the seat surface.

After WBV exposure the muscles in the back are fatigued and the discs are compressed. Thus the spine is not in an optimal state for sustaining larger loads. A worker then has an increased risk of sustaining LBP. Pope et al. (1998)

accordingly suggests that a person who has been exposed should not do any heavy lifting. This is an interesting finding in the light of "material handling" being a confounding factor to the relation between WBV and LBP (Hagberg et al. 2006). It thus seems possible that WBV increases the risk for LBP in workers doing heavy lifting. Okunribido et al. (2006) confirmed this by stating that driving has two effects on the driver. Firstly, the back muscles become fatigued and secondly the spinal discs lose height because of vibration. This loss of height causes the discs to become stiffer, less able to dissipate energy and shows decreased strength when put under severe loading. This situation places the driver at an increased risk when lifting materials.

From the literature it seems that many studies done in the past 20 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 multiple contributing factors.

2.1.3.2 Other Effects

The neck-shoulder, gastrointestinal system, female reproductive organs, peripheral veins and the cochleo-vestibular system are all assumed to be affected by whole-body vibration, although there is very limited research available on any of these effects (Bovenzi and Hulshof, 2007).

A study by Björ et al. (2006) found that work with high vibration exposure is associated with an increased risk of acute myocardial infarction. It was however stated that the occupations assessed included many other risk factors, such as noise, which could not be separated from vibration, which in itself has been found to have cardiovascular effects. In the context of the present study it is important to mention that low frequency noise exposure is also responsible for certain cardiac effects including thickened cardiac structures which lead to cardiac infarcts and stroke (Alves-Pereira and Castelo Branco, 2000). Von Willebrand

factor was increased in the blood after exposure to whole body vibration. This implies that there are vascular changes and these vascular changes could result in nutritional compromise of the tissues around the spine (Pope et al. 1998). Von Willebrand factor is secreted by the vascular endothelium and is involved in hemostasis as mediator for platelet adhesion to the subendothelium as well as platelet to platelet adhesion (Vischer and de Moerloose, 1999). Thus it seems that WBV could indeed have effects on the vascular system.

According to Ishitake et al. (1998) a high frequency of gastrointestinal disorders has been observed in workers exposed to whole-body vibration. There are however few studies available on the human gastrointestinal response to WBV and again there is uncertainty regarding the specific role of WBV amongst other factors. The findings in the study suggest that short term exposure to WBV can suppress gastric motility by decreasing contractile activity. This suppression can then lead to gastric disorders.

2.1.4 Factors Which Influence Vibration Measurements

A study done by Pinto and Stacchini (2006) evaluated the contributions of different factors to the uncertainty of daily WBV measurements. According to the authors, not taking into account all the factors which affect vibration would lead to inaccurate assessments of daily 8 hour vibration exposures. These measurement uncertainties were calculated in accordance with the ISO publication "Guide to the Expression of Uncertainty in Measurement". In this study the factors that cause uncertainty were isolated and quantified.

The major factors that influence field measurements were divided into categories relating to the operators, vehicles, working cycles and handling of transducers. In the category for operators differences in anthropometric characteristics, posture and working methods were taken into account. For this a single vehicle was operated in turn by different operators (Pinto and Stacchini 2006). In the

vehicle category changes in the characteristics and conditions of vehicles were taken into account. For this several vehicles in the same category (usually used to perform the same task) was operated by the same driver in the same working cycle. The working cycle category, focused primarily on the changes of the surface area a vehicle was travelling on, within typical working cycles (Pinto and Stacchini 2006).

The results of the study exposed the two factors that were described as "the most relevant uncertainty components". These were changes in the characteristics of machines and differing working cycles. An overall percentage uncertainty, p, was reported to be in the range $14\% < p < 32\%$. The percentage uncertainty caused by transducer and measurement equipment in a correctly calibrated system was found to be smaller than 4%. The authors conclude that the influencing factors should be taken into account to produce more accurate field measurements (Pinto and Stacchini 2006). Thus, when determining daily 8 hour exposures the use of different measurement equipment and different operators contribute least to the uncertainty of a measurement. On the other hand, characteristics of machines and working cycles contribute substantially to uncertainty. In this study vehicles of the same kind were grouped together and measurements were only used when each vehicle in a category followed the same working cycle, therefore minimizing uncertainty for the vibration levels obtained.

2.1.5 Control Measures

Engineering controls to reduce WBV exposure on vehicles or mobile machines can be divided into three groups. The first group focuses on the reduction of vibration at the source by taking factors such as terrain, vehicle/machine, loading and maintenance of the vehicle into account. The second group incorporates suspension systems at crucial points in order to reduce vibration transmission to the operator. These suspension points include the tires, vehicle suspension, cab

suspension and seat suspension. The third group strives to improve cab ergonomics and seat profiles to optimize operator posture (Donati, 2002).

Most off-road vehicles use pneumatic tires, while big machines using caterpillar tracks and some trucks using solid tires are the exceptions. Tires are selected based on factors such as rolling resistance, stability, grip, cost etc. In terms of vibration control it is stated that even large tires cannot compare to a suspension system. Thus vibration even builds up on relatively smooth surfaces. Tires would need to absorb five to ten times more vibration energy in order to improve their suspension ability. Such tires would be larger and softer, but will also have a higher rolling resistance thus decreasing its life span (Donati, 2002). Accordingly there seems to be little that can be done on tires to improve vibration attenuation.

Cabs can also be designed with a suspension. There is a distinction between cabs mounted on a rubber lining and cabs using a low-frequency suspension. These cabs may be designed to provide isolation in all three linear axes, but the main focus is on the vertical axis. These cabs have been successfully incorporated in agricultural vehicles, but are yet to become prominent in industrial vehicles. Acceleration measurements taken in the workplace revealed that the vertical axis was best attenuated for by cab suspension and on average a 30% reduction in acceleration was achieved (Donati, 2002).

Seat suspension is the final level of suspension before the operator and is also the only suspension present in some trucks. Seat upholstery has proven ineffective to reduce vibration exposure and the vast majority of seat suspensions are designed only to work in the vertical axis (Donati, 2002). In strengthening this point Pope et al. (1998) found that cushions were not effective in attenuating vibration and in fact increased the response. Low cost suspension seats, usually mounted on operated lawn mowers are a prime example of this. There are however seat suspensions which do improve the vibration energy transfer to the operator. One of the factors to be considered when choosing a

seat is the suspension attenuation frequency. A seat only attenuates frequencies above this level, while amplifying any vibration frequency below his level. Thus it stands to reason that the dominant vibration frequency of the vehicle as well as the suspension attenuation frequency should be known in order to choose an effective seat suspension (Donati, 2002).

To finally confirm the importance of suspension systems to attenuate vibration energy transfer, tests conducted at the Federal Institute of Agricultural Engineering in Wieselburg, found that a 50% vibration reduction could be achieved when an optimal combination of the three suspension systems (front axle suspension, cab suspension and seat suspension) was installed. This 50% reduction was in comparison to other similar tractors without the suspension systems (Donati, 2002).

Kittusamy and Buchholz (2004) made certain suggestions to control vibration exposure on heavy vehicle operators. These included that a seat design should take vibration transmissibility into account and not just comfort. It was further contended that seats should specifically damp vibration in the frequency range of 1-8 Hz. Lastly it was mentioned reduction of speed and good maintenance of heavy vehicles could reduce vibration. Paddan and Griffin (2002) found a wide range of vibration magnitudes when measuring vibration on many different vehicles. This led to the assumption that proper selection of vehicles and operating conditions could decrease vibration exposure for vehicle operators.

2.1.6 Quantifying WBV

WBV exposure is calculated using daily exposure A(8) which can be expressed in two ways. Firstly it can be expressed as an equivalent continuous r.m.s. acceleration over an eight hour period or secondly as vibration dose value (VDV). If frequency weighted acceleration is used, multiplying factors as specified in ISO

2631-1 for all three axes is applied. Regardless of how WBV is expressed, the axis with the highest vibration level is used to determine exposure (Griffin, 2004).

Donati (2002) states that the running r.m.s. method will underestimate vibration exposure, as it only takes the highest vibrational peak of each second into account. In spite of this Donati (2002) concludes that the r.m.s. method may be used, as it is only high vibration peaks that affect the health of a worker and not the lower level vibration which occurs continually.

2.1.7 Guidelines and Standards

ISO 2631-1 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. The guide is referred to as the health caution guidance zone (HGCZ).

The HGCZ is defined by the standard for weighted accelerations to be between 0.45 ms^{-2} and 0.90 ms^{-2} for the r.m.s. method and 8.5 $ms^{-1,75}$ and 17 $ms^{-1,75}$ for the VDV method. This exposure is for an 8 hour period and according to the standard, exposure above the HGCZ is likely to lead to health effects. Vibration within these parameters is a cause for caution, while lower levels produce no clear effects.

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 normalized over an 8 hour period and VDV which is the Vibration Dose Value. The action level for WBV is given as 0.5 ms^{-2} r.m.s. and 9.1 $ms^{-1,75}$. The exposure limit is given as 1.15 ms^{-2} r.m.s. and 21 $ms^{-1,75}$.

2.2 Noise and Low Frequency Noise

Sound exists in a range of frequencies, some of which is easily perceived by the human ear and some which is not (Leventhall, 2003). The human ear captures sound within the 20 Hz to 20 kHz frequency range, but is most responsive to the frequencies between 1 kHz and 10 kHz (Alves-Pereira and Castelo Branco, 2000). It has thus far been the aim of research to focus on sound and its effects on the human auditory system. Indeed this has been found to be a worldwide problem (Kurmis and Apps, 2007). Also specifically in mining, hearing loss caused by excessive exposure to noise, is present across different commodities and different mining occupations (McBride, 2004).

Low frequency noise is that sound which is found in the 20 Hz to 500 Hz range and can only be perceived by the human ear when very high levels are present. It gives rise to a condition called Vibroacoustic disease (VAD) and has been found to be present on airplanes and some vehicles (Alves-Pereira and Castelo Branco, 2007).

Thus this literature overview on noise is divided into a noise section and a low frequency noise section. The term "noise" refers to sound which is found in frequencies higher than 500 Hz (up to 1 kHz) and that affects the human auditory system, while "low frequency noise" is that which is found below 500 Hz and causes extra-aural effects.

2.2.1 Noise

Sound can be perceived differently by different people. Because of this fact it is difficult to define noise, but it is normally described as unwanted sound. This unwanted sound can have certain physiological effects (i.e. hearing loss) no matter if it is perceived as wanted or unwanted (Fernández et al., 2008). Hearing is the human sense that is specifically important for communication. Without it, most things in life become very challenging in an era where there is a premium on human interaction. Problems can range from day to day interaction, to struggling to communicate in a working situation (Kurmis and Apps, 2007).

Claims for hearing loss from negligent exposure to noise at work, make up the largest category of settlements under employer liability both in terms of number of claims and the total amount claimed (Lutman, 2000). Yet hearing loss worldwide is more prevalent than is commonly expected, with one in six adults struggling with some form of physiological hearing impairment. Despite increased awareness and ever increasing focus on the subject, noise-induced hearing loss (NIHL) remains a major cause of morbidity in and outside the workplace (Kurmis and Apps, 2007). In the European Union, NIHL is considered the most common occupational illness with 7% of workers suffering some form of hearing impairment. One in five people in Europe work in environments where they need to raise their voices in order to be heard (Fernández et al., 2008).

Noise exposure is a known hazard in the mining industry. Yet the prevalence of noise-induced hearing loss (NIHL) has not decreased. Noise is present in most mining activities and common to all commodities. NIOSH states that overexposure to noise is still a widespread problem in U.S. mines (McBride, 2004). According to McBride (2004) there is no doubt that most miners are exposed to noise levels exceeding an 8 hour L_{eq} of 85 dB(A) and some of these workers are even exposed to the peak exposure standard of 140 dB. Also sound levels associated with heavy construction equipment can range from 80-120

dB(A) with bulldozers, road graders and haul trucks being responsible for the highest levels (Spencer and Kovalchik, 2007). In South Africa, NIHL in gold miners was reported in literature more than two decades ago and it continues to plague the South African mining industry today. This is clear from statistics showing that 5617 cases of NIHL in the South African mining industry cost 135.8 million South African Rand in the year 2005 (Phillips et al., 2007).

Development of NIHL does not solely depend on exposure to a high noise level. Indeed the following factors should be taken into account: exposure duration, intensity, type of noise, frequency, use of hearing protection and whether or not the worker is being exposed to workplace chemicals (Rachiotis et al., 2006).

2.2.1.1 Noise Sources in Mining

Mines have many areas of high noise levels and many workers are potentially overexposed. Typical noise sources in mining include pneumatic drills which bore shot holes, extracting equipment, diesel powered haulage equipment, impulse noise created by blasting (McBride, 2004), drilling, cutting, materials handling, ventilation, crushing, conveying and ore processing (Donoghue 2004).

The diesel powered engines of haul trucks are generally a high source of noise. The engine noise may be emanated by the exhaust, the intake or the engine's cooling fan. The transmission, drive train and hydraulic system are other haul truck components that create noise. Noise can reach the ear via the air, or be reflected off other objects before reaching a person (Bealko, 2008). This study by Bealko (2008) assessed sound levels within the cabs of different haul trucks. Old trucks, new trucks and old trucks with cabs that were redone due to many hours of use were included. In the new vehicles no significant noise level was found, but in both categories of old trucks an average level of above 85 dB(A) was found. Factors like open windows and radios were found to increase the sound level within a cab.

Spencer and Kovalchik (2007) found operators of heavy construction equipment to be exposed to high noise levels. Levels of 95-99 dB(A) for bulldozers with cabs, 80-82 dB(A) for haul trucks with air conditioning and 90-92 dB(A) for haul trucks without air conditioning was reported. Also a road grader exposed the operator to a level of 97 dB(A). Excavators and front-end-loaders had lower noise levels at 76-78 dB(A) and 76-80 dB(A), respectively.

According to Fernández et al. (2008) sectors like manufacturing and construction have a clear problem with high noise levels. In the Spanish construction industry, it was found that between 60% and 70% of workers were exposed to levels above the recommended limits. The activities where machines had to be used were high risk areas in terms of high frequency sounds while low frequency sounds dominated other areas where machines were not used. Despite this, both areas had higher than acceptable noise levels.

2.2.1.2 Weightings in Sound Measurement

Measurement of sound is mostly done using a sound level meter. These measurements can be done by using different frequency weightings. The first is called the A-weighting and it allows the instrument to "focus" more on higher frequency sounds and specifically those in the frequencies that are normally perceived by the human ear. This is done by gradually attenuating for sound as the frequency declines below 1000 Hz (Leventhall, 2003). This A-weighting is used to asses the risk to human hearing and such measurements are expressed as dB(A) (Franz, 2007). The C-weighting includes most of the frequency range, only attenuating for sound below 50 Hz (Leventhall, 2003). It is useful for determining the presence of low frequency sound in a sound level meter that is not equipped with a frequency filter. This is done by comparing the A-weighted measurement to the C-weighted measurement. If the readings are similar it indicates that low frequency noise is absent (Franz, 2007). Lastly there is a Z-

weighting, which translates to having no weighting and all frequencies are thus equally included in the sound level that is measured (Leventhall, 2003). It is proposed that this Z-weighting should be used when measuring low frequency noise levels (Alves-Pereira and Castelo Branco, 2000).

2.2.1.3 Physiological Effects of Noise

2.2.1.3.1 Noise Induced Hearing Loss

Individuals who suffer from hearing loss are mostly "diagnosed" by people close to them who recognize an inability or a decreased ability to communicate (Kurmis and Apps, 2007). The reason why the persons are unaware of the damage is because they are not informed of the dose-effect relationship given that NIHL develops slowly but progressively (Fernández et al., 2008). This stage is typically followed by a doctor's consultation and audiometric testing (Kurmis, 2007). NIHL is most commonly noted at the audiometric frequency of 4 kHz (Lutman, 2000). Kurmis (2007) further states that such a person loses the ability to hear sounds of frequencies between 4 kHz and 6 kHz. Much of human speech falls into this frequency range and thus causes difficulty in understanding and discriminating speech.

The organ of Corti is the structure containing both the inner and outer hair cells. It is located on the basilar membrane within the cochlea in the inner ear. When sound vibrations reach the cochlea through the inner ear, they are conducted through the fluid in the cochlea. This in turn causes the basilar membrane to vibrate. Thus the organ of Corti also receives these vibrations and the sensory cells convert the vibrations into nerve impulses that are sent to the auditory region of the brain. The inner hair cells synapse with approximately 95% of the auditory nerves, thus showing the importance of the inner hair cells (Guyton and Hall, 2006). NIHL constitutes a progressive, sensorineural, hearing deficit caused by damage to the sensory hair cells in the cochlea of the inner ear (Kurmis and Apps, 2007). Physiologically, noise will cause excessive motion of

the cochlea's basilar membrane leading to structural damage of the organ of Corti. This structural damage manifests in the hair cells by detachment from surrounding cells as well as cellular changes like cell membrane leakage (Hu and Zheng, 2008).

The cell membrane is a very important structural part of the cell. It defines the cells boundaries and performs many functions that keep the cell healthy and functional. There is ample proof that acoustic trauma causes damage to membranes of hair cells and previous literature implicates membrane dysfunction in noise-induced cochlear pathogenesis. In fact it has been found that the hair cells in the cochlea are the most vulnerable type of cell to acoustic trauma. Many modes of cell death have been identified, but apoptosis has been found to be the primary cell death pathway leading to cochlear lesions (Hu and Zheng, 2008).

According to Le Prell et al. (2007) there is another significant factor that contributes to NIHL. It is the production of free radicals. It has been shown that noise exposure indeed causes the production of free radicals in the inner ear by increasing the metabolism of cells. These free radicals are produced by the mitochondria in the cells constituting the inner ear. Free radicals are molecules which contain one or more unpaired electrons and include reactive oxygen species (ROS). These are important for normal cellular functioning but an excess of these molecules damage cellular lipids, proteins and DNA (Le Prell et al., 2007). A variety of antioxidant agents, including the primary cellular antioxidant glutathione, serve as a treatment by neutralizing the free radicals caused by excessive noise. Thus the hypothesis is that hair cells would not be killed and hearing impairment reduced (Le Prell et al., 2007).

Exposure to noise does not only lead to permanent hearing loss, but shorter exposures may cause a temporary threshold shift (TTS). In most cases permanent hearing loss is caused by years of exposure to high noise levels, while an event like a rock concert will likely cause TTS. As the name implies this is temporary and full hearing will return within hours or days if exposure is not

repeated (Ross, 2007). According to Horie (2002) TTS is regarded as a predictor of future noise-induced hearing loss.

Mezoue et al. (2003) found that smoking is significantly associated with hearing loss at high frequencies. More specifically, a dose-response relationship between smoking and hearing loss in the range of 4 kHz was found. The mechanism of the effect of smoking on hearing loss is not known, but one hypothesis is that blood supply to the cochlea is decreased or carboxyheamoglobin in the blood is increased. Nicotinic receptors have also been found on the sensory hair cells giving rise to the possibility that smoking has a more direct impact on hearing loss. Previous studies hypothesize that there is a close association between smoking and high frequency hearing loss. The hair cells responsible for high frequency sounds are located at the end of the arteries that supply nutrients, thus implying damage by ischemic mechanisms. It was found that smoking does not enhance the effect of noise on hearing, but rather has an independent effect on high frequency hearing loss. It is also stated that smoking could be additive to the high noise levels in causing hearing loss and that no such effect was found for low frequency hearing loss (Mezoue et al. 2003). NIHL is permanent due to the fact that hair cells, once destroyed, can not regenerate (Rachiotis et al., 2006)

2.2.1.3.2 Stress and cardiovascular effects of noise

Noise activates the release of stress hormones which are associated with certain physiological effects including cardiovascular disease. This noise/stress hypothesis is well understood in that noise activates the pituitary-adrenal-cortical axis and the sympathetic-adrenal-medullary axis. Thus changes in the stress hormones epinepfrine, norepinephrine and cortisol are found after acute and chronic noise exposure (Babisch, 2002). For clarity, the adrenal glands are located on the superior poles of the kidneys. They are composed of the medulla and the cortex, each of which are responsible for the secretion of certain

hormones. The medulla is functionally related to the sympathetic nervous system and secretes epinephrine and norepinephrine, while the cortex secretes cortisol and aldosterone. Cortisol being important from a stress reaction point of view. The above mentioned sympathetic-adrenal-medullary axis refers to sympathetic stimulation of the adrenal medulla to secrete epinephrine and norepinephrine. The pituitary-adrenal-cortical axis in turn refers to the release of adrenocorticotropic hormone (ACTH) by the pituitary, which then controls secretion of cortisol from the adrenal medulla (Guyton & Hall, 2006).

Continuous noise is perceived by the body as a stressor and thus noise causes great amounts of corticotrophin releasing hormone (CRH) and ACTH to be released. This in turn stimulates the secretion of large amounts of cortisol by the adrenal cortex (Spreng, 2000). Chronically high levels of cortisol in human beings have many effects. These include catabolic effects (e.g. protein breakdown in muscles); anti-anabolic effects (e.g. reduced muscle protein synthesis); diabetogenic effects (e.g. inhibition of glucose transport and use); hypertonic effects (e.g. increased sensitivity of adreno receptors of vasomotors and increased renal sodium retention); immuno suppression (e.g. decrease of circulating leukocytes and of eosinophilic and basophilic granulocytes); stress ulcer (e.g. increased secretion of gastric juice and inhibition of healing); and lastly adipose tissue metabolism (e.g. lypolysis triglycerides increase the level of fatty acids in the blood and thus the risk for arteriosclerosis) (Spreng, 2000). The hypertonic effect and increased risk for arteriosclerosis from high levels of cortisol clearly show that noise can lead to an increased risk of heart disease. Also, the above mentioned increase in epinephrine and norepinephrine after exposure to noise has significance with regard to cardiovascular effects. Epinephrine stimulates the cardiac β-receptors to increase heart rate and force of contraction, while norepinephrine causes vasoconstriction of essentially all blood vessels in the body (Guyton & Hall, 2006). Babisch (2003) confirms that noise will cause an increase in epinephrine and norepinephrine. Stress hormones like epinephrine, norepinephrine and cortisol are neurotransmitters that form part of a complicated positive and negative feedback system affecting the activity of the

heart, blood pressure, blood lipids, blood glucose and blood clotting. These factors are all established biological risk factors for hypertension, arteriosclerosis and myocardial infarction (Babisch, 2003). Thus it seems possible that noise exposure could increase the risk of cardiovascular disease.

2.2.1.3.3 Other Effects

Cordeiro et al. (2005) found that workers exposed to high levels of noise were in fact more prone to other injuries. This correlation was found to exist even after correcting for confounding factors. It was concluded that hearing conservation programs are needed to conserve the actual hearing, but also to reduce work-related injuries. It is important to note that reduction of noise at the source was highlighted in reducing injuries. Fernández et al. (2008) confirms this point by stating that noise can contribute to accidents because of communication difficulty (also caused by hearing protection devices) and other physiological effects like loss of attention, increased blood pressure and stress.

Another possible health effect of noise exposure is voice problems, due to workers needing to raise their voices in order to be heard (Fernández et al., 2008).

2.2.1.4 Control of Noise Exposure

Control of noise levels is more than just a legal responsibility and will also be financially beneficial to a company. A safer and healthier workplace will decrease accidents and absenteeism and enhance performance (Fernández et al., 2008).

Treatment for NIHL is currently non-existent, with hearing aids being the best alternative. Yet these cannot guarantee a level of hearing as perceived by the normal human ear (Kurmis and Apps, 2007). There is however evidence of

antioxidants serving as a possible treatment by nullifying damaging free radicals caused by excessive noise (Le Prell et al., 2007). According to Lutman (2000) the risk for NIHL when exposed to a sound level of 80 dB(A) over a 45 year period in males, is negligible. At a level of 85 dB(A) the risk is described as "marginal" and at 90 dB(A) and higher this risk is very real and NIHL will surely occur. Because of this, the control of noise in occupational settings is very important in decreasing the prevalence of NIHL.

2.2.1.4.1 Engineering Controls

According to Steenkamp (2003) first-level industrial noise control (engineering controls) is a high priority in mining and that noise control such as hearing protection devices (HPD's) should always be a last resort. Steenkamp (2003) also states that noise control should not only focus on reducing NIHL, but also protect workers from other occupational, medical, "quality-of-work-life" and productivity related reasons. In substantiating this statement, effects like an increase in mistakes, lower productivity and uncomfortable working conditions are named, among others.

McBride (2004) states that a philosophy of "buying quiet" along with good maintenance programs of existing noise sources would effectively lower sound levels in mining. New technology or changed work procedures such as tele-controls for pneumatic drills, separate man from the noise source thus lowering noise exposure.

Noise control can be designed into new equipment, but the process is more difficult when applied to already existing machines. Existing equipment or machines in noisy environments were most probably selected based on efficiency and because it was economical. However, when looking to reduce sound emission from the source (e.g. machine noise) again economical considerations and operational necessities are taken into account. It seems that

buyers need to demand "quieter" machines/equipment in order to force suppliers to design "quiet" machines. In this way current noisy machines could be phased out in time (Standard, 2002).

Examples of noise-controls that reduce emitted sound is replacement with quieter machines, the use of vibration-isolation mountings and reduction of external vibrating parts. Also sound proof booths for operators, sound-absorptive material in a high noise areas and regular maintenance of existing machines are first-level noise control measures (Standard, 2002).

Bealko (2008) and Spencer and Kovalchik (2007) found that open doors and windows within haul truck cabs and bulldozers increased sound levels within the cab. Operators should be encouraged to keep these protective cab features closed. Improved education of operators regarding noise levels is recommended. Also the installation of warning lights or alarms when a window is open is put forth as a possible way in which to strengthen noise policies. This would also serve as a reminder to the operator that he is potentially exposed to high noise levels (Bealko, 2008). It is stated that if the air conditioning of the vehicles had been in working order, the operators might have been encouraged to keep the doors and windows closed (Spencer and Kovalchik, 2007).

According to the U.S. Department of Labor (1999) most large mining equipment is produced with sound protective cabs. This includes manufacturers like Caterpillar, Volvo and Komatsu. If vehicles have no noise controls there are many recommendations by which to improve the protection of the operator. For haul trucks, these recommendations include placing absorptive material on the walls and ceiling of the cab. An acoustical floor mat may be installed, all openings to the outside closed off and cracked or missing glass must be replaced.

Recommendations for older bulldozers (e.g. without sound protective cabs) include installation of an exhaust muffler with the tip above the cab and in a

backward direction; installation of rubber "boots" around the base of control levers to keep engine noise out of the cabin; tightening down loose floor pads and covering the floor with an acoustical floor mat; covering cab walls and ceilings with sound absorptive material (U.S. Department of Labor, 1999). For excavators and front-end-loaders the cab should be treated with sound proof material and again a muffler installed on the exhaust. Care should be taken to make sure there are no leaks in the cab. The same applies to graders, but as the major noise sources are behind the operator (engine, fan and exhaust) the back panel of the cab should be treated with a material consisting of a high density vinyl between two layers of fibreglass. Other examples of sound absorptive material are foams, glass fibre, mineral fibre, felts, perforated sheet metal and spray-on coatings (U.S. Department of Labor, 1999).

2.2.1.4.2 Administrative Controls

Administrative controls include any administrative means by which the noise exposure of employees can be reduced. This can mean the rotation of workers from noisy areas, scheduling machine operating times so as to expose the least amount of workers and transferring workers who are especially susceptible to noise to quieter working areas (Standard, 2002). In the case of mining vehicles this could mean rotating operators of new haul trucks (sound proof cabs) with bulldozer operators where noise levels may be much higher.

2.2.1.4.3 Hearing Protection Devices (HPD)

Hearing protectors should be a final way in which to counteract noise exposure (Steenkamp, 2003). Hearing protectors are either ear-muffs which cover the ear or ear plugs that can be inserted into the ear canal. Both these types of personal hearing protection come in different forms and with different degrees of protection. Ear-muffs consist of a cup shaped cover that is held over the ear by a spring loaded headband. A good seal around the ear is very important and thus

this area of the ear-muff is covered with a cushion or lining filled with liquid. The material of which ear-muffs are constructed is responsible for the degree of protection, but if the ear-muffs do not seal tightly the protection of a worker will not be successful. For that reason ear-muffs should be serviced and checked regularly with special focus on the seal area (Guild, 2001). According to McBride (2004) ear muffs is the best protection in high noise areas although plugs perform better, probably due to the fact that they are not as easily removed.

Ear plugs come in many forms and are produced from a variety of materials. Disposable plugs can be made from polyurethane foam, glass down or wax-impregnated cotton wool, while reusable plugs come in plastic and rubber combinations (Guild, 2001). McBride (2004) discussed hearing protection devices (HPD's) which are often used in mining. These mostly come in the form of ear plugs which do not protect against the hazard due to ineffective fit or poor compliance by the workforce. Often ear plugs are uncomfortable and also interfere with communication and thus are removed by workers. Where noise is intermittent, like in mines, it is even more likely that workers would not wear the HPD's. It is thus important to match the HPD to individuals as well as the noise environment in an effort to improve compliance and thus protection. Kurmis and Apps (2007) confirm the above mentioned non-compliance by pointing to a study in the U.S. on workers in high noise environments. This showed that 98% of workers were aware that HPD should be worn, but the actual number of workers complying was just over 50%. Education on noise exposure and the effects could serve as a tool in improving worker compliance (McBride, 2004); however it is discomfort that is considered the primary reason for non-compliance. Comfort is described by factors like physical fit, ventilation, sound control, speech discrimination and level of isolation (Steenkamp, 2003).

Steenkamp (2003) found in a study on mining workers, that workers regarded custom made hearing protection devices (CHPD's) as better than previously worn HPD's. Previously worn HPD's are a single type of ear plug applied to all workers, while the CHPD's were made for fitting each worker. Steenkamp (2003)

found that four points specifically caused workers to have a higher regard for the CHPD's. These were that they were more comfortable, that they protected the worker's hearing, that the colour was aesthetically pleasing and that they helped the subject to work safer. It was further observed that workers actually wore the CHPD giving rise to the hypothesis that CHPD's do in fact provide better hearing protection.

Hearing protection devices are assigned a Noise Reduction Rating (NRR). This is indicated on the packaging of the product. The NRR is the average attenuation provided by a HPD when worn by ten different people in a laboratory test (Guild, 2001). It is suggested that it must not be accepted that the NRR is valid for calculating attenuation in an actual working situation. Under actual working conditions HPD's only provide 30-50% as much attenuation as the NRR. Thus a method proposed is to subtract 7 from the NRR and then divide the remaining figure by 2 and only then does one have a practical estimation of the attenuation. Removal of a HPD will have a significant effect on overall attenuation. Therefore in some cases a less comfortable HPD with a high NRR may not be as effective as a comfortable HPD with a lower NRR, as workers are more likely to continuously wear the more comfortable version.

2.2.2 Low Frequency Noise

The assumption that noise only affects the ear, has given rise to the current way in which noise is viewed, measured and controlled. This leads to incomplete analysis of areas where excessive noise is present, with the focus only on those frequencies that cause hearing loss. The major frequency of concern for hearing loss is between 500 Hz and 10 kHz, as most NIHL occurs between 1 kHz and 10 kHz. The idea that no other health effects can be attributed to noise is common and exceptions to this are not easily encountered (Alves-Pereira and Castelo Branco, 2000).

According to Alves-Pereira and Castelo Branco (2000) low frequency noise is that which is found in the frequency below 500 Hz. It is important to note that LFN is audible but requires high levels at the lower frequencies in order to exceed the human hearing threshold (Leventhall, 2003). Despite the common assumptions about noise and its effects, an occupational disease has been identified that is caused by LFN exposure. It is called Vibroacoustic Disease or VAD (Alves-Pereira and Castelo Branco, 2000).

Alves-Pereira and Castelo Branco (2007) used an analogy between light and acoustic phenomenon to illustrate that LFN can not be ignored simply because it is not perceived by humans. Light exists in a range of frequencies, of which only a certain range can be sensed by the eye. Yet there are other frequencies, like X-rays, which can not be perceived by humans but still have detrimental effects on overexposed individuals. Research has even found that specific frequencies cause certain pathologies. When it comes to sound though, only those frequencies which affect the auditory system are recognised. This leads to scenarios where very high levels of LFN exist (90-100 dB), but the only motive of the health professional is to protect the hearing of the worker. According to Alves-Pereira and Castelo Branco (2007) this would be equivalent to protecting someone working with X-rays by giving them dark glasses. The authors

conclude that a new attitude is needed towards noise and suggest the term "acoustic pollution" to describe sound exposure across all frequencies, regardless of whether it affects humans or not.

Literature on the subject of low frequency noise is sparse. There are no exposure standards or dose-response relationships (Castelo Branco and Alves-Pereira, 2004) and VAD is yet to be recognised as an occupational disease and LFN as an occupational hazard (Alves-Pereira and Castelo Branco, 2000). From this it is clear that exposure to LFN and its effects is still a new and undiscovered field in occupational hygiene, and will most likely become more important in the near future.

2.2.2.1 Low Frequency Noise Sources

LFN is almost omnipresent in modern society, with most of it present in industrial areas as well as public transport and urban residential areas (Alves-Pereira and Castelo Branco, 2007). According to Leventhall (2003) LFN is produced by machines, all forms of transport and turbulence. Examples given include pumps, compressors, diesel engines, aircraft, shipping, combustion, air turbulence, wind and fans.

Symptoms of LFN exposure have been identified in certain occupations like aeronautical technicians, military pilots, commercial pilots and cabin crew, disc-jockeys (Alves-Pereira and Castelo Branco, 2000), ship machinists and restaurant workers (Castelo Branco and Alves-Pereira, 2004). Levels of more than 100 dB at 63 Hz and more than 95 dB at 250 Hz of LFN have been found in Canadian Forces armored vehicles when driven at speed (Nakashima et al. 2007).

2.2.2.2 Physiological Effects of Low Frequency Noise

There are to date no dose-response relationships available concerning LFN and human effects. Most likely it will be another few years before equipment like dosimeters with low frequency capabilities will be available to establish these dose-response relationships. Also it should be taken into account that different organs are affected by different frequencies and thus dose-response relationships would have to be found for different organs (Castelo Branco and Alves-Pereira, 2004). In spite of this, many effects have been observed and come in the form of Vibroacoustic disease.

2.2.2.2.1 Vibroacoustic Disease

"Vibroacoustic disease (VAD) is a whole-body, systemic pathology, characterized by the abnormal proliferation of extra-cellular matrices, and caused by excessive exposure to low frequency noise (LFN)" (Castelo Branco and Alves-Pereira, 2004).

VAD can develop in certain individuals who have been exposed to LFN over a period of years. More specifically, Alves-Pereira and Castelo Branco (2000) have classified the development of VAD in three stages. These are mild (1-3 years), moderate (4-9 years) and severe (10-15 years). LFN is a stressor and thus in early exposure (mild stage) is associated with stress-related symptoms such as indigestion and heart burn, slight mood swings and mouth/throat infections. It should however be noted that VAD is distinguishable from generalized stress-related syndromes (Castelo Branco and Alves-Pereira, 2004). In the moderate stage however, more serious changes, associated more specifically with VAD, begin to appear such as thickened cardiac structures, increased frequency of sister chromatid exchanges, immunological changes, altered hemostasis and coagulation values, neurophysiological and cognitive changes (Alves-Pereira and Castelo Branco, 2000). These physiological

changes of the "moderate" stage present as chest pain, definite mood swings, back pain, inflammation of the stomach lining, pain and blood in urine, conjunctivitis, allergies and fungal, viral and parasitic skin infections (Castelo Branco and Alves-Pereira, 2004).

Many years of exposure to LFN can give rise to cardiac infarcts, stroke, cancer, epilepsy, rage reactions and suicide (Alves-Pereira and Castelo Branco, 2000). This stage also includes haemorrhages of the nasal, digestive and conjunctive mucosa, varicose veins and haemorrhoids, duodenal ulcers, decrease in visual acuity, joint pain, severe muscle pain and spastic colitis (Castelo Branco and Alves-Pereira, 2004). The cardiac symptoms are caused by abnormal cell proliferation of collagen and elastin, leading to thickening of blood vessels and impeding normal blood flow. Other structures affected in the same way are the parietal pericardium and the aortic and mitral valves (Alves-Pereira and Castelo Branco, 2000). Three of the above mentioned effects are highlighted as serious, specifically while working. These are rage reactions, epilepsy and suicide. After a spell of one of the before mentioned effects, patients appear confused and cannot remember their actions. This clearly could be very dangerous for the affected person and other people working close to such a person (Alves-Pereira and Castelo Branco, 2000). Symptoms like late-onset epilepsy, balance disturbances, thyroid dysfunction, wide spread tumours and decreased respiratory drive are also mentioned as being clinically significant, although these were found in less than 50% of the population studied (Alves-Pereira and Castelo Branco, 2007).

All the above mentioned symptoms within the time frames are based on an 8 hour per day, 5 days per week exposure schedule. There are other occupations which could lead to much higher exposures like oil rig workers who spend much longer periods exposed. This might lead to accelerated development of symptoms. Then there are also roster type occupations where a ship machinist might spend 3 weeks on board and 2 weeks off. These factors need to be taken into account (Castelo Branco and Alves-Pereira, 2004).

Another important fact to take note of is that a certain number of persons exposed to LFN, do not develop the severe stages of VAD. This is stated to be around 30% of exposed persons. Although mild symptoms were present, it never progressed. Further research is needed to clarify what factors influence human susceptibility to LFN (Alves-Pereira and Castelo Branco, 2000).

Various methods of diagnosis have been identified by Alves-Pereira and Castelo Branco (2000) seemingly based on some of the different VAD symptoms. An echocardiogram is the diagnostic method of choice when testing for preliminary VAD. An echocardiogram uses the principles of ultrasound to visualize the thickened structures in the heart. Other methods for testing in the nervous system, blood testing and audiograms can also serve to help identify VAD (Alves-Pereira and Castelo Branco, 2000).

2.2.2.2.2 Other Effects

It is reported that persons working in high LFN environments show a significant decrease is social orientation (irritated, ill-tempered, feeling disagreeable and less co-operative). A decrease in coping with cognitive demands was also shown and these effects became pronounced with time. However, these findings are based on a very small subject group and only moderate levels of noise were used, therefore further research is recommended (Nakashima et al. 2007). It was also indicated that LFN produced by armoured vehicles had a negative effect on reaction time. Other studies have found that LFN can affect stress levels as well as cause what is described as "annoyance" in humans. It has been found that LFN causes disruption in the normal cortisol rhythm (Leventhall, 2003).

2.2.2.3 Measurement of Low Frequency Noise

A comprehensive assessment of a noise environment can only be done when the results reflect both the dB-level of the sound as well as the frequency distribution thereof. Yet the frequency analysis of noise assessments is rarely included, as the primary aim of these assessments is protection against NIHL (Alves-Pereira and Castelo Branco, 2000). This has led to many parallel studies which can not be compared despite similar dB-levels. They are incomparable due to the fact that even though the dB-levels are equivalent, the power of the sound for one might be in the middle frequency range while the other's sound power is located in the low frequency range. Extra-aural, whole-body, noise-induced pathology is a concept unfamiliar to most and this has contributed to only dB-levels being measured. Thus sound measurements should in future include frequency analysis (Alves-Pereira and Castelo Branco, 2000).

Alves-Pereira and Castelo Branco (2007) again confirm this later on by discussing the fruitlessness of assessing the effects of noise on a human by only using the A-weighted scale. The A-weighted scale causes lower frequency sound to be attenuated for, thus only giving a reading applicable to the human auditory system. It is stated that a reading using no weighting (e.g. dBLin) compared to a reading that used dB(A), from the same acoustical environment, are clearly different. Thus showing that A-weighted measurements are indeed not representative of the true acoustical environment and should therefore only be used for hearing conservation purposes and not for total noise exposure testing. The authors accordingly propose that all sound environments should also be measured using a 1/3 octave band analysis with no weighting (dB(Z) or dBLin) in order to take LFN into account.

2.2.2.4 Control of Low Frequency Noise Exposure

LFN is not legislated and thus no specific values for control are available (Castelo Branco and Alves-Pereira, 2004). In South Africa too, no legislation regarding exposure to low frequency noise is available (SANS 10083:2004).

Attenuation of low frequency sounds by air is very low. Also factors like absorption by the ground or shielding by barriers are ineffective where LFN is concerned. Air attenuations of LFN are represented by the following figures: 0.1 dB/km at 63 Hz, 0.35 dB/km at 125 Hz and 1.1 dB/km at 250 Hz. This is at 20° C and a relative humidity of 70%. This clearly shows that the attenuation by air increases as the frequency increases, as air is a good attenuator of high frequency sound. This fact causes sound that has travelled over some distance to have only the low frequency component left as the high frequency component has been completely attenuated by the air (Leventhall, 2003).

In order to effectively attenuate LFN a "massive single partition or a complex multiple partition" is needed, but such a shield would become progressively more effective as the frequency increases. In fact, most walls in buildings are ineffective in controlling LFN and thick sound absorptive material of a few centimetres does not disrupt the LFN waves (Leventhall, 2003).

Alves-Pereira and Castelo Branco (2000) recognize the difficulties encountered when attempting to control LFN exposure. Again, because of low frequency waves being meters long, it would take extraordinary thick walls to combat the spread of these waves. Yet, as part of control for specifically VAD, the authors suggest that LFN be included as an occupational hazard while VAD should be counted as an occupational illness. They further contend that workers who work in noisy environments and develop VAD symptoms, should be removed from the environment and placed to work somewhere else. Also, pre-employment echocardiograms should be taken in order to establish whether or not persons

are to be allowed to work in specific occupations or not. This would lead to major reshuffling of many organizations' employment principles and people might only be eligible for a job for a certain amount of time. Yet Alves-Pereira and Castelo Branco (2000) state that the alternative of wide spread VAD is much worse.

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Chapter 3

Instructions for Authors

- *Submission.* The manuscript should be prepared using a word processor using these instructions, and then processed using the on-line submission procedures.

  Any hardcopy correspondence should be sent to the Editor-in-Chief, Dr Trevor Ogden, The Annals of Occupational Hygiene, BOHS, 5/6 Melbourne Court, Millennium Way, Pride Park, Derby DE24 8LZ, UK.

  1. **Originality.** Only original work, not published elsewhere, should be submitted. If the findings have been published elsewhere in part, or if the submission is part of a closely-related series, this must be clearly stated and the submitted manuscript must be accompanied by a copy of the other publications (or by a copy of the other manuscripts if they are still under consideration). These should be uploaded in the submission as supplementary files, or in case of difficulty may be sent in hard copy to the Editorial Office.
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must have been approved by a competent ethics committee using the standards of the Helsinki Declaration of the World Medical Association. The ethics committee which gave approval must be named in the paper.

4. **Conflicts of interest.** The source of financial support for the work must be stated in the Acknowledgements, unless it is clear from the authors' affiliations. Other conflicts of interest must be declared to the Editor at the time of submission. These may include financial interest in products described, including stock or share ownership, and payment for consultancy or legal testimony using the material in the paper. These conflicts will not necessarily prevent publication, but the Editor may decide that the declaration should be included in the paper.
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6. **Brevity and supplementary material.** The necessary length of a paper depends on the subject, but any submission must be as brief as possible consistent with clarity. The number of words, excluding the abstract, references, tables and Figs, must be stated as a message to the Editor at the time of submission. If this length is more than 5000 words, a statement must be included justifying the extra length, and papers without this information may be returned unread. It is possible to include supplementary material, such as large data sets, in the on-line edition only, and authors are

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7. **Structure.** Papers should generally conform to the pattern: Introduction, Methods, Results, Discussion and Conclusions - consult a recent issue for style of headings. A paper must be prefaced by an abstract of the argument and findings, which may be arranged under the headings Objectives, Methods, Results, and Conclusions. Keywords should be given after the list of authors.
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.
9. *Units and symbols.* SI units should be used, though their equivalent in other systems may be given as well.
10. **Figures.** Good quality low resolution electronic copies of figures, which include photographs, diagrams and charts, should be sent with the first submission. It is helpful to reviewers to incorporate them in the word-processor text or at the end. The revised version, after refereeing, should be accompanied by high-resolution electronic copies in a form and of a quality suitable for reproduction. They should be about the size they are to be reproduced, with font size at least 6 point, using the standard Adobe set of fonts. Fine hairlines should be avoided and clear hatching patterns should be used in preference to solid grey shadings wherever possible. They should be on separate pages at the end of the text. All figures should be black and white unless the first author is willing to pay for colour reproduction at standard Oxford University Press rates (available on request). Authors should submit high-resolution electronic copies of the figures when they send the revised version of the paper. These should have a resolution of 600 dpi for line figures, and 300 dpi for half tones), saved as .tif, .jpg, .gif, .bmp or .eps files (with fonts embedded where appropriate). Graphics in Word, Excel and PowerPoint formats are acceptable so long as the

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    Jones and Brown (1995) observed total breakdown of control...
    or
    Total breakdown of control has sometimes been observed (Jones and Brown, 1995).
13. At the end of the paper, references should be listed in alphabetical order by name of first author, using the Vancouver Style of abbreviation and punctuation. Examples are given below. ISBNs should be given for books and other publications where appropriate. Material unobtainable by readers should not be cited. Personal Communications, if essential, should be cited in the text in the form (Professor S.M. Rappaport, University of California). References will not be checked editorially, and their accuracy is the responsibility of authors.

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Article

Exposure of vehicle operators to vibration and noise at a Tanzanian opencast goldmine

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Abstract

Objectives: The exposure of mining vehicle operators in Tanzania to whole-body vibration (WBV), A-weighted noise and low frequency noise (LFN) was assessed. The aim was to quantify levels of exposure in order to estimate the risk of health effects and also to report levels of these hazards that exist on mining vehicles.

Methods: In each case correctly calibrated instrumentation was used and internationally accepted methods were followed. A tri-axial seat pad accelerometer was used to measure WBV while a sound level meter was used to apply a frequency band analysis to the acoustic environments in different vehicle cabins. Personal noise dosimeters ensured further noise measurements.

Results: It was found that mining vehicles commonly exposed operators to levels of whole-body vibration within and above the ISO Health Guidance Caution Zone (HGCZ) and above the European action level, which indicates the need for intervention and control. A-weighted noise was present in high levels on mining vehicles, in each case equal to or above 85 dB(A). It was found that much of the sound energy measured on vehicles was located in the low frequency range. In the lowest frequency band measured, L_{eq} levels of more than 100 dB(Z) were generally found.

Conclusions: 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. These controls can include good maintenance of vehicles and roads to reduce whole-body vibration, sound proofing of vehicle cabs along with hearing protection devices to protect hearing and further research regarding the exposure and health effects caused by low frequency noise. Following literature indicating the physiological effects of LFN and presence thereof on mining vehicles, it is concluded that A-weighted measurements are not sufficient in describing the risk of acoustical environments.

Introduction

The term "miner" is relatively non specific in that the industry of mining draws on many different professions and trades (Donoghue, 2004). One of these includes the operation of mining vehicles like haul trucks, excavators, bulldozers, front-end-loaders and graders. In many cases these workers work shifts in excess of 10 hours (Eger et al., 2006), causing the possibility for high exposures to hazards specific to their occupation.

One of the prevalent hazards for operators or drivers is whole-body vibration. Indeed all occupational exposure to whole-body vibration (WBV) is categorized in some form of vehicle. This includes agriculture, aviation, construction and transportation (Smith and Leggat, 2005). It then seems feasible, that WBV would also be prevalent in mining vehicles. This has indeed been found by Eger et al. (2006). Levels of WBV on mining vehicles in Canada were above or within the ISO 2631-1 HGCZ (Health Guidance Caution Zone), implying a significant risk of health effects for haul trucks, bulldozers, graders and a personnel tractor. Other studies in mining and construction reported similar results (Kumar, 2004; Cann et al., 2003). Acute effects of WBV include headaches, increased heart rate, loss of balance and a decreased ability with regard to information processing. Lower back pain (LBP) is the most common long term physiological effect of WBV exposure (Smith and Leggat, 2005) and it is reported more by occupational drivers than by any other occupational group (Battié et al. 2002). Studies indicate that WBV is associated with an increased risk of LBP, sciatic pain and degenerative effects of the spinal system (Hagberg et al. 2006). ISO 2631-1 describes the HGCZ as being between 0.45 ms^{-2} and 0.90 ms^{-2}. Above this level health effects are likely, while levels within the HGCZ are a cause for caution (8 hours daily). The EU Directive 2002/44/EC states an action level of 0.5 ms^{-2} and a limit value of 1.15 ms^{-2} for 8 hour shifts.

Noise, a second hazard typical to mining, is common to all commodities and is present in all activities (McBride, 2004). This includes operators of large machinery. Noise induced hearing loss (NIHL) is considered the most common occupational disease in the European Union (Fernández et al., 2008) and despite it being a known mining hazard it is still a major problem in mines in the United States of America (McBride, 2004). In South Africa, NIHL in gold miners was reported in literature more than two decades ago and it continues to plague the South African mining industry today. This is clear from statistics showing that 5617 cases of NIHL in the South African mining industry cost 135.8 million South African Rand in compensation in the year 2005 (Phillips et al., 2007). Hearing is the human sense that is particularly important for communication and without it; even day to day activities become major challenges (Kurmis and Apps, 2007). For this reason, hearing conservation is very important and also specifically for mining vehicle operators. The South African National Standard specifies an 8 hour limit level of 85 dB(A) for noise (SANS 10083:2004).

Thirdly, low frequency noise (LFN) is emerging as an occupational hazard of note, especially considering findings that it causes extra-aural effects in the form of Vibroacoustic disease (VAD). VAD is a whole-body, systemic pathology, characterized by the abnormal proliferation of extra-cellular matrices. Substantial exposure may lead to thickened cardiac structures, immunological changes and altered hemostasis and coagulation values. After years of exposure LFN exposure may give rise to cardiac infarcts, stroke, cancer, epilepsy, rage reactions and suicide (Castelo Branco and Alves-Pereira, 2004). As LFN is almost omnipresent in modern society it is difficult to study, but aircraft have been identified as major occupational sources (Alves-Pereira and Castelo Branco, 2007). Armoured vehicles have also been found to emit high levels of LFN (Nakashima et al. 2007), which indicates that large mining machinery may also be responsible for high levels of LFN. There is currently no legislation concerning LFN.

Worldwide, research on whole-body vibration and noise found on mining vehicles is limited, and even totally lacking in the case of low frequency noise. Certainly no research of such a nature was found to have originated from Africa or even a study in Africa. Thus the present study serves as new information regarding such exposure on mining vehicles operating in Africa. In the absence of relevant regulations, the enforcement thereof and maintenance of vehicles is questionable. The aim of this study was to quantify the levels of exposure of mining equipment operators in Africa to whole-body vibration, noise and LFN.

Methodology

Selection of vehicles

The current study had an availability study design. Vehicles were selected based on participation in mining production and availability. Vehicles used primarily for transport of personnel were not included. Those that were included are different types of haul truck, bulldozers, excavators, graders and front-end-loaders.

Whole-body Vibration Measurements

Whole-body vibration exposure measurements were conducted in accordance with ISO 2631: Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration – Part 1: General Requirements (1997). A tri-axial accelerometer was placed between the seat surface and the ischial tuberosities of the sitting worker. The seat pad accelerometer was placed in such a way that the x-axis was in the saggital plane, the y-axis in the coronal plane and finally the z-axis in the vertical plane. A calibrated Quest HAVPro vibration monitor (Quest Technologies Inc.), model 356M172, was used.

Weightings (x-axis = W_d, y-axis = W_d and z-axis = W_k) and multiplying factors (x-axis, K=1.4; y-axis, K=1.4; and z-axis, K=1) were applied according to ISO 2631 for health effects of a seated person. Analysis of measurements was done using

Quest Suite Professional II software. Exposures were calculated into 8 hour equivalents. Results are reported as r.m.s. acceleration values (m/s^{-2}).

Due to the cycle pattern of the work done by haul trucks, vibration measurements of representative cycles were done. A cycle consisted of loading, then transferring the load to the dump site, dumping the load and returning to be loaded again. Two cycles of each vehicle ranging form 49 to 69 minutes were included in the measurements. These were considered to be representative measurements of typical vibration exposure on these haul trucks. Five different types of haul truck were included (Table 1).

Table 1: Description of vehicle categories and average measurement times for whole-body vibration and noise measured simultaneously.

Vehicle Type	No. of vehicles included	No. of cycles included	Average measurement time (min)
CAT 785	5	2	49
CAT 777	7	2	59
CAT 769	3	2	69
Volvo A40D	4	2	57
Komatsu HD325	3	2	55
Bulldozers	6	-	35
Excavators	4	-	33
Front-end-loaders	2	-	29
Graders	3	-	33
Scania	4	-	41

Different haul trucks travelled different routes depending on their function or the area being mined, which could impact vibration levels. The use of a standard route for all vehicles for the proposed measurements was not possible. Furthermore such a standard route would be less representative of actual "on the job" exposure. The influence of speed on vibration measurements was also considered. Speeds of different trucks of the same kind were uniform with no exception. The top speed on any haul truck on horizontal haul roads was 37 kph. The age or condition of vehicles was also considered and the number of working hours for each vehicle was recorded.

The Scania 164 V480 is used only in non-mining areas and it never enters the active mining area. These vehicles used haul roads similar to that of active mining equipment. The cycle of these vehicles were much longer and only one cycle was included.

Aside from haul trucks, 30 minute measurements on the remaining mining operation vehicles (bulldozers, excavators, graders and front-end-loaders) were recorded. Of the six dozers included there were four different model track dozers serving the same function in different areas of the mine. This included working on the pit floor and mine dumps. The models included are: CAT D8R, CAT D9R, CAT D10T and Komatsu D155A. The excavators included were: an O&K RH170, two O&K RH120's and one Liebherr 984, while a CAT 988F and a CAT 988G were included in the front-end-loader category. The grader category consisted of a CAT 140H, a CAT 14G and a CAT 16H. Despite different models in the mentioned categories, all vehicles in a category were of similar size and were performing the same function. All measurements were done when the vehicle was performing its typical function.

Noise Measurements

Noise measurements for this study were performed according to the SANS 10083:2004: The measurement and assessment of occupational noise for

hearing conservation purposes. A calibrated Quest SoundPro DLX integrating sound level meter with a built in octave filter and ½" microphone was used to perform the measurements. This instrument allowed for simultaneous measurement of A-weighted sound as well as Z-weighted sound. The same vehicles mentioned for vibration were included in the noise measurements and both hazards were recorded simultaneously. In the case of haul trucks, excavators and graders the microphone was held at the approximate position of the operator's ear. This is important for the A-weighted measurement. As for the measurement of LFN there are no guidelines for measurement as it is not yet recognised as an occupational hazard (Alves-Pereira and Castelo Branco, 2000). Thus the Z-weighting (zero-weighting) was used to ensure that no specific frequency was of more importance.

Concerning the sound measurements on bulldozers and front-end-loaders, it was not possible for the sound level meter to be held near the operator's ear because of the cabin only having space for one person. Thus the sound level meter was positioned in the vehicle cabin, as stable as possible and as close to the operator's ear as possible. The meter was always within 1 meter of the operator's ear. It is important to note that the sound measurements using the sound level meter and the vibration measurements were done at the same time. This means that the measurement time averages in Table 1 applies to vibration, A-weighted noise and Z-weighted noise. The sound level meter was also calibrated at the beginning and end of every day, according to SANS 10083:2004 using a Quest QC-10 sound calibrator with noise measurements being discarded if the two calibrations differed > 1 dB.

Calibrated noise dosimeters were used for monitoring personal noise exposure of operators. Quest NoisePro DL noise dosimeters with ¼" microphones were used. The dosimeters were attached to operators (dosimeter on belt and microphone attached to collar) at for the duration of the shift, with the threshold setting deactivated and the exchange rate at 3 dB.

Note that because sound measurements are obtained in log format, the mean sound levels were calculated by converting the measurements into the original format before averaging the figures. The final figure was again converted into the log format.

Statistical Analysis

In order to test whether or not there is a statistically significant difference between the mean measurements obtained from the Z-weightings compared to the A-weightings, a hypothesis testing procedure was undertaken. Since there is a dependency between the paired values (the measurements were recorded simultaneously on the same vehicle), the sample was treated as a dependent sample.

From statistical theory it is known that the mean is approximately Normally distributed for large sample sizes (30 or more as a rule of thumb), and also that the mean follows an approximate t_{n-1} distribution for sample sizes less than 30. This allows calculation of exact significance levels even though the sample sizes are small, thanks to the t-distribution and characteristics of the sample mean. Thus a t-test was performed and throughout a significance level of $\alpha = 0.05$, or 5%, was assumed. This implies a 95% surety that the null hypothesis is incorrect and must be rejected. The decision whether or not to reject the null hypothesis was made based on the p-value.

For a comparison between the A-weighted SLM and the dosimeter measurements, the data from all categories was pooled and a t-test performed. Lastly, it was tested whether a correlation between WBV levels and the amount of working hours done by each vehicle was present.

Results and Discussion

Whole-body Vibration

Table 2 summarizes the mean frequency weighted r.m.s. acceleration values for each vehicle category in the three vibration axes. ISO 2631-1 states that only the axis with the highest acceleration level is used to asses the health effects of vibration. The Health Guidance Caution Zone (HGCZ) is between 0.45 m/s^2 and 0.90 m/s^2. According to ISO 2631-1 a vibration exposure level above the HGCZ is likely to lead to health effects. Levels within the parameter indicate a risk of causing health effects while levels below the HGCZ cause no clear health effects.

The same is true for EU Directive 2002/44/EC in that the highest level measured in the three orthogonal axes should not exceed the limit level as stated in the directive. The Directive states 0.5 m/s^2 as the action level and 1.15 m/s^2 as the limit level. In the case of exposure being above the action level the EU Directive 2002/44/EC states that "the employer shall establish and implement a program of technical and organizational measures intended to reduce to a minimum exposure to mechanical vibration". It further states that the exposure limit should not in any case be exceeded and that the employer shall take immediate action to reduce exposure to below the limit. Thus the highest vibration acceleration values in each vehicle category are also compared to the action value and limit value of EU Directive 2002/44.

It is clear from Table 2 (and figure 1) that all vehicle categories exposed the operator to a level above the EU action level. It is also indicated that all levels of WBV are within or above the HGCZ. This in itself indicates that operators of large mining machinery are exposed to WBV that could lead to potential health effects. According to the current standards, health effects for these WBV levels are expected.

Table 2: Summary of WBV exposure per vehicle category, compared to two standards/guidelines (highest axis value per category is indicated in bold).

Vehicle Type	n	A(8) equivalent if exposure time is 8 hours in m/s² (mean SD)			EU Directive	ISO 2631-1
		X-axis	Y-axis	Z-axis		HGCZ
CAT 785	4	0.49 ± 0.07	0.46 ± 0.14	**0.54 ± 0.07**	Above action level	Within HGCZ
CAT 777	7	0.57 ± 0.06	0.50 ± 0.07	**0.83 ± 0.14**	Above action level	Within HGCZ
CAT 769	3	0.73 ± 0.18	0.52 ± 0.16	**1.07 ± 0.18**	Above action level	**Above HGCZ**
Volvo A40D	4	0.68 ± 0.12	**0.93 ± 0.22**	0.80 ± 0.21	Above action level	**Above HGCZ**
Komatsu HD325	3	0.51 ± 0.05	0.46 ± 0.06	**0.77 ± 0.06**	Above action level	Within HGCZ
Scania 164 V480	4	0.44 ± 0.09	0.55 ± 0.05	**0.64 ± 0.22**	Above action level	Within HGCZ
Bulldozers	6	**1.28 ± 0.32**	1.12 ± 0.23	1.05 ± 0.23	**Above limit level**	**Above HGCZ**
Excavators	4	0.52 ± 0.08	**0.59 ± 0.30**	0.26 ± 0.06	Above action level	Within HGCZ
Front-end-loaders	2	**0.79 ± 0.09**	0.66 ± 0.09	0.56 ± 0.16	Above action level	Within HGCZ
Graders	3	0.45 ± 0.11	**0.59 ± 0.07**	0.54 ± 0.12	Above action level	Within HGCZ

In terms of the HGCZ, only the CAT 769, Volvo A40D and the bulldozers exposed the operator to levels above the HGCZ. Only bulldozers exceeded the European limit level. The CAT 769 category's high levels of vibration seemed to originate from other factors such as the rough terrain on which these vehicles

were operated. Measurements were taken while the Cat 769's were transferring waste material to the remote areas of the mine property, as part of constructing a dam wall. The first of the three CAT 769's had the lowest 8 hour equivalent acceleration level (0.92 m/s^2) in the Z-axis and the operator commented on the good condition of the vehicle. The second and third vehicles in this category had 8 hour equivalent acceleration levels of 1.27 m/s^2 and 1.02 m/s^2 respectively. The second CAT 769 had a broken and totally loose seat suspension. This meant that the operator bounced up and down and when terrain was rough he literally had to grasp the outside part of the cabin's roof in order to stay on his seat. It is interesting to note that the operator was not concerned about this, showing that health related education of the operators may be lacking. In the third CAT 769 the operator reported that the vehicle's own suspension system was damaged. This was evident when the vehicle was operated and is also shown in the Z-axis acceleration level. Thus in this category, vibration results are exaggerated due to bad maintenance of the vehicles, but even a vehicle in good condition had acceleration levels high enough to be of concern.

In the Volvo A40D category seat suspension was always very stiff, due to improper functioning. The word stiff describes a seat with a built in suspension, but the ride is hard and no suspension activity is observed. These vehicles also had to manoeuvre very rough terrain which could also account for high vibration levels. Thus it is possible that vibration levels might have been lower if the above mentioned factors were not present. With few exceptions the conditions of the seats of all the vehicles monitored during this study were poor and would contribute to the levels of WBV exposure.

As illustrated in Figure 1, bulldozers clearly exposed operators to the highest levels of WBV, being the only vehicle in the present study to exceed the EU limit value. Not only in the X-axis, which was the highest, but also in the Y-axis and Z-axis very high levels were found with average acceleration levels of 1.12 m/s^2 and 1.05 m/s^2 respectively. Because of the nature of work bulldozers perform, continuously moving backward and forward while pushing material, it may have

been expected that the highest levels of vibration were found in the X-axis. But the other axes also showed very high acceleration levels close to the limit. In spite of this, operators were observed to be comfortable while working and no broken or damaged seat suspensions were observed. A factor that could contribute to the high vibration levels is the tracks on which the vehicles move. Aside from creating high noise levels, these tracks also make for a less than smooth ride due to a lack of suspension for the bulldozer itself.

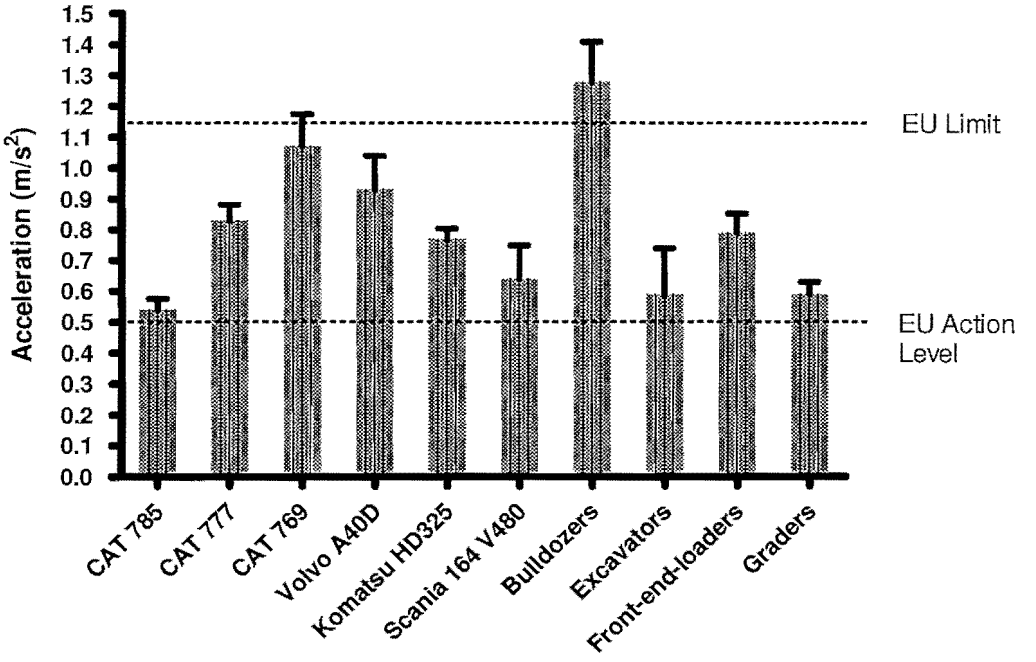

Figure 1: Highest mean frequency weighted RMS value in an axis, per vehicle category.

When the mean working hours of vehicles were compared to the highest WBV level in each category, no significant correlation was found. In fact, a very slight negative correlation was found implying that vibration decreased as working hours increased. As stated, this was not statistically significant. This is due to the variety of other confounding factors that could have influenced vibration values. It seems clear that high WBV exposures are present on mining

equipment and all possible ways in which it can be reduced should be employed. This can include regular maintenance of vehicles and cabins, insuring roads are kept in good condition and possible shorter shifts in order to reduce equivalent exposures.

These results are similar to literature, in that vibration levels capable of causing health effects were found. Eger et al. (2006) found mean r.m.s. levels of WBV on 150 ton surface haulage trucks (comparable to CAT 785's) of 0.28 m/s^2 and 0.37 m/s^2 in the Z-axis, indicating marginally lower levels for surface haul trucks. Bulldozers were also found to expose operators to the highest WBV levels, with a mean r.m.s. level of 1.96 m/s^2 in the X-axis. Although the present study presented lower levels, it is noteworthy that both studies found bulldozers to expose operators to the highest level of WBV in the X-axis. Kumar (2004) found vibration levels on larger mining haul trucks (240 tons and 350 tons capacity) to be above the recommended HGCZ levels. Research on construction vehicles indicated that front end loaders, dump trucks, graders and bulldozers expose operators above the ISO 2631-1recommendations based on measured vibration dose values (Cann et al., 2003). Thus, the findings for WBV in the current study confirm previous literature with regard to the presence of levels of WBV on mining/construction vehicles that can have a significant effect on the health of operators.

Noise

Table 3 presents the mean equivalent sound levels measured per vehicle category using different equipment and different frequency weightings. The South African National Standard (SANS 10083:2004) states that a worker should not be exposed to an 8 hour equivalent sound level of equal or more than 85 dB(A). This is also stated by the regulations under the South African Mine Health and Safety (MHSA) Act 1996 (Act 29 of 1996). The readings that were included are all L_{eq}'s over a 7-8 hour period and are thus considered to be representative.

Table 3: Mean Leq's in different weightings per vehicle category with the p-value included for the statistical comparison of A-weighted and Z-weighted measurements.

Vehicle Category	n	Mean sound level per vehicle category			
		Sound level meter			Dosimeter
		dB(Z)	dB(A)	p-value	dB(A)
CAT 785	4	104 ± 1.5	84 ± 2.1	0.0000168	85 ± 1.2 (n=4)
CAT 777	7	111 ± 2.9	85 ± 3.7	0.0000002	87 ± 2.9 (n=5)
CAT 769	3	107 ± 0.8	80 ± 3.0	0.0023527	85 ± 1.5 (n=3)
Volvo A40D	4	102 ± 2.5	74 ± 0.4	0.0000692	85 ± 1.0 (n=4)
Komatsu HD325	3	105 ± 2.4	78 ± 4.2	0.0026848	86 ± 3.6 (n=3)
Scania 164 V480	4	99 ± 4.3	77 ± 5.9	0.0027406	-
Bulldozers	6	110 ± 2.2	88 ± 2.5	0.0000013	91 ± 2.2 (n=5)
Excavators	4	103 ± 3.8	81 ± 2.1	0.0023632	86 (n=1)
Front-end-loaders	2	100 ± 4.8	84 ± 2.3	0.0361334	88 (n=1)
Graders	3	98 ± 2.8	87 ± 3.3	0.0118866	89 ± 0.2 (n=2)

A-weighted measurements are used to asses the risk to human hearing (Franz, 2007) by de-emphasizing sound outside human perception. The A-weighting gradually attenuates as sound frequencies drop below 1000 Hz (Leventhall, 2003). The reason for including a Z-weighted measurement (zero-weighting) is to illustrate that there is also sound present in other frequencies, as no sound is attenuated for in this measurement. This is clearly seen in Table 3 by comparing the sound levels in the SLM Z-weighted column to those in the SLM A-weighted column. The highest A-weighted level is 88 dB(A) while the lowest Z-weighted level 98 dB(Z). All p-values are less than 0.05, indicating that there is a statistically significant difference (at 95% significance) in the mean

measurements of the two weighting schemes. Statistically there is significant sound energy located in frequencies that are attenuated for when the A-weighting is applied to sound measurements.

When the average sound level obtained by dosimeters over an 8 hour period per vehicle category is compared to the current legislation, it is clear that on average all vehicle operators are exposed to higher levels of noise than is permissible. This is illustrated in Figure 2. The results obtained using dosimeters is also higher in all categories when compared to the sound level meter readings. This can be explained by other possible unknown noise sources that operators were exposed to during the shift. The SLM measurements were conducted in cycles as to be representative of the continuous sound level during operation of a vehicle, but the dosimeters are considered to be more representative of "on the job" exposure.

The official length for an operator's shift on the mine is 10 hours. The worst case scenario would be that a worker continuously worked for 10 hours, in which case the permissible exposure limit is reduced to 84 dB(A) according to calculation done based on ISO 1999:1990 Acoustics – Determination of occupational noise exposure and estimation of noise-induced hearing impairment. Thus the average dosimeter readings can be compared to the 10 hour permissible noise levels. This comparison is presented in Figure 2. All vehicle categories exceed the 10 hour permissible level. These results are comparable to the findings of Bealko (2008) where sound levels above 85 dB(A) were found on old mining haul trucks. Levels of 95-99 dB(A) for bulldozers with cabs, 80-82 dB(A) for haul trucks with air conditioning and 90-92 dB(A) for haul trucks without air conditioning were reported in other research. Also a road grader exposed the operator to a level of 97 dB(A). Excavators and front-end-loaders had lower noise levels at 76-78 dB(A) and 76-80 dB(A), respectively (Spencer and Kovalchik, 2007). Values are lower in the present study when compared to that of Spencer and Kovalchik (2007) except in the cases of excavators and front-end-loaders. As is the case

for WBV, bulldozers are identified in the current study and previous research as the vehicle category which exposes operators to the highest levels of noise.

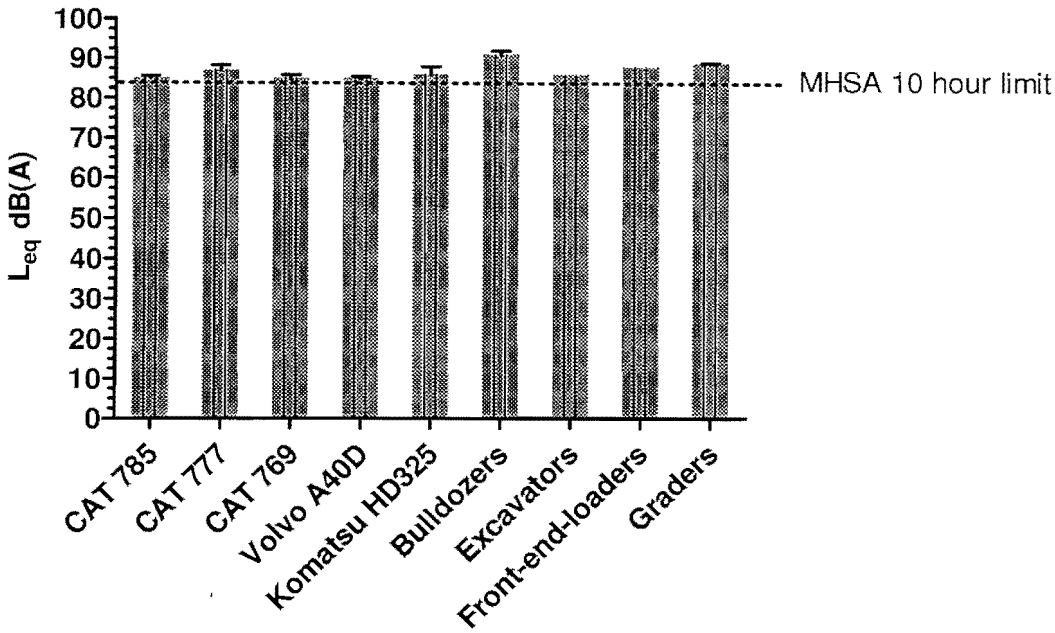

Figure 2: Comparison of average A-weighted dosimeter readings per vehicle category with permissible levels.

A statistical comparison of the A-weighted SLM measurements with the dosimeter measurements showed no statistical difference between measurements for all but three categories (CAT 769, Volvo A40D, Komatsu HD325). This indicates that in all the remaining categories the measurement strategy with the SLM was sound as no difference was found. The three categories where a statistical difference was found are all vehicles belonging to a vehicle contracting company which is employed by the mine. This fact may explain why these operators had much higher dosimeter readings, as these workers may have been exposed to other unknown noise sources.

Low Frequency Noise

Castelo Branco and Alves-Pereira (2004) found high levels of low frequency noise in three different vehicles which included the cockpit of an Airbus-340 while in cruise flight, a common automobile (Fiat Punto) and a subway train in transit. This was primarily reported in an effort to convey areas were high levels of LFN may exist. In the current study, results of sound measurements depicting high levels of LFN on mining equipment are reported. It is clear from Figure 3 and Figure 4 how the sound energy is distributed across the frequency range in each vehicle category. These graphs illustrate why the Z-weighting measurements (mentioned above) were found to be statistically different from the A-weighted measurements. It is clear that the difference is primarily located in the lower frequency bands. If the physiological effects of LFN exposure reported by Alves-Pereira and Castelo Branco (2007) are taken into account, it becomes obvious that A-weighted measurements alone are an insufficient method of quantifying the risk to a worker within a noisy environment. The A-weighting attenuates for sound in frequency bands lower than 1000 Hz and thus LFN exposure of operators/workers is not taken into account.

The trend as seen in Figure 3 and 4 is evident for all vehicle categories with the 125, 63 and 31.5 frequency bands showing the highest sound levels. From these graphs it can be seen that mining operators in the current study are exposed to high levels of LFN daily, ranging from 88 dB(Z) to 106 dB(Z) in the 31.5 Hz frequency band and from 81 dB(Z) to 103 dB(Z) in the 63 Hz frequency band. As stated before this exposure can be in excess of 8 hours per day. Nakashima et al. (2007) reports sound levels of more than 100 dB at frequencies below 63 Hz and more than 95 dB at 250 Hz in Canadian Forces armoured vehicles when driven at speed. These results are consistent with levels found on mining vehicles in the present study.

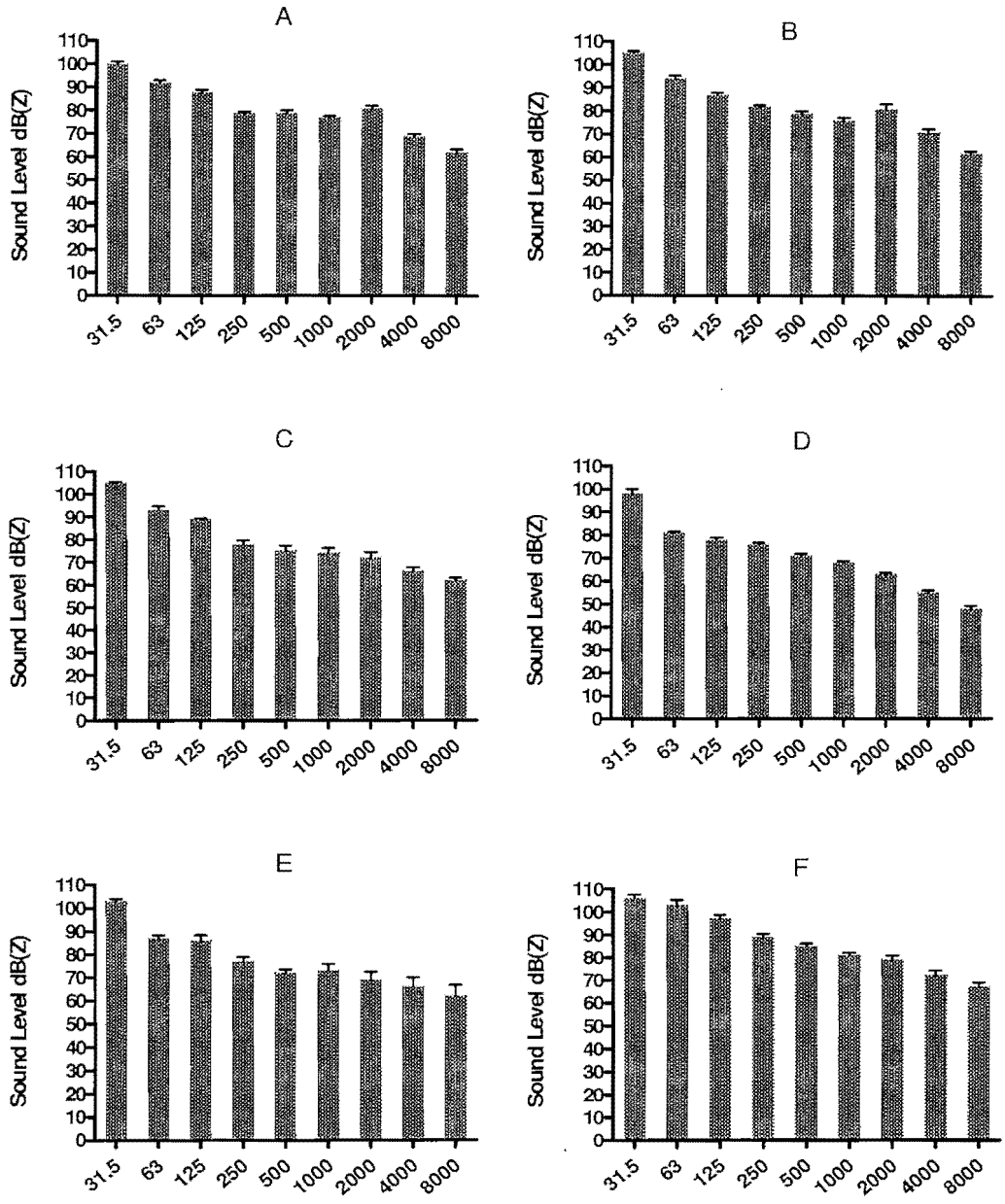

Figure 3: Mean sound frequency distribution in Hertz (HZ) per vehicle category, within the 31.5 – 8000 Hz range, with A = CAT 785; B = CAT 777; C = Cat 769; D = Volvo A40D; E = Komatsu HD325; F = Bulldozers.

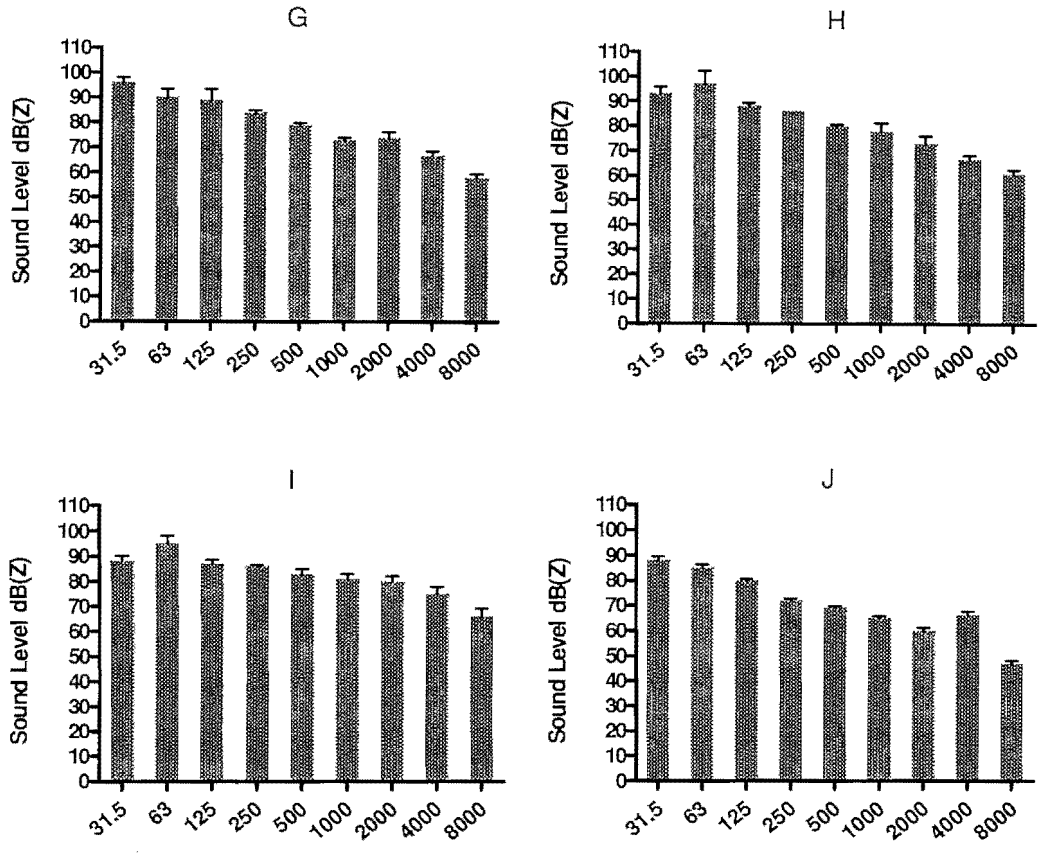

Figure 4: Mean sound frequency distribution in Hertz (HZ) per vehicle category, within the 31.5 – 8000 Hz range, with G = Excavators; H = Front-end-loaders; I = Graders; J = Scania.

Conclusion

This study described the levels of risk that may be expected for mining vehicle operators with regard to whole-body vibration and noise. WBV was found to be present on all mining vehicles to the degree of probably leading to health effects. All vehicles exposed the operator to levels above the European action level, indicating the need for employers to be informed regarding WBV and also to implement all possible controls in an effort to reduce operator exposure. The first major control method would be to insure that maintenance of vehicles is

improved, with specific regard to vehicle and seat suspensions. It is recommended that vehicles are periodically serviced by introducing a schedule which can be followed by operators and the heavy machine shop alike. A further recommendation is for the employer to insure that road conditions are kept in optimum condition by graders.

This study further indicated the need to perform sound measurements which include the entire spectrum of sound frequencies. Although A-weighted measurements are useful in determining the risk to a human ear, it does not deliver an accurate picture of the total noise risk an operator is exposed to. Accordingly it was found that operators of mining vehicles are exposed to levels of A-weighted noise which exceed the limit value. Noise levels on mining vehicles may be controlled by introducing noise policies such as keeping windows and doors of cabs closed while working. Such a policy is much more practical to enforce when the air conditioning of vehicles are in working order. Furthermore absorptive material can be placed on the walls and ceiling of the cab with all openings to the outside closed off. Any broken windows should also be repaired. In cases where no cab is present, an exhaust muffler tip should be installed above the operator. Lastly it was found that much of the sound energy captured during measurement was located in the low frequency range, thus exposing operators to high levels of LFN. LFN is difficult to control, but if operators are observed to present VAD symptoms they should be removed from the area of exposure. At this stage it is an impossible task to recommend permissible levels for LFN. What can be recommended is that further research must be done in order to establish dose-response relationships, physiological effects and occupational sources of LFN. The levels of exposure for all risks found in the current study are comparable to previous research.

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Chapter 4

Concluding Chapter

Conclusion

This study quantified the exposure of mining vehicle operators to whole-body vibration, noise and low-frequency noise. Exposure was found to be of a significant level and likely to cause health effects. WBV levels, when compared to ISO 2631, indicated that all vehicles exposed operators to levels that would potentially lead to health effects. When these same values were compared to a European Directive 2002/44/EC, it was found that all vehicles exposed operators to a level above the action level. Only one vehicle category exposed operators to levels that would potentially lead to health effects, namely bulldozers. A-weighted noise was found to be equal or in excess of the limit value, indicating the need for control of noise exposure. Vehicle cabins could be sound proofed and quieter engines designed, while exhaust mufflers could be installed above the operator (facing backwards) which would offer a reduction in noise exposure. HPD's could also offer protection if engineering methods fail to reduce sound levels to a significant level. Low frequency noise was found to be prevalent on all vehicle categories, while the literature indicates that LFN has many physiological effects. Regarding LFN, it is recommended that further research into sources of exposure, physiological effects and dose response relationships are conducted.

A further finding was that an A-weighted measurement was not sufficient for quantifying an acoustic environment. The A-weighting emphasizes sound in the frequencies that humans can perceive, while attenuating for sound energy in other frequencies. In this study a statistically significant difference was found when the same measurement was compared with no weighting and after filtering using the A-weighting. This difference was found in all vehicle categories, indicating that sound energy outside the A-weighting was present. Frequency band analysis of the same measurement indicated this sound energy to be located primarily in the low frequency bands. Thus it is concluded that analysis of acoustical environments should not only be done by using the A-weighting, but

frequency analysis should be applied to show in which frequency bands sound energy is located.

One shortcoming of this study was the limited availability of vehicles. A future study could possibly find even more significant results when a larger sample is available for measurements. This could be specifically important if comparisons between vehicles is to be made because vehicles can then be included or excluded based on confounding factors such as amount of working hours, surface operated on, condition of the seat, function performed and the type of vehicle. Such a study could be important in identifying vehicle types or functions which pose a greater risk to operators.

The hypothesis of this study was proven to be correct.