WHOLE BODY VIBRATION, AND ITS EFFECTS ON LOAD-HAUL-DUMP OPERATORS, IN UNDERGROUND MINING

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Whole body vibration, and its effects on load-haul-dump operators, in underground mining

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ABSTRACT

Operators of load-haul-dump (LHD) vehicles, common in underground mining, are exposed to a range of whole body vibration (WBV) and jolting from normal vehicle operation. Whole body vibration has acute detrimental effects on visual acuity, equilibrium, manual dexterity and muscular fatigue. Chronic effects include back, digestive and circulatory disorders. This study was designed to quantify the nature and extent of WBV from LHD vehicles and investigate the health, safety and performance effects on LHD operators.

The WBV levels, measured in 11 LHD vehicles from two Ontario mines, ranged from 0.1–2.8 $m.s^{-2}$ with dominant frequency bands from 1.6–3.15 Hz. When mean daily exposure levels were compared with the International Standards Organization (ISO) guidelines, the 6-hour exposure limit was exceeded in the transverse and vertical directions by 71% and 90% of the LHD vehicles respectively. Exposure ratios using a summed acceleration vector were found to exceed the ISO recommended permissible value in all LHD vehicles tested. Vibration signals also contained high level random peaks among various operational tasks and for all directions. Statistically significant differences were calculated among LHD sizes and operational tasks, with the smaller vehicles and the driving tasks producing the highest vibration levels.

The incidence of accident and injury among LHD operators in Ontario was similar to underground miners; 180 and 183.5 injuries per 1000 workers respectively. The most frequent LHD operator injuries were to the back, eye, neck, finger and hand. Injuries to the neck were more prevalent among LHD operators than among other occupations underground. The majority of LHD injuries occurred during vehicle operation. Major contributing factors were found to include the sudden start-stop motion of the vehicle and the rough road surface. It was hypothesized that the high level WBV and jolting may have contributed to the incidence of back and neck injuries.

There were no significant differences in visual acuity among LHD operators following a workshift of WBV exposure; however, a significant decrement in manual dexterity test scores was found. This post-shift decrement may indicate even greater decrements occurring during operation of the LHD vehicle.

Procedures for reducing the levels of WBV in underground LHD vehicles are discussed.

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CHAPTER I

INTRODUCTION

In the early days of underground mining, ore was manually chipped away from rock with a pick and hammer, shovelled into carts, and hauled out by mules. As with all types of industries, the industrial revolution brought mechanization into the mining industry. Today pneumatic drills and explosives break the ore and a rubber-tired, diesel powered load-haul-dump (LHD) vehicle shovels the ore from a muckpile into its bucket, and hauls a full load to a nearby chute or dumping zone. The job of the LHD operator today is not nearly as demanding as that of the earlier miners. However, there are some disadvantages of mechanized production as well.

The seated operator is exposed in each working shift to a range of jolting, jarring, and whole body vibration (WBV) in the course of normal vehicle operation. In a working lifetime of thirty years it is estimated that an LHD vehicle operator is exposed to approximately 45,000 hours of whole body vibration. The elasticity of the human locomotor system is sufficient to absorb or attenuate the normal jolts and vibration generated in natural locomotion and movements utilizing the body's own muscular strength (Carlsoo, 1982). However, the LHD vehicle operator today is chronically exposed to levels of vibration which exceed those naturally produced. When the limits of the body's protective structures are exceeded this may have adverse effects on the worker.

Vibration may be conveniently defined as a fluctuating mechanical disturbance which is transmitted through solid structures (Weaver, 1979). There are three basic types of vibration exposure: 1. vibrations transmitted simultaneously to the whole body surface, or substantial parts of it; 2. vibrations transmitted to the body as a whole through a supporting surface; i.e., feet when standing, buttocks when seated, supporting area when reclining; 3. vibrations applied to particular parts of the body such as head or limbs (ISO, 1978). This study is mostly concerned with the measurement of whole body vibration transmitted to seated operators in underground LHD vehicles. The most important vibration parameters include direction, frequency, duration and intensity (amplitude or acceleration in $m.s^{-2}$). Vibration can be characterized by three mutually perpendicular axes; vertical (z-axis), transverse (y-axis), or longitudinal (x-axis). Vertical vibration is considered the most severe and has been most intensely studied.

At frequencies of less than 2 Hz, the body responds to vibration as a single mass (Wasserman, 1987). At greater than 2 Hz, relative motion occurs between regions and organs due to resonance effects. Human body resonance is the condition in which a forcing vibration is applied to the body at such a frequency that some anatomical structure, part, or organ, is set into measurably or subjectively noticeable oscillation greater than that of the related structures (Guignard, 1979). Whole body vibration in the 4–8 Hz range is important for vehicle operators, as it leads to considerable amplification of vibration between the buttocks and the upper torso (Wasserman, 1987).

Estimates from the National Institute of Occupational Safety and Health (NIOSH) in the U.S. in 1978 suggested that approximately 6.8 million workers were exposed to WBV from various vehicles such as tractors, heavy equipment, trucks, etc. (Wasserman, *et al.*, 1978). The health and safety effects on the workers of such WBV exposure are poorly understood. There have been no published reports measuring WBV from underground LHD vehicles. Little is known about the actual operating levels of WBV in LHD vehicles or the effects of such vibration on the worker. Vibration is simply considered by many workers to be a natural, although undesirable, part of the working environment.

CHAPTER II

REVIEW OF LITERATURE

Introduction

There are two broad categories of WBV effects: 1. Vibration elicits frequency-dependent responses due to oscillatory displacement or deformation of body organs and tissues. This occurs especially at resonance; 2. Vibration elicits a generalized reaction much like the reaction to stress, or noise. This reaction is not frequency dependent, but related to overall cumulative severity (Guignard, 1979). Both categories of WBV effects will be discussed in terms of: vibration detection; acute effects including cardio-pulmonary, human activity and task performance, vestibular, central processing of information, external activity and task execution (motor function), performance skills and high intensity WBV exposure; chronic effects; and legal aspects of WBV.

Detection of WBV in the Human Body

Low frequency motion and vibration are detected in humans by a variety of sensory organs and receptors. These sensory organs and receptors include the eye, the vestibular (balance) organs of the inner ear, and a range of microscopic end organs (mechanoreceptors) distributed in skin, muscles, tendons and visceral organs (ISO/DP, 1987). The response of mechanoreceptors which are stimulated during vibration is dependent upon the frequency of the vibration. Slow adapting (SA) receptors respond to low frequency (0.1–60.0 Hz) vibration while fast adapting (FA) receptors respond to higher (greater than 60 Hz) frequencies (Pykko, 1986). The receptors which respond to contact with objects having small sharp edges are one type of slow adapting receptor (SA1), the Merkel discs, and one type of fast adapting receptor (FA1), the Meisner's corpuscles (Pykko, 1986). The receptors which respond to contact with objects having large, obscure borders are the (SA2) Ruffini endings and the (FA2) Pacinian corpuscles (Pykko, 1986). Pain receptors can also signal the effect of very high intensity vibration (Dupuis & Zerlett, 1986).

Acute Physiological Effects

Cardio- Pulmonary Effects

Low frequency (1.2–20 Hz) whole body vibration of moderate intensity (0.1–10 $m.s^{-2}$) elicits a general cardio–pulmonary response resembling the reaction to exercise or alarm (Ramsey, 1975; Huang & Suggs, 1967). Changes in cardio–pulmonary function are attributed to the increased metabolic activity associated with an increased activity of the skeletal muscles provoked by vibration (Guignard, 1979).

Huang & Suggs (1967) measured human cardio–pulmonary responses to vertical, longitudinal and transverse vibration at four levels of acceleration (2.5–15 $m.s^{-2}$) between 1 and 7.5 Hz frequency. In conditions of vertical vibration, the subjects' heart rate, ventilation rate and oxygen uptake increased as a function of vibration amplitude. In the longitudinal direction, only ventilation rate showed increases with increasing vibration amplitude. Ventilation rate again increased in the transverse direction as a function of amplitude, but oxygen consumption showed no increases. In the transverse direction, a decrease was measured in heart rate as the acceleration exceeded 10 $m.s^{-2}$.

Cardio–pulmonary responses to WBV were found to vary between different studies. There was also variance between similar parameters; tidal volume and oxygen uptake increased at 5–7 Hz of moderate vibration intensity while vital capacity decreased (Ramsey, 1975). The same measure may also vary with frequency. For example, blood pressure increases at 5 Hz of moderate vibration amplitude but decreases in the 10–20 Hz range (Ramsey, 1975). It is difficult to come to any general conclusions with regard to the cardio-pulmonary effects of WBV since all of the parameters can also be varied by stressors other than vibration such as heat, noise, and exercise (Dupuis & Zerlett, 1986).

Mild hyperventilation sometimes accompanied by signs and symptoms of hypocapnia have been measured under conditions of strong vertical vibration in the resonance range of the human body (Ramsey, 1975). It was hypothesized that this effect may be due to widespread vibratory stimulation of somatic mechanoreceptors in the lungs and respiratory passages (Guignard, 1979). Dupuis & Zerlett (1986) report that the main cause of hyperventilation is the passive movement of the diaphragm and abdominal wall due to vibration of the viscera.

Several hypotheses have been developed to explain other acute cardio-pulmonary effects of WBV. Huang & Suggs (1967) hypothesized that the increase in oxygen uptake at higher accelerations is due to static contraction of the muscles, consciously or unconsciously, to compensate or make the vibration less annoying. Grandjean (1981) postulated that the increases in energy consumption, heart rate and respiratory rate during vibration are due to a muscle-reflex activity.

Human Activity & Task Performance Effects

Several classes and varieties of human activity and performance may be disturbed by motion or vibration. This has been recognized by the International Organization for Standards (ISO) Working Group Technical Committee and a Draft Taxonomy has recently been been issued (ISO/DP, 1987) to list these activities. The taxonomy is reproduced in Table 1, and the major catagories which relate to load-haul-dump operation will be discussed.

Table 1. Draft standard taxonomy of vibration and motion-sensitive human activity and performance*.

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1. Acquisition of Information

   a. Visual System:

      (1) Visual stimulus (signal) detection
      (2) Visual motion detection
      (3) Visual resolution (acuity)
      (4) Other visual functions (e.g., colour discrimination)

   b. Other Sensory Systems:

      (1) Hearing
      (2) Vestibular system
          (i) Sense of balance and orientation
          (ii) Low-frequency motion sense
      (3) Distributed mechanoreceptors
          (i) Vibrotactile sense
          (ii) Sense of gravity and incident mass
          (iii) Sense of posture (position of body members)

2. Central Processing of Information (Cognitive Function)

   a. Visual pattern recognition
   b. Visual search
   c. Spatial perception and orientation
   d. Recognition and processing of speech and other auditory signals
   e. Vigilance (visual and auditory) and concentration
   f. Time perception and estimation
   g. Mental computation
   h. Reasoning
   i. Other cognitive functions

3. External Activity and Task Execution (Motor Function)

   a. Static Postural Function:

      (1) Stability of stance/whole-body (or head) orientation
      (2) Maintenance of fixed postures of limbs/extremities

   b. Kinetic (moving) Postural Function:

      (1) Locomotor skills (human locototion; load carrying and handling; coarse manual and pedal control operations, including continuous tracking)
      (2) Fine manipulative skills (manual dexterity)
      (3) Speech

---

*Prepared by the International Standards Organization as a draft proposal ISO/DP 1987.

Visual System

Visual acuity is the ability to resolve two objects at a given illumination, size, distance from the eye, and configuration (Lange & Coermann, 1962). Under optimal conditions of illumination and contrast, the normal eye can resolve two points when the visual angle is approximately one minute.

Whole body vibration causes the image projected on the retina to rapidly oscillate, thus blurring the perceived image. This effect can occur from vibration of the object such as a control panal, as well as through WBV exposure as with a vehicle operator. The site of vibration transmission into the body and body posture are important factors affecting visual perception. The preciseness of visual perception is determined by the relative movement between the eye and the site object and the compensatory secondary movements of the eye. This relative movement between eye and site object is frequency dependent (Dupuis & Zerlett, 1986). It has been shown that at frequencies less than 2 Hz, the human body responds as a single mass and moves with the vibration (Lange & Coermann, 1962). The eye follows the target, compensating for the vibration. This compensation however, may lead to fatigue and blurring. Blurring occurs in the 5–90 Hz frequency range, and has been shown to peak at specific frequencies of 15 and 30 Hz, and again between 40–70 Hz (Hornick, 1962). The critical flicker fusion[1] of the human eye is between 8.0 and 16 Hz suggesting that movements of the image at frequencies higher than the flicker frequency cannot be analyzed in the brain and that the image becomes blurred (Lange & Coermann, 1962).

The loss of visual acuity is proportional to the amplitude of vibration with the greatest effect shown at 10–25 Hz (Grethier, 1971; Ramsey, 1975). Visual acuity losses are dependent

[1]The frequency of an intermittent light stimulus just great enough to give no impression of flickering (Grusser, 1983).

upon viewing distance as well. The greatest decrement in visual acuity was measured by Grethier (1971) at a 4 m distance, while at 1 m and 0.4 m the decrement in visual acuity increased progressively as vibration frequency decreased to 5 Hz.

Lange & Coermann (1962) tested the visual acuity of subjects exposed to various frequencies up to 20 Hz and accelerations half that of short time tolerance.[2] They found the first substantial decrement in visual acuity at 5 Hz. Since this is the resonant frequency of the whole body, visual acuity is hampered mechanically by the amplification of movement to the head. According to Lange & Coermann (1962) the physical stresses and discomforts produced at the whole body resonance frequency such as pain in the chest (resonance effects at 7 Hz) interferes with mental concentration during a visual acuity task. In addition, there is a sustained decrement in visual acuity after vibration cessation, since recovery from chest pain is not immediate (Lange & Coermann, 1962).

Lange & Coermann (1962) also report residual effects of visual acuity one minute following vibration exposure, with the greatest effects between 5.0 and 10 Hz corresponding to the whole body resonance frequency. At frequencies above 12 Hz the visual acuity is practically normal one minute after vibration unless the intensity of the vibration is severe. Hornick (1961) found no decrement in visual acuity during vibration exposure of 0.9–6.5 Hz in the vertical direction and 1.5–5.5 Hz in the transverse direction at acceleration amplitudes of 1.47–3.43 $m.s^{-2}$. There was, however, a decrement in peripheral vision at 1.5 and 2.5 Hz which recovered to normal following vibration exposure. At higher frequencies, blurring is also dependent upon posture and frequency, but there is little effect of fatigue (Bowden, 1985). The best way to minimize visual problems is by careful design of the task; i.e., increasing target size, visual angle, illumination and/or the contrast ratio (Ramsey, 1975).

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[2]The exposure limit of the ISO 2631 (1978) in Figure 1 is equal to approximately half the limit of voluntary tolerance.

Vestibular System

Transient disequilibrium and increased postural sway have been reported following exposure to WBV of moderate duration and intensity (Ramsey 1975; Guignard, 1979). Sensations of oscillatory motion at frequencies below 10 Hz are enhanced by stimulation of the vestibular receptors. Vestibular stimulation, augmented by visual cues, becomes paramount at frequencies below 2 Hz (Guignard, 1979).

Equilibrium effects were studied in blindfolded subjects by Coermann *et al.,* (1962) to minimize the visual effects on equilibrium. Subjects were required to maintain an upright posture through appropriate hand control action in an equilibrium chair producing ±20 degrees about the pitch and roll axis. The chair was mounted on a shake table which produced sinusoidal accelerations in the 2.0–20 Hz range at an amplitude of one–third short time tolerance for each frequency. The subjects showed the greatest difficulty in maintaining equilibrium in the 3.0–12 Hz frequency range where the main resonances in the human body occur. There were considerable individual differences in ability to maintain equilibrium even without vibration. There were also individual differences in the degree to which vibration affected subject performance. Coermann *et al.*, (1962) also found the disequilibrium continued one minute after vibration cessation indicating a residual effect of vibration on equilibrium performance.

Johnston (1972) used a body orientation task that required subjects to manipulate hand control in order to orient their body posture as quickly and accurately as possible toward a target. The vibration exposure included a range of frequencies (2.0–8.0 Hz) with amplitude held constant through varying accelerations (0.4–5.7 $m.s^{-2}$) in both a standing and seated posture. The time to orient toward a target increased as the frequency of the vibration increased (Johnston, 1972). Accuracy in the body orientation task was highest at 2 Hz. In addition, there was a residual decrement in body orientation accuracy following vibration cessation which Johnston (1972) postulated as fatigue.

The physiological basis for disturbances in equilibrium and posture regulation due to WBV is ill-defined (Guignard, 1979). Guignard (1979) postulated that the effects are due to an overstimulation of muscle receptors and to competition in the neural pathways and their central connections serving both the regulation of posture and the low frequency somatic and vestibular vibration senses. Transient disequilibrium and postural sway are not specific to WBV stress, but are also observed during or following conditions of high arousal and in fatigue associated with sustained demanding workload and environmental stress (Guignard, 1979).

Central Processing of Information

There are varied findings on the effects of WBV on the central nervous system (CNS) (Guignard, 1979). Low frequency (1–2 Hz) whole body oscillations at moderate intensities such as swings and rocking chairs are relaxing, however higher frequencies, higher intensities and inconsistency of stimulus are arousing (Guignard, 1979). There is considerable adaptation (habituation) if the vibration is regular and uninterrupted such as in aircraft or ship environments. Guignard (1979) postulates that the habituation to this type of vibration is a central nervous system phenomenon with some adaptation occurring at the receptor level as well.

Dupuis & Zerlett (1986) reviewed the literature and report inconsistency in animal and human electroencephalogram (EEG) responses as a result of WBV. According to these authors, part of the inconsistency problem is due to the wide range of individual differences. Yamazaki (1977) used EEG measures to determine the depth of sleep during low frequency (2.5 Hz), low amplitude (0.001–0.01 $m.s^{-2}$) vibration. Levels greater than 0.01 $m.s^{-2}$ were found to affect sleep. The EEG findings, in agreement with heart rate, showed that the higher the vibration levels, the greater the disturbance in sleep (Yamazaki, 1977).

A variety of central nervous system and neuro-vegetative system impairments including headaches, abdominal pains, giddiness, physical weakness, moodiness and physical exhaustion are recognized by the International Labour Office as related to WBV (ILO, 1976). These impairments are dependent upon the intensity, duration and demands of task performance in conditions of vibration, rather than to the frequency of the vibration (ILO, 1976; ISO/DP, 1987).

There has been little research investigating the effect of WBV on intellectual functions such as mental arithmetic, problem solving and perceptual judgements (Grethier, 1971). Functions such as complex reaction time, target identification, vigilance and monitoring have been studied and show essentially no decrements during WBV exposure (Grethier 1971). These tasks all involve primarily central neural processes but do not place very difficult intellectual or cognitive demands on the subjects. Grethier (1971) concluded that the data indicate intellectual functions to be minimally affected by whole body vibration.

External Activity & Task Execution (Motor Function)

Under conditions of WBV exposure man will consciously or unconsciously attempt to counteract the motion if it is annoying by an increasing muscular activity (Dupuis & Zerlett, 1986). During sinusoidal vibration of low frequency the muscles displayed tension and relaxation phases in a synchronous pattern which counteracted the vibration (Dupuis & Zerlett, 1986). When the vibration was random the muscles could not counteract the pattern and contracted statically with no relaxation phases. In a study of seated postural muscles in 1973 by Bjurvald *et al.,* (as translated by Carlsoo, 1982) the authors also report an increase in muscle contraction during exposure to random WBV. Specifically the erector spinae and abdominal muscles were active during both vertical and lateral vibration. Wilder *et al.*, (1983) also subjected seated subjects to random vibration. He demonstrated muscle fatigue in the erector spinae and external oblique muscles, as measured by EMG, as a result of WBV for a 30 minute duration.

There are several possible hypotheses to explain why muscle contractions might occur in response to WBV. Exposure to WBV may result in an attempt by the body to decrease the annoyance of the vibration by consciously or unconsciously shifting posture and contracting muscles to change the natural frequency and the damping of the body. Alternatively the muscle contractions may be a reflex action designed to maintain equilibrium by muscle action (Dupuis & Zerlett, 1986). Hansson (1981) suggests that under conditions of WBV there is a general increase in muscle activity throughout the body in order to stabilize the position of the joints. It has been hypothesized that high levels of vibration may cause cramps and decreased muscular strength (Hansson, 1981).

Carlsoo (1982) reviewed the effects of WBV on muscles, noting the earliest muscle spindle studies in vibration research dated back to 1938. Carlsoo (1982) summarized the various recent studies and proposed that contractions due to stimulation of muscle spindles by vibration be referred to as "tonic vibration reflexes". As indicated in the review, impulses from the stretch receptors increased as amplitude of vibration increased (up to 2 mm) and the frequency increased (up to 200 Hz). The more a muscle was stretched the greater was its sensitivity to vibration. When the vibration ceased, the impulses from the muscle spindles and subsequent muscle contraction also ceased (Carlsoo, 1982).

Generalized vibration of muscular tissue, both throughout the body and of individual postural muscles or their tendons, in a wide range of frequencies (10–200 Hz) increases tonicity. Phasic spinal reflexes (tendon jerks) however, may be inhibited or depressed (Guignard, 1979). Tendon vibration results in a decreased sense of limb position as well as fatigue of the arm and leg muscles resulting in a disturbance of human movement control (Guignard, 1979). In general, it appears that vibration distorts the perception of the state of contraction and tension in arm and leg muscles (Carlsoo, 1982).

A study by Lewis & Griffin (1976) investigated whether WBV causes disturbances of kinesthetic feedback which might contribute to the degradation of control performance during WBV. Subjects were required to perform a co-ordinated manual tracking test under experimental condtions involving a combination of vibration frequencies (3.5 and 8 Hz) and acceleration amplitudes (0.25–1.0 $m.s^{-2}$). Different spring stiffnesses allowed for variations from isometric to isotonic control[3] in the task. An increase in the elastic stiffness of the control resulted in a significant increase in channel capacity (therefore a decrease in errors) during vibration, but not in the absence of vibration. In conditions of zero stiffness (isotonic) and high vibration the effectiveness of feedback information concerning limb motion and position was reduced, causing the movements to continuously overshoot and undershoot the target. Lewis & Griffin (1976) called this movement, which is predominant in the 1–2 Hz frequency range, "hunting oscillations" of the limb.

Isometric control is dependent upon the golgi tendon organs whose firing rate is directly proportional to isometric tension in the muscle, and muscle spindles which respond predominately to rates of change of tension. Isotonic control is more complex. Feedback from joint receptors is slow adapting and of little use during quick control movements. During dynamic isotonic conditions it is only the muscle spindles which provide information quickly enough to be effective in controlling movement. Isometric control is fairly resistant to

[3]Isometric means the length of the muscle is constant during the contraction. Isotonic means the muscle length changes while its tension (force output) remains unchanged.

disturbances by vibration because feedback of absolute force is available almost immediately. Isotonic control of movement is more susceptible to vibration disturbances because the muscle spindles are more sensitive to vibration than other receptors (Lewis & Griffin, 1976). The isometric manual tracking experiment therefore contained less error in the frequency range of 1–2 Hz than the isotonic control.

Performance Skills

A vast amount of research since 1960 has used simulated driving conditions in various vibration environments to investigate performance effects such as steering ability, foot pressure constancy and reaction time. The impetus for this research was from both the military and the space programs. The military were interested in the effects of air turbulence on operators in high speed flights at low altitude. The space program was interested in astronaut performance under various vibration environments.

Hornick (1961) exposed subjects to low frequency (0.9–6.5 Hz) sinusoidal vibration in the vertical and transverse directions at varying intensities (1.5–3.5 $m.s^{-2}$). Performance measures were integrated into a simulated driving task which included controlling an oscilloscope blip with a steering wheel, maintaining travel speed by foot pressure constency on an accelerometer, braking in response to certain coloured lights (choice reaction time) and pressing a horn when noticing lights to the side (peripheral vision). The results indicated a significant steering impairment in both the vertical and transverse vibration directions, and a significant impairment in foot pressure constancy in both directions. This impairment increased with increasing frequency and additionally with increasing intensity. Choice reaction time was not impaired in either direction during exposure but, following vibration, the reaction time was slower than before the vibration. Frequencies of 1.5 and 2.5 Hz caused the greatest decrement in peripheral vision in the transverse direction (no measurements were made in the vertical).

Recovery to pre-vibration levels was immediate upon vibration cessation. Overall the performance decrements were greatest at 1.5 Hz vertical and 1.5–2.5 Hz transverse vibration.

Matthews (1966), in a literature review, summarized that a very definite, but not alarming, degredation is repeatedly shown in simulated driving tasks. The degredation is dependent upon both the frequency and intensity of the applied vibration. The maximum overall performance decrement among the studies occurred at 3.4 Hz which Matthews (1966) felt was due to maximum head movement at this frequency. The main limitation of these performance tests was that the applied oscillations were of a fixed amplitude and frequency. In addition, the subject could develop a considerable counteraction to the motion, as discussed in the previous section.

High Intensity WBV Exposure

Studies of the acute effects of severe WBV have mainly utilized animals (Guignard, 1979). Guignard (1979) reported the work of a Russian scientist who demonstrated contusion, abrasion, and hemorrhage of the internal organs and tissues (lung, myocardium, intestinal tract and kidney) of animals at accelerations up to 200 $m.s^{-2}$ and frequencies up to 50 Hz. In 1986 Witt & Fisher (translated by Dupuis & Zerlett, 1986) exposed guinea pigs to approximately three hours of vibration at 6 Hz and 1.4 $m.s^{-2}$ in the direction of the vertebral column. After exposure for up to 203 hours, histological examination revealed lesions in the vertebral joints, the paravertebral muscles and in the blood-filled spaces of the spongiosa.

In tests of voluntary tolerance Magrid *et al.* (1960) described the sensations which subjects reported in various body parts at the time of self termination of WBV exposure. At the self-termination level and higher frequencies (14–20 Hz) vibration disturbed muscle tone and speech, caused head sensations, and led to the urge to defecate and micturate. Between

5–10 Hz subjects reported chest pain, voluntary muscle contraction, abdominal pain, lumbosacral pain, valsalva and general discomfort. At lower frequencies (2 Hz) the subjects reported dyspnoea. Therefore at frequencies below 10 Hz the chest and abdomen were the primary targets of discomfort while above 10 Hz organ tissue complexes located in the periphery were most uncomfortable. At lower levels of vibration these same body areas have been linked with subjective complaints of pain, annoyance and discomfort (Grandjean, 1981).

Tolerance curves for human exposure to WBV are important for military and space applications. The tolerance curves are based on equal tissue strain under impact stress. The transmission ratios[4] observed in human impact acceleration experiments as well as the data obtained from accident analysis support the trend of these impact curves (Goldman & vonGierke, 1960). The maximum obtainable deceleration measured while braking in an automobile was found to be 7.0 $m.s^{-2}$, while a potentially survivable crash may involve decelerations of 200–1000 $m.s^{-2}$ for a duration less than 0.1 second (Goldman & vonGierke, 1960). An aircraft seat ejection measured an acceleration of 100–150 $m.s^{-2}$ for 0.25 seconds and a fall into a fireman's net was 200 $m.s^{-2}$ for 0.1 second. The approximate survival limit with well distributed forces (fall into a deep snow bank) is 2000 $m.s^{-2}$ for 0.015–0.03 seconds (Goldman & vonGierke, 1960).

[4]Vibration transmission ratio is the ratio of vibration acceleration appearing at one point divided by impinging vibration at another point, where both are applied in the same direction. Therefore, a ratio greater than one indicates amplification and a ratio less than one indicates attenuation (Wasserman, 1987).

Chronic Effects

The chronic effects of WBV are less well investigated and also less well defined than the acute effects. Much of the research has involved epidemiological studies of seated vehicle operators, including farm tractor operators, haulage truck drivers, bus drivers, heavy equipment operators and helicoptor pilots.

One of the earliest and most cited pieces of research on chronic WBV effects is Rosegger & Rosegger's study of the health effects of farm tractor driving (1960). Medical examinations and X-rays of 328 tractor drivers revealed 228 drivers with pathological abnormalities and degenerative changes of the spine, especially adolescent kyphosis.[5] Among the 20-30 year age group, 72% had some form of spinal deformation as compared to 14% in the general population which served as controls. The pathological X-ray findings increased steadily with years of service. Rosegger & Rosegger (1960) mention that pathological deformations such as those listed above are high among other occupations; specifically miners (71-76%) and labourers (98%). However, the average age range in these occupations was 51-56 years, while the average age of tractor drivers was 26 years. X-ray examination revealed that the incidence of stomach troubles such as gastroptosis and gastritis among farm tractor drivers was 76% compared with 46% in control groups. The incidence of subjective complaints increased steadily with the number of years of driving, and the percentage of chronic diseases in the spine and stomach increased with greater than four years of service. Rosegger & Rosegger (1960) concluded that the ill-effects on the health of the operator are largely due to the repeated vibration and shocks, and partly to the cramped unhealthy posture. They noted a danger of premature crippling and ageing causing illnesses such as lumbago and rheumatoid arthritis with long periods of service. No data were presented on the vibration levels the tractor drivers

[5]Kyphosis is an angular curvature of the spine.

were exposed to, nor were any statistical analyses conducted.

Denis (1972) also showed an increased incidence of back problems (prolapsed IV disc) in Saskatchewan tractor operators with farm acreage greater than 600, compared to farmers with less than 600 acres. Hulshof & vanZanten (1987) translated the findings of a longitudinal study of tractor drivers by Dupuis & Christ (1972). A cohort of 211 tractor drivers (mean age 17 years) was followed from 1961 to 1971 (number reduced to 106 in 1971). Physical and radiological examination showed a clear increase in pathological changes of the spine (spondylotic, osteochondrotic and arthrotic) from 57% in 1966 to 80% in 1971 in the same drivers. In 1961 only 20% of the drivers complained of back pain compared to 58% in 1971. No vibration data were presented, however, a relationship was found between back pain and pathological changes of the spine and exposure time per year. A statistical analysis of the results was not presented.

The National Institute for Occupational Safety and Health (NIOSH) in the U.S. sponsored two studies examining heavy equipment operators. Milby & Spear (1974) conducted a morbidity study of construction vehicle operators exposed to WBV, compared to control groups at similar work sites, but with no WBV exposure (n=3900). The morbidity data were gathered from the International Union of Operating Engineers' health plan record-keeping system and were adjusted for age and work experience. Significantly elevated relative risks[6] of disease were found for three of the 30 disease categories investigated including ischemic heart disease, obesity of non-endocrine origin, and musculo-skeletal disorders such as displacement of the inter-vertebral discs. In no disease category did the control group possess a significantly higher risk of medical services. The incidence of disease did not increase continuously with exposure however. Greater than half of the disease categories showed an increase in relative risk between 0-9.75 years and 10-19.75 years work, followed by a decrease after 20 or more years

[6]Ratio of incidence among exposed workers divided by incidence among unexposed workers

of work. The authors suggested a selection bias (healthy worker effect) may have occurred where workers with back trouble may have left the jobs where there was WBV exposure (Spear *et al.*, 1976b).

A follow-up study (Spear *et al.*, 1976a) was designed to evaluate the extent to which workers left jobs with WBV, and to provide additional evidence that WBV was the cause of the significant disease findings. Results of the follow-up study showed that few workers left vibration-exposed jobs for unexposed jobs. There also appeared to be no difference between the exposed and the control groups in the probability of leaving a job. Workers with disease left their jobs at about twice the rate of non-diseased workers in both exposed and control groups. Spear *et al.*, (1976a) concluded that for some diseases there was a higher probability that WBV-exposed workers would leave than non-WBV-exposed workers. However a definite conclusion about a differentiated selection process could not be made. The authors concluded that WBV exposure may have hastened the onset of certain diseases, such as degeneration of the lumbar spine, but it did not increase the overall incidence above that of controls (Spear *et al.*, 1976a).

At about the same time, Gruber & Ziperman (1974) looked at the morbidity patterns of 1448 male motor coach operators by analyzing periodic physical examination records. The control groups, including drivers with less than five years experience (n=560), the general population (n=2452), and office workers (n=530), were matched for age and sex. Gruber & Zipermann (1974) found the digestive (bowel disorders), circulatory, and musculo-skeletal systems were most affected by the demands of motor coach operation. A significant increase in the occurrence of inguinal hernias, displacement of IV disc, and operations on IV cartilage was found among the exposed drivers in comparison with all control groups. Trend analysis showed a significant correlation between prevalence rate and exposure level in years. The authors believe that vibration resonance of the contents of the abdomen causes large periodic increases in intra-abdominal pressure (IAP) which further produces spasm of the paravertebral muscles. If continued, this can lead to the development of mesenchymal defects such as ligamentous thinning and tearing, and extrusion of the IV disc material. According to Gruber & Ziperman (1974), vibration resonance also causes fluctuating colonic pressure which can explain the occurence of venous and bowel disorders. The authors concluded that "it is reasonable to postulate a causal link between displacement of the IV disc (and chronic low back pain in general) and exposure to WBV" (Gruber & Ziperman, 1974).

In a case control study (Kelsey & Hardy, 1975) 223 herniated lumbar IV disc patients were compared to a matched group with no history of back trouble, and to a second group with prior symptoms of herniated discs, but were free of symptoms for a year. The study was concerned with the causes of herniated discs rather than back symptoms. When occupations were compared in all groups, those workers who drove vehicles regularly carried a significantly increased risk of disease. Men who spent greater than one-half their working hours driving (commercial vehicles) were three times more likely to develop a herniated lumbar disc. A study by Frymoyer *et al.*, (1980) of 3500 patients from a family practice center in Vermont also concluded that low back pain was more common in individuals exposed to vibration (truck, tractor, and heavy construction equipment operation).

An excellent prospective study was carried out by Grzesik (1980) in Polish coal and sand mine workers. Miners who had at least three years of various sources of WBV experience in two exposure groups (less than 0.3 $m.s^{-2}$, and greater than 0.3 $m.s^{-2}$) and who were at least five years from retirement, were medically examined twice, three years apart. Comparison of the first and second medical examination showed that men in the younger age group with higher levels of WBV exposure showed an increased incidence of: circulatory system complaints; hunger and thirst disorders; heartburn and nausea; gaseous condition; fullness of stomach; and complaints of the upper limb. It is very difficult to find appropriate comparison groups for studies of whole body vibration. Hence, a longitudinal study is the best possible way to monitor the health changes. When the vibration characteristics and exposure are known, it can be linked to the health effects.

Some recent epidemiological WBV studies have involved helicoptor pilots and aircrew members. In a questionnaire survey of 802 U.S. army helicoptor pilots (Shanahan *et al.*, 1984), 584 (72.8%) pilots reported experiencing back discomfort during flights within the last two years compared to a general population rate of back pain of less than 30%. The mean flight duration before onset of back pain symptoms was 88 minutes for this group of pilots, and half of these pilots were asymptomatic 10 hours after flight cessation. One–third of the pilots were symptomatic longer than 24 hours, and, in a small group, pain was reported to be induced only by flying helicoptors. A significant percentage (28.4%) of aviators with back pain admitted to rushing through missions because of the pain, and 7.5% refused missions due to pain. Bowden (1985) contrasted this with the general population in which back pain is not usually of such rapid onset, and patients often cannot remember when the pain started. The group with pain persisting greater than 48 hours had greater years of flight status and a higher incidence of numbness of the legs. The two etiologic factors implicated in helicoptor pilot back pain were vibration and poor ergonomic design, although the authors did not statistically evaluate the effects of poor ergonomic design. It was concluded that repeated exposure to vibration leads to pathological changes in the spine (Shanahan *et al.*, 1984).

A study by Wilder *et al.* (1984) addressed low back pain (LBP) in two–bladed helicoptor environments where pain may be attributed to posture or vibration. The helicoptor pilot assumes a slumped, asymmetric posture and is required to use all four extremities simultaneously in control of the helicoptor. EMG recordings were taken prior to and following two hours of exposure to the static posture in a helicoptor simulator, and prior to and following two hours exposure to a simulated vibration environment with identical posture. The authors concluded that greater fatigue, as well as subjective discomfort resulted from the two hour static posture. A variety of acceleration levels were combined with a vibration frequency of 10.8 Hz. This frequency is above whole body resonance frequency. Vibration environments closer to the whole body resonance frequency (4-8 Hz) may have had a different effect. This study illustrates the difficulty of separating posture effects from vibration effects.

In a recent study of tracked armoured vehicle operators at a combat arms school (Beevis & Forshaw, 1985) medical histories of 'Pool' drivers[7] (n=18) for three years prior to the investigation were compared with two other groups of drivers matched for age, height and weight. One group called 'RCR' drivers (n=24) drove the same vehicle but for fewer hours per week and the second group, 'Centurion' drivers (n=20), drove a slower heavier vehicle also for fewer hours per week. A questionnaire distributed to all drivers asked about factors such as driving speed and hours driven per day. A third aspect of the study involved measurement of the WBV exposure in each vehicle.

The results from examination of medical histories showed that the three groups did not differ in their frequency of visits to the Doctor over the three years but the longer exposed Pool drivers reported significantly more back pain than the other two groups. The questionnaire data were subjected to factor analysis and the variables found to be significantly associated with back pain were high total hours driven per week, long hours on all types of terrain and a high personal weight to height ratio. WBV measurements showed that the vertical vibration levels in the 'Pool' and 'RCR' drivers tank were much higher than in the 'Centurian'. The ISO exposure limit would not be exceeded for 24 hours in the Centurion tank, compared to 4 hours in the other tank. The authors concluded that although the number of subjects were few, a statistically significant increase in reported low back pain was related to exposure of drivers to intense levels of vibration and shock for periods exceeding

[7]Drivers who drove M113 armoured personnel carriers

the recommended ISO limits.

The mechanism of spinal injury due to exposure to WBV has been called "vibrocreep" (Troup, 1978; Wilder *et al.*, 1982; Wilder *et al.*, 1983). Vibrocreep is a loss of disc space height due to vibrational loadings. Wilder *et al.*, (1983) measured a mean loss of 0.77 cm in standing height after 30 minutes of vibration exposure. Troup (1978) hypothesized that when compressional load exceeds osmotic pressure in the disc, fluid is slowly expelled. As a result the disc becomes less compliant, thereby changing the kinematics of the motion segment. There was also evidence of a dose–response relationship in that the greater the amplitude of vibration, the greater the reported vibrocreep effects (Troup, 1978).

A study was carried out by Wilder *et al.*, (1983) to investigate the mechanism of back injury, by collecting data on the responses of the spinal system to vibrational inputs in a seated posture. Spinal resonances were found to be present at fairly uniform frequencies for all subjects. The first resonance occurs at 4.5–6 Hz, and the second between 9.4–13.1 Hz. At the first resonance, the spinal system input motion (vibration measured at the seat), is less than the output motion (vibration measured at the head helmet). This ratio or transmissibility factor is 1.79 at the first resonance. The dominant vibration frequencies of many different vehicles were measured and found to be in the 3–6 Hz range (Hornick, 1961; Wasserman, 1978; Caza, 1983). According to Wilder *et al.*, (1983) the vibration "may well be placing such an individual's spine at risk; prolonged vibration exposure may cause fatigue of the spinal structure, just as can occur in complex mechanical structures through material fatigue".

Surface topography and filming of subjects exposed to WBV revealed a pattern of spinal flexion during the downward motion of the seat and spinal extension during the upward part of the vibration cycle (Wilder *et al.*, 1983). During resonance however, subjects were out of phase with the seat, going up when the seat went down (Wilder *et al.*, 1983). A standing person can subconsciously reduce his vibrational load by shifting his feet, knees and hips. But a seated individual does not have these options and responds to vibrations by stiffening his joints (Carlsoo, 1982). Studies in animals exposed to vibration have shown increased stiffness in subchondral bone[8], destruction of cartilage tissue and numerous microscopic fractures in the trabeculae (reported by Carlsoo, 1982). Carlsoo (1982) hypothesized that joint degeneration may be a natural consequence of repetitive jolts even when the jolts are within physiologically tolerable limits; i.e., body weight. Wilder *et al.*, (1983) has also demonstrated fatigue of the spinal structure in vitro by creating lesions in young human discs subjected to vibration. Most previous attempts to produce disc herniations in vitro by loading motion segments have been unsuccessful.

Body posture also affects the transmissibility of vibration along the spinal system, especially at the first resonance (Wilder *et al.*, 1983). Although EMG measurements from paraspinal muscles and intradiscal pressure increased in positions of increased spinal flexion, axial rotation and lateral bend, transmissibility and spinal stiffness are reduced. Vehicle operators will consciously or unconsciously alter their posture, probably shifting their own resonant frequency away from the frequency of the vehicle, but at the expense of increased muscular activity and a different set of mechanical stresses on the spine.

The difficulty of relating WBV to morbidity stems from the interrelatedness of many factors. Apart from individual susceptibility, many of the medical conditions associated with WBV such as back pain and gastrointestinal disorders may be caused by: 1. vibratory stress; 2. postural stress, i.e. static loading of muscles with little chance for movement or relaxation; 3. muscular effort which is often required in control and operation of the vehicle; and 4. shocks or impacts (Troup, 1978). The effects of vibration depend upon individual factors such as age, degenerative changes of the spine and body mass. Situational factors may also play a

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[8]Situated beneath cartilage

role such as the time of day, effects of previous static and dynamic loading, worker orientation, degree of body coupling to the vibratory source, diet and eating regularity and worker clothing. Other stressors which affect the body such as noise, heat, fumes, and dust may interact with, or compound, the vibration stress. Equipment factors affecting the vibration include vehicle suspension, tire pressure, wheel base, gauge, multiple vibratory sources (dual engines), vehicle speed, facilities for changing speed, equipment weight and wear, location of driver's seat, vibration damping facilities, etc. (Hansson, 1981; Wasserman *et al.*, 1978; Troup, 1978). Task variables include road design, road terrain and driving tasks. Also, in heavy equipment operation, vibration may enter the body from multiple sources such as the seat, floor, controls where feet are placed, steering wheel, or other hand controls.

The difficulty in drawing causal relationships from the literature between associations of medical conditions and WBV exposure is due in part to: 1. the inability to separate WBV effects from other environmental and postural stressors; 2. a lack of knowledge of the relationship between specific effects such as psychological stress, prolonged sitting, noise, and vibration; and 3. inadequate understanding of the mechanism of action of low level WBV for a long exposure time. The etiology between mechanical vibration exposure and vibration-related disorders are difficult to establish epidemiologically and experimentally (Guignard, 1979). Although there are consistent findings of back pain associated with vibration exposure, with the current state of knowledge, even the best epidemiological studies cannot differentiate whether chronic LBP is due to high levels of vibration, or poor posture (Sandover, 1979).

Other less well substantiated chronic WBV effects include increased circulatory disorders in organs of the lower extremities (varicose veins and hemorrhoids), disorders of male genitalia, decreased blood supply to the pelvic region, glandular troubles, menstrual disturbances, disorders in pregnancies, and circulatory disorders of the eyes (International Labour Office, 1976).

Legal Aspects of WBV

At present in North America no work-compensable diseases are attributed to WBV. In the Soviet Union a systemic illness called "vibration illness" characterizes the "totality of vibration-induced changes in the human organism" (Dupuis & Zerlett, 1986). At vibrations of less than 35 Hz the Russians report symptoms of vessel atonia, hemostasis, bone and joint changes (including the vertebral column) and minor perception disorders. This opinion is not shared by other researchers. The recognition of vibration-related disorders, however, is increasing. The International list of Occupational Diseases, ILO Agreement no. 121 (1980) contains a vibration related occupational illness (no. 23) with the following definition: "Illnesses caused by vibration (illnesses of the muscles, the tendons, bones, joints, peripheral vessels or nerves)". The International experts who drew up the list of diseases also "recognize the significance of illnesses resulting from low-frequency vibration in the drivers of motor-driven machines, tractors, etc. (ailments of the lumbar vertebral column, sciatica, etc), however they emphasized that the ailments are not typical (specific) and the occupational-related origin is therefore often difficult to prove" (Dupuis & Zerlett, 1986). Also, the exact incidence of disease in relation to exposure data (dose-response) is not known.

The German Democratic Republic recognizes occupational degenerative diseases of the vertebral column (vertebrae, vertebral disc endplates, spinal process, ligaments, vertebral joints) as related to many years of (WBV) mechanical overstress (Dupuis & Zerlett, 1986). In Germany, a vibration-related occupational disease of the vertebral column may be compensable if it results in considerable limitation of function of the locomotive system and cessation of the occupation connected with vibration. Extensive epidemiological studies on high exposure groups are required with clear clinical findings and precise occupational case histories. An adequate control group for comparison to the vibration-exposed group is also important.

Standards & Measurement Technique

The biological effects of WBV may be measured in three general ways: 1. quantitative physiological responses such as heart rate, oxygen uptake, muscle electromyography; 2. effectiveness of job performance, for example, reaction time and visual perception; and 3. qualitative verbal response to stimuli. Each of the above three measures may serve different purposes.

A great deal of effort has gone into the development of equal sensation contours based on subjective responses (Ashley & Rao, 1974; Oborne & Humphreys, 1976(b); Shoenberger, 1975; McCullough, 1974). The methods generally fall into one of three catagories (Oborne, 1978):

1. Presentation to subjects of separate stimuli of varying frequency and intensity for vibration rating using a comfort label.
2. Presentation to subjects of a comfort label for the subject to adjust vibration stimulus to describe sensation induced by the vibration.
3. Recording of resonance of parts of the body and galvanic skin response in addition to subjective comment.

Research into the development of equal sensation contours has provided information about the WBV frequency ranges where various areas of the body are maximally affected; i.e., maximal deflection of head, shoulders and lumbar spine at 4 Hz, maximal deflection of stomach at 4.5 Hz, maximal movement of neck vertebrae at 3.5 Hz, and a pump effect on the diaphragm at 5 Hz (Ashley & Rao, 1974). Some investigators have maintained that a composite or average contour does not adequately indicate the overall subjective response to WBV (Oborne & Humphreys, 1976b), and that for any given contour there are inconsistent data with respect to the shape of the contour and subjective response (McCullough, 1974; Oborne, 1983). Buried within an average may also be a wide range of individual responses, and therefore the production of an average curve may be inappropriate (Oborne *et al.*, 1981b). Environments comfortable to some people are distinctly uncomfortable to other people. Oborne *et al.*, (1981a) used a modified matching procedure to derive individual sensation contours from 100 subjects exposed to a frequency range of 2.4 to 60 Hz. The results indicated a wide range of individual contour shapes among different subjects. Although Oborne *et al.*, (1981a) found no male/female differences in contour shape, Jones & Saunders (1974) demonstrated significant differences between males and females in response to high frequency (greater than 30 Hz) vibration.

Matthews (1966) obtained reasonable agreement between measured accelerations and the operator's subjective assessment of the ride; exposures rated as "good" had natural frequencies of less than 2.4 Hz, while those rated "poor" had frequencies greater than 3 Hz. Hansson (1981) used a 9 point scale for subjective rating of discomfort, and found high correlations between discomfort and the vibration measurements as well. Vibrations less than 1 Hz, however, had no major effect on driver ratings. It has been suggested that a quantitative numerical ratio scale instead of semantic labels for estimation of comfort may make the data more useful (Sandover, 1979). In addition to contour curves, other subjective measures include the "Janeway Limit" which is often used by automobile designers, and the British Rail "Ride Index" (Sandover, 1979).

The greatest difficulty with subjective criteria is that comfort is a very abstract perception which may be psychologically confusing. For example, a particular level of WBV experienced over rough track may appear to give a more comfortable ride than an identical vibration level experienced over a clearly smooth surface (Matthews, 1966). Much of the comfort research has been conducted in a laboratory setting using sinusoidal inputs (Oborne, 1976a). There appears to be a wide range of results and very little agreement between investigators as to what frequencies and levels of vibration are acceptable. This lack of agreement may be attributed to experimental problems such as; too few subjects, no control for physical dimensions of equipment, distorted waveforms from mechanical vibrators, uncontrolled length of exposure, differing instructions and type of semantic label.

There have been some studies comparing lab measurements with field studies. Oborne (1978) used comfort curves with subjects exposed to WBV in a lab setting and in a hovercraft. He compared this with results obtained from hovercraft passengers. In the lab studies, at a frequency below 20 Hz, the highest vibration level considered comfortable was approximately 0.25 $m.s^{-2}$. When the subjects were exposed to WBV in the hovercraft, the highest comfortable WBV level was 0.6 $m.s^{-2}$. Passengers in the field rated a hovercraft WBV level of 0.9 $m.s^{-2}$ as comfortable. Oborne (1978) argued that the measured differences between lab and field conditions are due to the extraneous stimuli in the field which distracts the passenger's attention. Parks (1962), in agreement with Obornes' (1978) findings, noted that vibration in operational systems often exceeds levels described as "intolerable" in the literature (lab studies). Also, these "intolerable" levels can vary between individuals by as much 10 $m.s^{-2}$.

A lack of agreement between results of different studies hampered the development of WBV guidelines or standards. WBV is similar to noise exposure in many respects. Although much information is available regarding noise and its prevention, the development of standards is approached in different ways in different countries. The **International Labour Office Report on Noise & Vibration in the Working Environment** (1976) compares the setting of standards for noise with that for vibration. Setting standards for WBV was deemed more difficult because; "existing scientific information was not sufficient to allow the establishment of numerical exposure limits" (ILO, 1976). The ILO stressed the importance of pursuing and intensifying research so that methods of measurement and assessment of risks can be developed and applied in the working environment.

The first attempt at setting WBV guidelines was by the International Standards Organization (ISO) which published a Guide for the Evaluation of Human Exposure to WBV (ISO 2631) in 1974. The second edition, incorporating new data, was published in 1978. The international standard was designed for the purposes of facilitating evaluation and comparison of data from individual investigators gained from continuing research in the field, and giving provisional guidance as to acceptable human exposure to WBV (ISO 2631, 1978). The standard specifies usage of explicit numerical terms to avoid ambiguity, and to encourage precise measurement in practice. The standard is written specifically for vibration transmitted to the body as a whole through a solid supporting surface (i.e., feet when standing, buttocks when seated), in the range of 1-80 Hz. The WBV may be sinusoidal (periodic) or non-sinusoidal (random). There are also provisions for shock-type WBV (jolts). Limits are specified with respect to vibration frequencies, acceleration magnitude, exposure time and direction of vibration (see Figure 1). The data used in establishing the limits came from laboratory studies using aircraft pilots and drivers.

The standards specify three criteria: 1. preserving comfort (reduced comfort boundary, RC); 2. working efficiency (fatigue or decreased proficiency boundary, FDPB); and 3. safety and health (exposure limit, EL). As seen in Figure 1, the EL is equal to two times the FDPB (or an increase of 6 dB). This is considered to be one-half the level of the threshold of pain (or limit of voluntary tolerance). The RC boundary is equal to approximately one-third the FDPB (a decrease of 10 dB). This boundary is related to difficulties with eating, reading, and writing. If the vibration exposure occurs in more than one axis simultaneously, the limits apply separately to each component in the three axes.

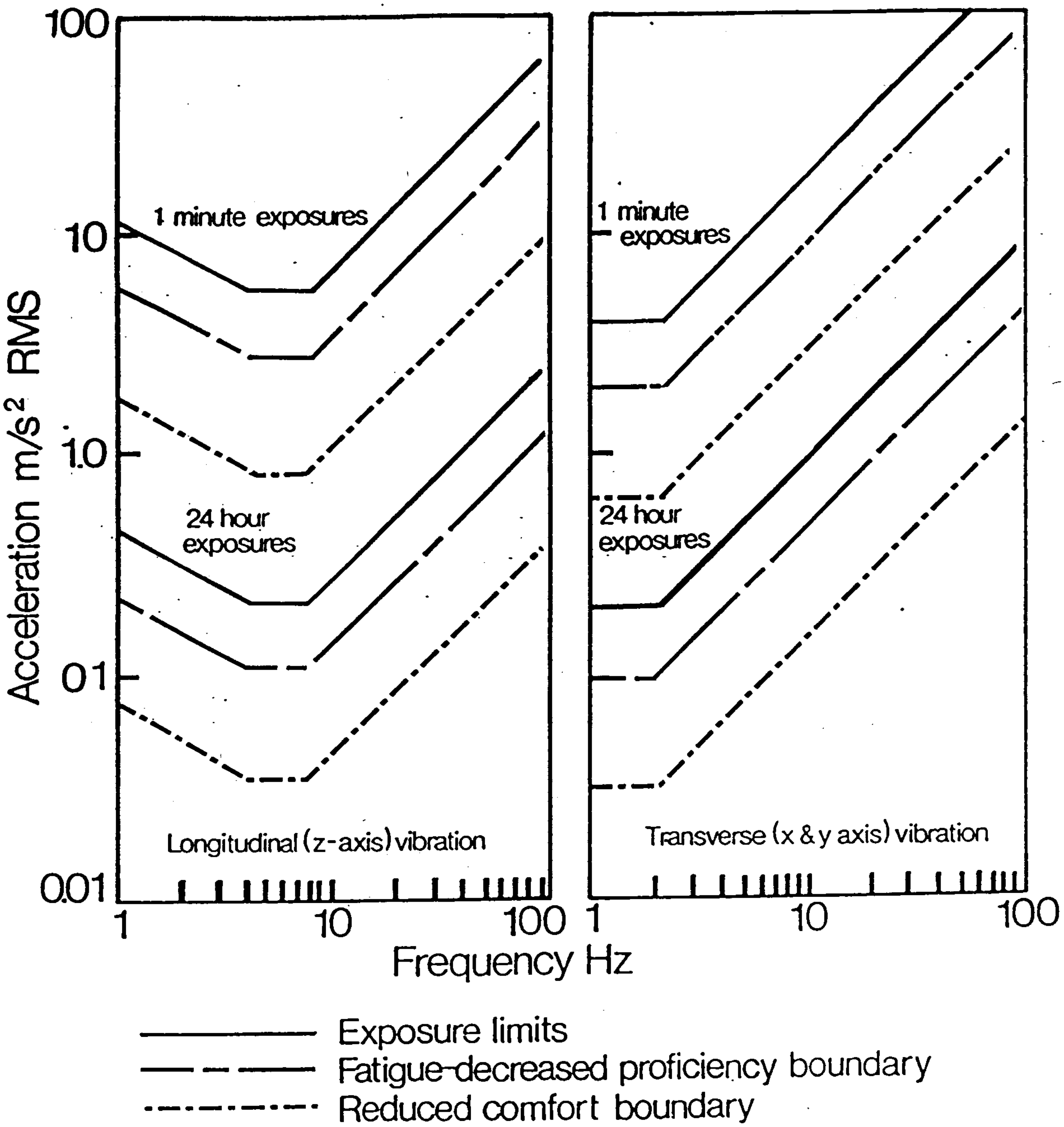

Figure 1: ISO Limits for Longitudinal (z-axis) & Transverse (x & y) axis Whole-Body Vibration

The duration of exposure is presented for one minute through to 24 hours. The 1978 ISO 2631 was written when few data were available on the recovery effects from WBV. A 1982 amendment (ISO 2631/DAM 1, 1982) gives a method for approximating the manner in which acceleration levels decrease with increasing exposure, up to eight hours. The ISO was also written when few data were available for frequencies less than 1.0 Hz. Appendum 2 (1980) outlines a limit for vibration in the frequency range of 0.1 - 1.0 Hz, with a tentative extrapolation between 0.6 and 1.0 Hz. This was intended to minimize the severe discomfort associated with motion sickness and allied symptoms. Due to a lack of data, Appendum 2 is confined to the z-axis.

The measured quantity used to define the ISO limits is acceleration in $m.s^{-2}$, expressed as a root mean square (RMS) value. This is essentially an average which is mathematically equivalent to the standard deviation of the instantaneous values of the quantity (Guignard, 1979). When the WBV is non-sinusoidal, random or broad band vibration, a crest-factor ratio is determined. The crest-factor is the ratio of maximum peak vibration to average RMS vibration. The ISO 2631 (1978) was written for crest-factor ratios less than three. As more data were made available, the crest-factor ratio limit has been extended up to six (1982 amendment).

Equipment for the measurement of WBV includes a transducer or accelerometer, an amplifying device (electrical, mechanical or optical), and a level indicator or recorder. The accelerometer is an electromechanical transducer which produces a voltage that is proportional to the mechanical vibrational acceleration to which it is subjected. This is accomplished by a piezoelectric element. The frequency range of measurement may be limited using a frequency weighting applied to the input signal. A tape recorder may be used for permanent data storage. Proper calibration of all equipment is essential and it is important to report frequency sensitivity, dynamic properties (time constant), dynamic range, and resolution of equipment.

Also, when appropriate, the precision of the RMS rectifying, frequency weighting, tape recording, and frequency analysis should be reported. A publication from the International Electrotechnical Commission (No 184-1965), provides a useful guide and standardization of electromagnetic transducers for measuring shocks and vibrations.

The placement of the accelerometer when measuring WBV is important, and controversial. The ISO 2631 (1978) specifies that the accelerometer should be placed at the point of entry of vibration into the human body, and should be fastened to the rigid structure (floor, platform or seat). Where a resilient material exists between the body and the supporting structure (seat cushion), the transducer contained within a rigid support (thin metal sheet) should be interposed. Seat transducers consisting of a deformable pad which follows the seat contour and contains triaxial accelerometers for simultaneous measurement in three axes are manufactured according to standardized (SAE J1013, 1973) guidelines (Sandover, 1979). One problem with using the seatpan accelerometers is that the driver, on a rough road surface, frequently leaves the seat. This results in large jolts or impacts in the vibration signal as the driver decelerates into the seat. True body vibration input intensity can be measured by mounting the accelerometer on the person. This is rarely done, however (Matthews, 1966).

The ISO limits (2631, 1978) have resulted in a great deal of discussion and controversy. It is not clear from the document which studies were used to define the curves, and some studies had major methodological problems in subject selection and size (Oborne, 1983). The limits were designed for the 1-80 Hz range although insufficient data were available past 30 Hz (Ramsey, 1975; Sandover, 1979). Also, some U.S. data were omitted which would have modified the recommended limits (Oborne, 1983).

As was seen in Figure 1, all three ISO curves are parallel and thus have the same frequency weighting. There is some concern that this frequency weighting is too simplistic with no experimental basis for use of the same shape for all three curves. Oborne *et al.,* (1981a) used 24 subjects to derive equal sensation contours for varying degrees of vibration intensity. They concluded different weightings should be applied in environments with different vibration intensities to yield equal comfort sensations. There is also no information in the ISO Standard (2631, 1978) explaining how the weighting method for non-sinusoidal vibration was derived (Oborne, 1983).

The curves for vibration are not as complete as the equal-loudness curves for tones of sound since the sensation of vibration is not localized, but felt throughout the body, and different systems operate to provide sensation (Weaver, 1979). One researcher has suggested that perhaps an expected range of responses should be indicated rather than straight-line boundaries (Sandover, 1979). Also, vibration entering the driver/operator via the seatback, feet, thighs and hands was not considered (Griffin, 1978).

Another major criticism of the ISO limits is the specification of exposure times; the longer the WBV exposure, the less the recommended vibration intensity. There are very few data on dose-effect information, or time dependency (Griffin, 1978; Oborne, 1983). The curves in the ISO standards are based on extrapolations of short exposures rather than actual prolonged exposure. Allen (1975) notes that the flat portion of the time-dependency curve between 1 and 4 Hz is based on data involving the pilot's fear of structural damage to the aircraft, rather than subjective responses to motion. Performance studies utilizing exposure criteria indicate that for tracking, vigilance, visual search, and handwriting tasks, efficiency is almost independent of duration of exposure. Similar conclusions have been drawn for comfort and exposure duration (Oborne, 1983). Griffin & Whitham (1976) allowed subjects to adjust the vibration magnitude in order to obtain equivalent discomfort during exposures between 4 and 16 Hz. Their results were also independent of exposure time up to 36 minutes.

The ISO limits leave a number of questions unanswered. For example: what percentage of passengers will be dissatisfied at the RC boundary; is FDPB applicable to complex and simple control tasks, and to cognitive performance; what is decreased proficiency – a 50% reduction or loss of control? Sandover (1979) suggests a new vibration standard in which the degree of risk is outlined such that a user can decide the limits for his particular situation. More studies are required before this type of standard could be introduced. Sandover (1979) reports that the emphasis in the WBV standards should be on vibration conditions which lead to a decrease in vital skill and an increased risk of accidents. These limits would fall well below levels indicating an increased health risk. Sandover (1975) also suggests design guidelines be written for the designer/engineer.

Despite their inadequacies, the ISO standards have served as a catalyst for generating information, and a number of countries have adopted them, including Britain (BSI, 1974 and 1987) and the USA. Australia wrote a guide and set of standards on WBV (AS 2670) in 1983 which were very closely based on the ISO 2631. Germany, Sweden and Austria have written standards more specific to seating suspension designs. The German standard is very elaborate, based on a vibration level called a K–factor. The seats must be load–tested on a hydraulic simulator and approved by official bodies prior to being fitted onto vehicles. In Sweden, vibration measured at the operator's shoulder must not exceed 0.8 G. In Austria, vibration measured at the seat in the 0.5 to 8 Hz frequency range is compared to a limit curve. The seat, when loaded with a 50 kg mass, must not exceed a vibration amplitude of ±10 mm between 0.5 and 4 Hz, and ±5 mm between 4 and 8 Hz. The standards for vibration in the USSR are very strict for workers and machinery. They were also reporting the introduction of anti–vibration protective clothing (Lehmann, 1974).

It is generally agreed by most researchers that, in theory and practice, a natural frequency of less than 2 Hz is a must, and 1.4 Hz, or less would give still better comfort

(Longchamp, 1973).

Whole Body Vibration and Heavy Equipment

The vibration frequency range of almost all heavy equipment (tractors, scrapers, dozers, loaders, skidders, haulage trucks, forklifts, scooptrams (LHDs), etc.), corresponds to the resonant frequency of the lower back at approximately 5 Hz (Simons, 1952; Hornick, 1961; Wasserman *et al.*, 1978; Caza, 1983; Grandjean, 1981). A pilot study by a major mining corporation in Ontario and Quebec (Caza, 1983) evaluated the WBV exposure at the seat on a range of heavy equipment including scooptram (LHD), payloader, teletram, grader, forklift, bulldozer and haulage truck (unpublished study). All seven pieces of equipment exceeded the FDPL, and the EL for 330 minutes (5 1/2 hr) of exposure. The scooptram (LHD) vibration measured exceeded the recommended FDPL by a factor of 20.

In a recent review, Crolla *et al.*, (1984), compared the vibration levels of unsuspended vehicles (for example, tractors, earthmoving, and forestry equipment) with suspended vehicles (for example, military) as measured at the driver's seat. For compliance with the ISO (2631, 1978) 8-hour WBV limits, the vibration levels in some vehicles required a 50% reduction. The authors concluded that vibration levels in off-road vehicles are often unacceptably high (Crolla *et al.*, 1984). Hansson & Wikstrom (1981) measured WBV in forestry equipment and found high vibration intensities in greater than one axis, with a substantial amount of vibrational energy in the 1.5–3 Hz vertical range, and the 0.6–1.6 Hz lateral ranges. The crest-factor ratios were often greater than three. The vibration levels in off-road vehicles appeared to differ from levels in on-road vehicles in that severe vibrations were found in several directions and the vibration levels and peaks were substantially higher.

Wasserman *et al.* (1978) measured WBV in the seat of a variety of tractors, graders, scrapers and loaders with similar results to Crolla *et al.*, (1984). The major frequency bands were between 0.12 and 2.6 Hz, with a range of acceleration between 0.52 and 1.3 $m.s^{-2}$. The authors determined that most of the high level vibration occurred in frequency bands less than 4–8 Hz, with a large component occurring at less than 1 Hz. Typically, vibration in the ≤ 1 Hz range, if continuous, causes motion sickness (Wasserman, 1987). Motion sickness was not considered a problem in the vehicles measured by Wasserman *et al.*, (1978) due to the transient nature of the work and the high crest–factor ratios. Wasserman *et al.* (1978) suspected that the low frequency peaks were due to changes in vehicle path and speed such as accelerating, braking, steering through turns, and changing grade or slopes in terrain. The authors found little difference between experienced and inexperienced drivers, or between different operator masses.

Only one published study could be identified (Redmond & Remington, 1986) where WBV was measured in mining machinery. Field measurements were taken of 61 surface coal mining vehicles and 25 underground coal mining vehicles. The authors did not separate the vibration signals into distinct tasks, but simply averaged the vibration over several cycles of normal operation. A RMS was calculated in each frequency band along with a probability density of RMS acceleration level. The probabilities of each machine were then averaged to yield the mean probability of exceeding the ISO recommended exposure limits. The authors found that, in general, the vibration levels of underground vehicles were lower than the surface vehicles due to slower travelling speeds. Among the surface vehicles tested, the probabilities of exceeding the ISO limits were greatest for scrapers, dozers and loaders (0.425, 0.338 and 0.311 respectively). The LHD was classified with a group of underground haulage vehicles. Exposure data were lacking for the LHD machine so the authors assumed its exposure to be similar to a shuttle car (4.8 hr/day operation). Unfortunately, the type and size of LHD machine were not specified. It was mentioned that the LHD machines were rarely used to transport coal. Instead, they transport equipment and materials. The probability that underground haulage vehicles would exceed the exposure limit was found to be 0.22. In summary, 7-22% of surface vehicles, and 9-14% of underground vehicles exceeded the exposure limits. Due to insufficient numbers of vehicles and a lack of exposure data, the authors concluded that the "primary sources of overexposure measured in underground mines occurred in shuttle cars, and possibly (LHD vehicles) scooptrams" (Redmond & Remington, 1986).

Isolation of the operator from terrain-induced vibration is difficult, especially in off-road vehicles because there is generally no suspension system between the frame and the wheels (as in automobiles and trucks). The only isolation elements are the tires and seat suspension (Guignard, 1979). The important parameters in the design of a seat suspension, whatever the type, include: 1. natural frequency of the spring system; 2. damping; 3. available vertical movement; 4. mode of vertical movement; and 5. inclusion of horizontal resilience (Matthews, 1966).

Seating suspension systems may be either passive, or active. Most vehicle and seat suspensions are passive, which make use of the inherent properties (elasticity and damping) of springs and resilient materials (Guignard, 1979). The most common method of passive suspension of a seat is by a spring (mechanical or pneumatic) and a shock absorber tuned for acceptable isolaton over a narrow frequency range and for specific settings of system parameters. Passive suspensions are not capable of a wide range of frequencies or operator weights (Gunderson & Wilson, 1981). To be effective in isolation against vibration, the suspension system's natural frequency must be low compared with the exciting frequency of the vehicle (which should be at least 1 1/2 times that of the suspension system). At resonance a large amplification may be caused by such a system unless there is 100% damping. A damping factor of 0.2 - 0.5 is recommended (Auyoub & Ramsey, 1975). Elastic seats with a very low natural frequency (1 Hz) cause approximately 5 inches of deflection of the driver, making operation of controls difficult (Ayoub & Ramsey, 1975). To achieve isolation from 2–5 Hz vibration by means of a cushion, a 10 inch deflection is required to decrease the frequency to 1 Hz. Such a large seat deflection would make vehicle control difficult (Ramsey, 1975).

For specialized applications with severe large amplitude motion and vibration of 1–10 Hz, an active system may be desirable (Guignard, 1979). This is accomplished by an accelerometer or other sensor which monitors the forces reaching the vehicle or seat, and generates a signal used to drive an actuator (usually electro–hydraulic) to oppose the motion. Gunderson & Wilson (1981) at the University of Saskatchewan designed an active suspension system for agriculturural tractors called the **Zero–G** Seat Suspension. The seat is attached to the piston rod of a hydraulic actuator. An electrical signal from an accelerometer mounted on the vehicle's frame is amplified and used to drive an electro–hydraulic valve. This directs hydraulic fluid to the actuator so the piston moves in the direction opposite that of the vehicle. Although the seat yields greater than 90% attenuation over a wide range of frequencies, the authors have not had much commercial success with it due to high cost and safety and maintenance problems (Gunderson & Wilson, 1981).

A more difficult and expensive means to dampen the vibration, is to damp the entire cab. Zylberstein (1981), for example, built a special roll–over–protection–system (ROPS) and cab, mounted with simple springs and shock absorbers, allowing vertical cab movement of 150 mm and horizontal movement of 100 mm from neutral. When field tested against a rigid cab with a suspended seat, the machine with the suspended cab could drive faster without increasing WBV exposure (from 0.8 to 1.2 $m.s^{-2}$). A reduction in speed in the rigid cab of 30% reduced the vibration to a level equilavent to the cab with resilient mounting (Zylberstein, 1981).

There are marked advantages to consideration of seat design as well. A 110 degree inclination of the seat back allows distribution of the body's mass over the backrest as well as the seat, therefore decreasing the spinal stress caused by road shock and vibration (Troup, 1978). But, care must be taken to avoid bending vibration (backslap) to the spine in this position (Wilder *et al.*, 1983). When muscle activity was measured by electromyography (EMG) in erector spinae muscles, the level of muscle activity was unchanged in the 110 degree inclined position in a vibration environment, but the external oblique muscle activity increased. The addition of arm supports resulted in vibration transmission to the arms and increased scapular motion, but decreased the bending of the trunk (Wilder *et al.*, 1983). According to Wilder (1983), postural supports (lumbar, arm and foot) are generally helpful but shift the load elsewhere, affecting adjacent structures. Based on Wilder's extensive work (1983) the following seven desirable features of vehicle seats were summarized: 1. 3–axis damping of seat pan; 2. damped but rigid lumbar support; 3. conforming thoracic support of graded stiffness caudally; 4. no neck rest; 5. damped arm support; 6. tilted seat pan; and 7. seat back reclined from the vertical. In addition the features should be adjustable and tuned for the individual. Wilder also hypothesized that a vehicle operator can decrease the effects of fatigue due to WBV by abdominal and back extension exercises, as well as by resting periodically. He warns that heavy manual materials handling after vibration exposure is particularly dangerous due to vibration causing fatigue of the lower back muscles.

Several European countries have specifications with respect to seating anthropometrics to ensure that 90% of the population can adjust the seat appropriately. The specifications include: 1. weight adjustment for 50–110 kg (given that 75% of a driver's weight is applied to the seat); 2. vertical adjustment ±30 mm from median; and 3. horizontal adjustment of ±75 mm (Longchamp, 1973). Apart from the problem of the operator bouncing due to a soft suspension, an adjustment between 50 and 110 kg corresponds to a 10 cm extension of the seat, or 50 turns of a knob with a 2 mm thread. It is questionable whether the average driver will take the trouble to make the appropriate adjustment.

CHAPTER III

HYPOTHESIS & OBJECTIVES

Research Hypothesis

It is hypothesized that:

1. LHD operators who experience WBV will have a different injury profile than other mine workers.
2. LHD operators are exposed to whole body vibrations within the frequency range of 1 to 10 Hz, which exceed the ISO Standards (2631) daily exposure limit.
3. Whole body vibration of LHD operators effects decrements in both visual acuity and manual dexterity over the duration of a normal daily exposure.

Objectives

In order to better understand the nature and extent of whole body vibration (WBV) in underground load-haul-dump (LHD) vehicles, and its effects on operator health and performance, the purpose of this study was:

1. To identify the most frequent types of accidents and injuries incurred by LHD operators, by comparing the accident and injury records of all LHD operators employed in Ontario (approximately 600) to those of three control groups of mine workers.
2. To identify the dominant vibration frequencies, acceleration amplitudes, and peak accelerations (jolts and impacts), to which LHD operators are exposed.
3. To measure the effects of WBV on two performance indices critical for vehicle operation; visual acuity and manual dexterity.

CHAPTER IV

ACCIDENT & INJURY ANALYSIS

Introduction

LHD operators often complain of back problems, and the back injury rates among this group of workers are high (MAPAO Internal Report). The majority of work time however is spent sitting and operating the vehicle. The LHD operator performs very little lifting and handling. From the literature it is apparant that other types of vehicle operators (bus drivers, tractor drivers, heavy construction vehicle operators) also complain of back problems (Gruber & Ziperman, 1974; Milby & Spear, 1974; Matthews, 1966; Rosegger & Rosegger, 1960). There is evidence of an association between back problems and exposure to WBV (Hulshof & vanZanten, 1987; Dupuis & Zerlett, 1986, Seidel *et al.*, 1986). The main objective of this analysis was to compare the incidence of back injuries and other types of injury among LHD operators exposed to WBV with the injury records among mine workers not exposed to WBV.

Methods

In order to identify the most frequent types of accidents and injuries incurred by LHD operators, the accident and injury records from the Mines Accident Prevention Association of Ontario (MAPAO) of all LHD operators employed in Ontario in 1984 and 1985 were compared with three groups:

1. all mineworkers underground (excluding LHD operators)
2. all office workers
3. all underground supervisors

Rationale for Selection of Comparative Groups

There was no ideal control group with which to compare LHD operators. The ideal control group would work primarily from a seated posture, operating controls and monitoring. The environment would be similar to that of LHD operators with respect to lighting, noise, and temperature, but would not expose the workers to WBV or jolting/jarring. Due to the nature of the database and job classification scheme at the MAPAO it did not seem possible to identify a control group with all the appropriate exposure criteria. Several jobs were often grouped together within each classification, and many included manual lifting and handling functions.

It was therefore decided to compare the accident and injury experience of LHD operators with that of all underground mineworkers (excluding LHD operators); all occupations combined. This would allow identification of differences in LHD operator accidents and injuries from the general pattern of the workforce as a whole. The office worker was chosen as a second comparative group because the job takes place primarily from a seated posture. However, the office worker was not exposed to WBV or the underground environment and may have been male or female. The underground supervisors were chosen as the third comparative group since they work in the same physical environment, were not exposed to WBV, perform only limited amounts of lifting and handling tasks, and are all male. The supervisor spends approximately half of his day walking and checking his employees, and the other half seated in an underground lunchroom/office completing office functions.

Description of Database

The database for statistics of traumatic injuries was formed from the investigation reports received and entered into the computer by statistical clerks at the MAPAO. The information recorded on the investigation report includes medical aid (MA) injuries (with no lost time from work), lost time (LT) injuries, and fatalities. Prior to 1984 the accident forms were identical to those used by the Workers' Compensation Board to award compensation funds. These forms provided very little detail with respect to accident causes. A new accident investigation form was implemented in 1984 to provide more causative information than was previously collected. Training courses were organized by the MAPAO within mines across Ontario to standardize the procedures for recording information.

The accident and injury information was retrieved from the database according to the four comparative occupation groups outlined above. The database for statistics of traumatic injuries provided tabulations of injury frequency and percentages of total accidents. Figure 2 summarizes the six categories from which frequency data were utilized for this analysis, including; part of body injured, task (e.g. handling material, operating mobile equipment), nature of injury (e.g. ache/pain, sprain/strain), accident type (e.g. struck by falling object, overexertion push/pull), contributing factors (e.g. inattention, posture, equipment/tool design), and underlying factors (e.g. knowledge/skill, physical fitness suspect).

There are a number of limitations associated with the MAPAO database. First, the categories are definitive, which means that all accidents and injuries are slotted into one of a list of predetermined types. Second, the information obtained depends heavily on the completeness and accuracy with which the accident investigation form is prepared at the mine site. Third, the form is then handled through a number of stages including nurse or first aid attendant, supervisor, MAPAO clerks who code the information, and finally data entry operators who computerize the information. Interpretation takes place at each step and the possibility of error is apparent. Finally, a general concern for all accident/injury data is the amount of under-reporting of injuries. A 12 month retrospective review of incident reports at Centenary Acute Care Hospital in Toronto revealed that only 57% of the incidents were reported estimating the extent of under-reporting at the mine sites under investigation.

STATISTICS FOR TRAUMATIC INJURIES - PERIOD ________ TO ________

ANALYSIS FOR ______________ MINE

COUNT OF CLAIMS: Medical aid only
Lost Time
Fatal
TOTAL

PART OF BODY	#	%
back		
eye		
neck		
finger		
hand		
multiple		
shoulder		
chest		

TASK	#	%
handling material		
travel to/from work		
mucking		
operating mobile equip.		
drilling		
rockbolting		

NATURE OF INJURY	#	%
ache/pain/swelling		
crushing/bruise		
cut/puncture		
scratches/abrasions		
sprain/strain		
multiple		
fracture		

ACCIDENT TYPE	#	%
struck by falling object		
struck against stationary object		
overexertion lifting		
caught between moving/stationary object		
sudden start/stop		
involuntary reaction		
struck by falling object		
fall same level		
overexertion push/pull		
fall from stationary vehicle		

CONTRIBUTING FACTOR	#	%
improperly completed		
inattention/careless		
rules/procedures not specified		
position/posture		
surface slippery		
surface rough		
equipment heavy (>20 kg)		
action of others		

UNDERLYING FACTORS	#	%
knowledge/skill		
preventative maintenance		
person's attitude		
equipment/tool design		
physical fitness suspected		
recurrence		
location deficiency		

Figure 2: MAPAO Database Categories

Data Analysis

The database did not include any denominator data (i.e., the number of LHD operators employed in all firms). The personnel departments in each of the thirty-two mines in Ontario were contacted. A set of standardized definitions for each occupation group was used and the following information was requested for 1984 and 1985: number of LHD operators; number of office workers; number of underground supervisors; and number of underground miners. It was not necessary to calculate person-hours since mine workers are unlikely to vary their number of work hours in a given year and transient workers are rare.

The frequencies and the denominator data were utilized to compute incidence rates for LHD operators and each of the control groups for each of the six investigation form classifications. Incidence rates were expressed as shown in the following example:

$$\frac{\text{number of back injuries in LHD operators in 1984}}{\text{total number of LHD operators employed in 1984}} \times 1000$$

The incidence rate was then compared with the corresponding incidence rate of other groups. For example:

$$\frac{\text{number of back injuries in all mineworkers in 1984 (excluding LHD operators)}}{\text{total number of mineworkers (excluding LHD operators) in 1984}} \times 1000$$

The incidence rate for LHD operators was divided by the incidence rate for all other mine workers in order to yield an index of relative risk (RR). A relative risk of 1.0 would suggest that the risk of back injuries is the same for LHD operators as for other mine workers, while a relative risk of 3.0 for example, would suggest that LHD operators have three times the risk of back injuries than for all other mine workers.

Using incidence rate and relative risk calculations the rate of accident types, part of body injured, nature of injuries, etc. in LHD operators were compared with those of all mineworkers, office workers, and underground supervisors.

Rationale for Choice of Index

Comparing accident and injury frequencies, or percentage ratios without denominator data may be misleading since the four comparative occupation groups vary with respect to total number of workers employed, and also with respect to the nature and types of accidents and injuries incurred. An incidence rate measures the number of accidents/injuries in a given time period, and is adjusted to reflect a given number of workers. The denominator base (number of workers) allows accurate comparison between groups. Incidence rates are then direct indicators of risk in a population. Ranking jobs on the basis of incidence rates (over other indices) better utilizes the accident and injury data, and emphasizes jobs that tend to be more hazardous (Anderson, *et al.*, 1985).

The major advantage of comparing the incidence rates in LHD operators with the total population of mine workers (excluding LHD operators) is in minimizing the "healthy worker effect" (Mausner & Kramer, 1985). If a general population rate of back injuries were used instead, it would include individuals who are too sick to work. The very fact of employment implies a certain level of health. Because the database yields the entire population of each occupation type and all occupations combined, there was no possibility of error due to sampling. Therefore, it is not necessary to employ statistics to determine whether a particular risk was greater than that expected by chance. If a difference in relative risk is found in LHD operators as compared to other groups, this represents a true difference for that particular year. Comparison of relative risks between the two years helps to establish if this difference may be due to an unusual occurrance in that particular year such as a change in technology, work schedule, or the threat of a strike.

Cost Analysis

The incidence rates simply provide information about the relative frequency of injuries. It may be that the incidence rates are similar between occupations but the severity or number of days lost per injury is quite different. Information concerning the days lost per injury cannot be obtained from the accident investigation form. An analysis of the injury costs, however, will reflect the severity. Mine A and Mine B employ a large population of LHD operators. The approximate dollar costs for LHD operator injuries in these two mines were calculated from information obtained from the Ontario Workers' Compensation Board. The percent of total Workers' Compensation costs which were paid to LHD operators for accidents and injuries in Mine A and Mine B was compared with the percent of employees who were LHD operators at each mine..

Results

The denominator data obtained from the personnel department in each of the thirty-two mines are displayed in Table 2. Of approximately 28,000 Ontario mine workers in 1984 and 1985, 584 were LHD operators, 10,357 were underground miners, 2,071 were office workers and 743 were underground supervisors. Nine of the thirty-two mines either did not employ LHD operators or did not have a job listing for LHD operators. In these mines, an LHD machine may be operated by an underground miner for part of a shift, but there were no permanent full shift LHD operators. The numbers are, in most cases, an approximation since miners change jobs and mines, and the number of operators may vary slightly within a given year. There was no definitive data on the number of days, or the number of hours per day worked by LHD operators for calculation of person-hours of exposure. There were however,

Table 2. Average number of workers in four occupation groups for all Ontario mines in 1984 and 1985.

Ontario Mine	Occupation			
	Underground Miners	LHD Operators	Office Workers	Underground Supervisors
Adams Mine	0	0	12	0
Agnico-Eagle	40	0	4	7
Algoma Ore	66	0	30	0
Campbell	210	0	10	16
Canadian Gypsum	55	0	15	8
Canadian Salt	75	16	15	8
Chromasco	0	0	66	0
Denison	1059	71	111	95
Detour Lake	0	0	36	0
Dickenson	135	0	37	16
Dome	350	30	48	31
Domtar-Sifto Salt	285	0	16	13
Domtar-Gypsum	69	9	4	6
Falconbridge	1374	55	112	108
Inco Metals	3443	126	461	136
Indusmin	0	0	17	0
Kerr Addison	192	0	19	15
Kidd Creek	691	100	390	50
Lac Minerals-Marathon	104	20	43	9
Lac Minerals-Macassa	166	0	22	11
Lac Minerals-Lakeshore	27	0	0	4
Mattabi	220	51	43	20
McBean	0	0	4	0
Noranda-Geco	305	14	84	26
Hemlo	55	9	10	5
Pamour	239	19	46	26
Renabie	93	12	8	7
Rio Algom	998	46	217	117
Sherman	0	0	84	0
Steetley Talc	0	0	11	0
Teck Corona	80	0	26	6
Westroc	26	6	3	3
Total	10357	584	2071	743

no major layoffs or strikes during the 1984 and 1985 period, and the number of workers in each group should therefore be representative of a normal working year.

Tables 3 through 8 display the incidence rate in each occupational category for part of body injured, task, nature of injury, accident type, contributing factor, and underlying factor as calculated from the compiled database on accident investigations and from the denominator data in Table 2.

Table 3 displays the "part of body" data. The incidence rates for LHD operators were similar between 1984 and 1985, with the exception of finger, shoulder and chest injuries. The incidence of both finger and shoulder injuries increased in 1985 in all three underground occupation groups. The incidence of chest injuries decreased in 1985 for all underground occupation groups. The highest incidence rate in all occupations was for back injuries. The back injury incidence for LHD operators was slightly less than for underground miners (relative risk average for 1984-1985 RR=0.87), but was much higher than for office workers (RR=5.2), or for underground supervisors (RR=2.0). The averaged 1984-1985 incidence rate for neck injuries in LHD operators was 18.0. This was not listed in the 10 most frequent occurrences for other underground miners. Multiple injuries also did not rank in the top 10 for underground miners, but LHD operators had an incidence of 8.6 in both years.

In Table 4, the incidence rates for the "task" performed while injured are listed. The most frequent tasks for injury in LHD operators were "mucking"[1] and "operating mobile equipment"[2]. The combined incidence rate for these two tasks in which the operator is in his normal seated position was 87.4. The third highest incidence rate was for "handling material". For underground miners, the most frequent task for injury was "drilling", followed closely by

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[1]General term for filling the bucket with rock and driving with a full bucket

[2]Operator may be driving with an empty bucket, or using the LHD to transport equipment/materials

Table 3. Analysis of accident and injury incidence rates by part of body injured for 1984 and 1985.*

Part of body		Occupation			
		LHD Operator	Underground Miner	Office Worker	Underground Supervisor
Back	1984	32.5	41.5	7.2	12.2
	1985	30.8	32.1	7.2	24.2
Eye	1984	20.5	18.6	2.9	----
	1985	18.8	19.4	3.4	----
Neck	1984	20.5	----	1.9	2.7
	1985	15.4	----	1.9	5.4
Finger	1984	10.3	25.7	4.8	6.7
	1985	20.5	34.7	4.8	16.2
Hand	1984	10.3	11.9	2.4	----
	1985	10.3	11.8	2.4	4.0
Multiple	1984	8.6	----	3.4	4.0
	1985	8.6	----	4.8	4.0
Shoulder	1984	----	7.8	2.4	----
	1985	12.0	8.4	1.9	2.7
Chest	1984	12.0	8.6	----	4.0
	1985	6.8	7.4	----	----

*Incidence Rate = $\frac{\text{number of injuries among workers in given year}}{\text{total number of workers exposed in same year}}$ X 1000

----Not among 10 most frequent occurrences of injury in that year and therefore not listed by computer print-out

Table 4. Analysis of accident and injury incidence rates by task for 1984 and 1985.*

Task		Occupation			
		LHD Operator	Underground Miner	Office Worker	Underground Supervisor
Handling Material	1984	27.4	23.9	9.7	6.7
	1985	17.1	27.8	10.6	18.8
Travel to/ from work	1984	15.4	----	8.2	8.1
	1985	6.8	11.9	8.7	13.5
Mucking	1984	42.8	----	----	----
	1985	42.8	----	----	----
Operating Mobile Equipment	1984	37.7	----	----	----
	1985	51.4	----	----	----
Drilling	1984	----	32.9	----	----
	1985	----	28.1	----	----
Rock-bolting	1984	----	16.6	----	----
	1985	----	13.1	----	----

$$\text{*Incidence Rate} = \frac{\text{number of injuries among workers in given year}}{\text{total number of workers exposed in same year}} \times 1000$$

----Not among 10 most frequent occurrences of injury in that year and therefore not listed by computer print-out

"handling material", and then "rockbolting". The incidence rate for "handling material" was higher among LHD operators than among underground miners in 1984. However, this trend reversed in 1985 and the overall combined 1984-1985 incidence was higher for underground miners (RR=1.2). The incidence of "drilling" and "rockbolting"[3] among miners did not approach the incidence of "mucking" and "operating mobile eqiupment" among LHD operators.

Table 5 displays the "nature of injury" data. All groups remained fairly consistent between 1984 and 1985. The highest incidence among all groups was "ache/pain/swelling" with at least three times the incidence rate of other categories. The incidence rate for "ache/pain/swelling" among LHD operators was similar to that of underground miners (RR=1.1), but much higher than that of office workers (RR=6.5), and underground supervisors (RR=2.9). The subsequent nature of injury categories include "crush/bruise", "cut/puncture", "scratches/abrasions, and "sprain/strain"; all of which were slightly less for LHD operators than other miners. Multiple injuries were higher among LHD operators than miners (RR=2.0), but fractures were lower (RR=0.55).

Table 6 displays the "accident type" data. For LHD operators, the highest averaged 1984-1985 incidence was for "sudden start/stop" which did not occur in the 10 most frequent accident types for the other groups. LHD operators also experienced "falls from stationary vehicle" accidents which did not occur in other groups. High incidence rates were found for "struck by falling object", "struck against static object", and "caught between moving and stationary object". These three accident types were also frequent in miners since both groups are vulnerable to falls of ground, and to moving equipment and machinery. The highest two accident types for underground miners were "struck by a falling object" and "overexertion lifting". LHD operators were not completely removed from materials handling tasks but their incidence rate for "overexertion lifting" was much lower (RR=0.5). The remaining accident

[3]To drill a hole in rock and fill it with a steel bolt to support the rockface

Table 5. Analysis of accident and injury incidence rates by nature of injury for 1984 and 1985.*

Nature of Injury		Occupation			
		LHD Operator	Underground Miner	Office Worker	Underground Supervisor
Ache/Pain/	1984	89.0	79.2	14.0	25.6
Swelling	1985	83.9	72.4	13.0	37.7
Crushing/	1984	32.5	35.4	2.9	6.7
Bruise	1985	25.7	32.3	6.3	6.7
Cut/	1984	29.1	33.9	6.8	9.4
Puncture	1985	24.0	31.3	7.2	17.5
Scratches/	1984	27.4	21.0	3.4	----
Abrasions	1985	17.1	21.0	3.9	2.7
Sprain/	1984	17.1	22.1	6.8	8.1
Strain	1985	15.4	24.9	4.3	9.4
Multiple	1984	5.1	2.1	0.97	2.7
	1985	6.8	4.1	1.45	4.0
Fracture	1984	3.4	7.5	0.97	2.7
	1985	5.1	8.0	0.97	6.7

$$*\text{Incidence Rate} = \frac{\text{number of injuries among workers in given year}}{\text{total number of workers exposed in same year}} \times 1000$$

----Not among 10 most frequent occurrences of injury in that year and therefore not listed by computer print-out

Table 6. Analysis of accident and injury incidence rates by accident type for 1984 and 1985.*

Accident type		Occupation			
		LHD Operator	Underground Miner	Office Worker	Underground Supervisor
Struck by falling object	1984	25.7	26.9	2.4	5.4
	1985	13.7	27.8	----	----
Struck against stationary object	1984	15.4	13.5	3.4	2.7
	1985	8.6	7.9	1.4	5.4
Overexertion lifting	1984	6.8	18.7	3.9	4.0
	1985	8.6	13.5	2.4	10.8
Caught between moving and stationary object	1984	6.8	10.7	----	----
	1985	8.6	7.9	1.9	2.7
Sudden start/ stop	1984	27.4	----	----	----
	1985	22.3	----	----	----
Involuntary Reaction	1984	15.4	11.8	4.3	6.7
	1985	----	11.2	2.4	6.7
Struck by flying object	1984	----	10.6	1.9	2.7
	1985	18.8	15.4	2.4	2.7
Fall on same level	1984	6.8	10.2	2.9	5.4
	1985	----	8.0	6.8	5.4
Overexertion push/pull	1984	----	8.8	0.97	----
	1985	----	8.6	----	5.4
Fall from stationary vehicle	1984	6.8	----	----	----
	1985	8.6	----	----	----

$$\text{*Incidence Rate} = \frac{\text{number of injuries among workers in given year}}{\text{total number of workers exposed in same year}} \times 1000$$

----Not among 10 most frequent occurrences of injury in that year and therefore not listed by computer print-out

types were inconsistent from year to year.

Table 7 displays the "contributing factors" data. A number of contributing factors were common to all occupational groups including; "improperly completed", "inattention/careless", "rules/procedures", "position/posture", and "surface slippery". LHD operators had a lower incidence rate than miners for "inattention/careless" (RR=0.75). The contributing factor "surface rough" had a high incidence rate among LHD operators but was not a factor for other occupations. Conversely, "equipment heavy" was a factor for miners but not in the top 10 occurrences for LHD operators.

"Underlying factors" (Table 8) which may contribute to an accident or injury are often difficult to determine, even with a detailed accident investigation. Since this new investigative procedure and accident form only came into use in 1984, many forms are incomplete in this category of information. This results in low, and possibly misleading, incidence rates. Therefore, Table 8 may not be representative of all underlying factors.

Examination of accidents and injuries occurring to all LHD operators in Ontario (population total=584) in 1984 revealed that there were 80 medical aid injuries, 28 lost time injuries and 2 fatalities. In 1985 there were 85 medical aid injuries, 11 lost time injuries, and 1 fatality. The incidence per 1,000 workers of overall injury in LHD operators was compared to underground miners (excluding LHD operators), office workers and underground supervisors in Table 9. The likelihood of injury to an LHD operator was almost identical to that of other underground workers and remained fairly stable over the two years. However, the relative risk for LHD operators compared to underground supervisors was 3.0. Compared to office workers, the relative risk for LHD operators was 5.0.

The LHD operator injury costs from the Workers' Compensation Board statistics in Mine A and Mine B (see 'Methods' for clarification) in 1984 and 1985 are tabulated in Table 10.

Table 7. Analysis of accident and injury incidence rates by contributing factor for 1984 and 1985.*

Contributing Factor		Occupation			
		LHD Operator	Underground Miner	Office Worker	Underground Supervisor
Improperly completed	1984	34.2	38.4	3.9	5.4
	1985	29.1	34.6	5.8	16.2
Inattention Careless	1984	30.8	38.9	5.3	10.8
	1985	24.0	33.4	4.8	26.9
Rules/ procedures	1984	29.1	26.2	2.4	8.1
	1985	10.3	17.8	2.9	5.4
Position/ posture	1984	22.3	23.2	2.9	----
	1985	17.1	16.1	2.4	6.7
Surface slippery	1984	12.0	10.5	2.9	6.7
	1985	12.0	10.4	5.8	9.4
Surface rough	1984	15.4	----	----	2.7
	1985	8.6	----	----	----
Equipment heavy (20 kg)	1984	----	9.8	2.4	----
	1985	----	12.3	----	6.7
Action of others	1984	----	9.9	1.9	4.0
	1985	----	----	----	6.7

*Incidence Rate = $\frac{\text{number of injuries among workers in given year}}{\text{total number of workers exposed in same year}} \times 1000$

----Not among 10 most frequent occurrences of injury in that year and therefore not listed by computer print-out

Table 8. Analysis of accident and injury incidence rates by underlying factor for 1984 and 1985.*

Underlying factor		Occupation			
		LHD Operator	Underground Miner	Office Worker	Underground Supervisor
Knowledge/ skill	1984	5.1	3.7	0.5	4.0
	1985	5.1	4.8	0.5	1.3
Preventative maintenance	1984	5.1	1.1	----	----
	1985	3.4	1.5	1.0	----
Person's attitude	1984	3.4	4.8	1.5	1.3
	1985	6.8	6.5	0.5	----
Equipment/ tool design	1984	3.4	4.2	0.5	----
	1985	12.0	5.1	2.5	4.0
Physical fitness suspect	1984	1.7	2.3	----	2.6
	1985	----	1.9	1.0	1.3
Reccurrence	1984	1.7	6.9	0.5	1.3
	1985	3.4	4.6	1.0	2.6
Location deficiency	1884	----	0.77	----	----
	1985	8.6	2.7	2.0	----

$$\text{*Incidence Rate} = \frac{\text{number of injuries among workers in given year}}{\text{total number of workers exposed in same year}} \times 1000$$

----Not among 10 most frequent occurrences of injury in that year and therefore not listed by computer print-out

Table 9. Analysis of overall accident and injury incidence rate by occupation for 1984 and 1985.*

Occupation	Year 1984	Year 1985
LHD Operator	190	170
Underground Miner	193.3	173.5
Office Worker	35	36.7
Underground Supervisor	48	84.8

$$\text{*Incidence Rate} = \frac{\text{number of injuries among workers in given year}}{\text{total number of workers exposed in same year}} \times 1000$$

The total injury cost was divided by the total amount of compensation dollars paid out to that particular mine's employees in each year. This yields a percent of WCB funds which were distributed to injured LHD operators per mine. This percentage may be compared to the percentage of workers at each mine who are LHD operators. However, the sum paid by the WCB includes not only accident and injury costs for injured LHD operators of the current year, but costs carried over from LHD operators remaining on lost time from previous years, and capitalized pensions.

Table 10 reveals that at Mine A in 1984, 3.6% of the compensation dollars were paid out to LHD operators, who represent 3.18% of the mine's employees. In 1985, this increased to 5.4% of the compensation dollars for LHD operators, who were 3.38% of the mine's employees. Of the $92,980 paid to LHD operators in 1984, 53% was for back injuries. There were no lost time neck injuries in that year. In 1985, $165,136 was paid to LHD operators, 14% for back injuries and an additional 28.5% for neck injuries. Mine B's overall compensation costs are a quarter of Mine A's. However, the sum paid to LHD operators was 10.6% of the total compensation dollars, while the percentage of LHD operators remained at 3.6%. There were no lost time neck injuries and back injuries represented a smaller proportion of the costs at Mine B; 17% in 1984 and 28% in 1985. At Mine B especially, the cost of injuries to LHD operators is higher than expected based on the proportion of workers who are LHD operators. At Mine A, the most costly injury is to the back and neck.

Discussion

The overall accident and injury incidence as well as the incidence of injury to the back, eyes, and hands among LHD operators were similar to that of underground miners. The types of accidents however, were different. This was expected since the two occupations

Table 10. Analysis of LHD Operator accident and injury costs from Ontario Workers' Compensation Board for Mine A and Mine B in 1984 and 1985.

Year	1984		1985	
Mine	A	B	A	B
Number of LHD injuries	23	3	19	9
Cost of LHD injuries	$92,980	$54,044	$165,136*	$77,528
Total Compensation costs	$2,612,756	$790,988	$3,034,079	$730,222
Percent of Compensation costs paid to LHD operators	3.6%	6.8%	5.4%	10.6%
Percent of employees who are LHD operators	3.18%	3.6%	3.38%	3.6%

*Excluding costs of 1 fatality at Mine A contain quite different job functions, even though both groups are exposed to the underground environment. The office workers, although seated, are free of many of the typical underground injury types such as "struck by falling object" and "caught between moving/stationary object". The most frequent part of the body injured for office workers was also the back. The most frequent nature of injury was "ache/pain/swelling", and "handling material" was the most frequent task. Underground supervisors were exposed to all of the underground hazards of LHD operators, but not to the physical work suspected of contributing to many of the accidents and injuries in underground miners. The most frequent part of body injured for supervisors was also the back, followed by the finger. "Handling material", and "travel to and from work" were the most frequent tasks, "ache/pain/swelling" was the most frequent nature of injury, while "overexertion lifting" and "involuntary reaction" were the most frequent accident types. It clearly seems that the types of accidents and contributing factors among LHD operators are unique to their job demands.

From the data presented, a summary can be made of the more common accidents and injuries experienced by LHD operators. The majority of accidents and injuries occurred while "mucking" or "operating" the LHD vehicle. The accident types were most often "sudden start/stop" and "falls from a stationary vehicle", with the "surface rough" as a contributing factor. The most common nature of injuries was "ache/pain/swelling". The most frequent injury sites were the back, eye, neck and finger. A smaller proportion of injuries occurred due to being "struck by a falling object", "struck against a static object", or "caught between a moving and stationary object". It is likely these more traumatic injuries accounted for the "crushing/bruising", "cut/puncture", "scratches/abrasions" nature of injuries. These injuries were more likely to occur to eyes, fingers, hands, and multiple body sites.

The back injury incidence was similar between LHD operators and other underground miners. An underground miner performs a wide variety of functions, most of which involve heavy materials handling and strenuous physical work (a jackleg drill weighs 100–120 lbs.). A LHD operator, on regular duty, performs very little lifting and handling. There may be occasion once a day when an LHD operator stops and helps another underground worker with a manual task or loads some equipment into his LHD. The similar back injury incidence was likely due to a different cause. The LHD operator spends approximately 5.5 hours per day seated in his LHD vehicle (time–motion data displayed in Table 17 and 18). Another half hour was spent cleaning and servicing the vehicle. The remaining two hours can be accounted for by lunch, getting to and from the worksite including the ride down in the cage, receiving instructions from a supervisor and getting changed before and after shift. The incidence of back injuries among office workers who are predominately seated is less than one–quarter that of LHD operators but the seated work environment is not comparable. The incidence of back injuries for all workers employed in Ontario in 1983 was 14 per 1000 workers (Bombardier *et al.*, 1985). The office workers investigated had an incidence rate which was half of this, but the underground miners and LHD operators had an incidence rate more than two times the overall Ontario rate for workers. The occupations with the highest back injury incidence rates in Ontario in 1983 were machining and metal shaping and transportation operating (29 per 1000 workers). This is still slightly lower than the incidence rates for LHD operators (31.65) and underground miners (36.8).

Vibration, per se, is not listed anywhere on the accident investigation form since it is an unknown causative factor in accidents and injuries. If the driver's perception of machine jolting during operation was thought to play a part in the accident or injury, the closest categorizations are "sudden start/stop", and "surface rough". Both of these categories had high incidence rates for LHD operators. In a recent U.S. study analyzing back injuries in underground coal mines (Plummer *et al.*, 1986) three groups of vehicle operators were found to be highly susceptible to back injuries; continuous miner car, shuttle car, and motor car.

The authors found 15.6% of injuries among these drivers classified as "riding" and a further 3% classified as "operating a machine". It is reasonable to assume that the vibration and jolting of LHD operation may be contributing to the incidence of back injuries among LHD operators.

The incidence of neck injuries among LHD operators was found to be high. This was the only category in which the LHD operator differs dramatically from other underground workers. Neck injuries were not among the ten most frequent body parts injured for other underground miners. It should be noted that the LHD operator is not facing his direction of travel, but rather sits sideways in the vehicle with his head and neck turned to the side. When filling the LHD bucket with ore the operator faces the bucket to scoop the ore, but turns 180° to face the rear of the machine to back up and prepare to scoop forward again. There is a continual turning of the head and neck from side to side. Half of the driving time would be in the machine rear direction and the other half in the bucket direction, both necessitating extreme head and neck postures. Seidel & Heide (1986) report a high incidence of neck disorders associated with a lower intensity of WBV suggesting that non-vibration related conditions dominate as causes for the neck problems. It cannot be ascertained whether WBV is the cause of the high incidence of neck injuries, or whether it is the strained work posture. It may be a combination of both poor posture and WBV.

The cost levied on individual mining companies by the WCB for back injuries is extreme. In 1983 an average back injury in Ontario had an estimated compensation cost of $8,000 (Bombardier *et al.*, 1985). The mean duration of time off work with a back injury claim was 55.2 days, while the time off work for all injury claims combined was 39.8 days. At Mine A in 1984, 53% of the approximately $93,000 paid by the WCB to LHD operators was for back injuries. In 1985, 42.5% of $165,000 was paid to LHD operators for back and neck injuries combined. The costs dramatize the seriousness of the back injury problem and necessitate a continuing effort to disclose the factors which may be responsible for high back and neck injury rates among LHD operators.

A major shortcoming of accident and injury data, especially with respect to the back, is that injuries are not representative of pain. Cumulative back pain which is not related to a traumatic incident may not show on accident data (Riihimaki, 1985). Riihimaki (1985) in a study of back pain and heavy construction work estimated that the proportion of current attacks of back pain, which are associated with an accident, heavy lifting or some unaccustomed activity, varies from 20 to 50%.

In 1984–1985 the MAPAO conducted a Miners' Back Care Program across several mines in Ontario with full participation from hourly employees. Workers participating in the program were required to fill out a questionnaire asking for occupation, lost time back injuries, attacks of back pain, etc. A total of 1,898 forms were collected from Mine A and 2,373 from Mine B. When the LHD operators were separated from the rest, 39% at Mine A and 41.5% at Mine B reported having had at least 1 lost time back injury while working in this occupation. When asked about significant back pain, 51% at Mine A and 54.7% at Mine B reported having back pain (MAPAO Internal Reports, 1985). In these two mines we can see a much higher incidence of back pain and injury than was displayed in a yearly accident and injury rate.

Many studies have established a relationship between WBV and possible back disorders (Dupuis & Zerlett, 1986). However, the intensity and duration of WBV exposure on a daily and yearly basis, as well as over an entire occupational life are not well defined. It has not been possible as yet to estimate the minimum exposure time to WBV before back problems begin to occur with a higher prevalence than expected. In individual cases it is difficult to prove that degenerative changes in the spine are causally related to WBV because changes in the spine are expected as a result of normal ageing, wear and tear. When degenerative changes of the spine are found to occur in young people who have been exposed to high level WBV, it is easier to suspect WBV as the cause (Dupuis & Zerlett, 1986).

A recent review (Hulshof & vanZanten, 1987) critically evaluated the literature with respect to the health effects of occupational exposure to WBV. The authors concluded that since almost all studies, particularly those with better methodology, showed a strong tendency in a similar direction, long-term exposure to WBV may be harmful to the spinal system (Hulshof & vanZanten, 1987). However, firm conclusions on exposure-response relationships cannot yet be drawn. The quality and quantity of the available exposure data constitute the weakest part of most studies (Hulshof & vanZanten, 1987).

In 1980, the U.S. Bureau of Mines sponsored a Human Factors Analysis across mines to produce a list of critical human factor problems in mining (Crooks *et al.*, 1980). The authors analyzed the accident and injury data; then critical operations were rated based on health, safety, productivity and comfort. A list of 10 problem areas were derived based on frequent accident/injury occurrence across a large number of operations or having potentially serious consequences. Three of the 10 problem areas sited relate directly to LHD operation; vibration, control design and restrictive operator compartment (Crooks *et al.*, 1980).

The 1984–1985 accident and injury data on LHD operators showed three fatalities. There were a total of eight fatalities in underground mining during those two years. The fatality incidence for LHD operators is 5.13 compared to 0.77 for all underground miners. This represents a RR of 6.7 for LHD operators. A study by the U.S. Department of the Interior (McLellan & Speirer, 1973) found LHD's to be one of the three types of mining equipment most frequently involved in haulage fatalities. In underground coal mines in the U.S. between 1971 and 1973, 33 operators were killed in LHD's and tractors (McLellan & Speirer, 1973).

All of the accidents were related to crushing of the operator and usually involved injuries to the head, neck or chest. This information should provide a warning signal of the serious potential of injury in LHD's. This investigation has shown two of the three LHD fatalities in Ontario mines during 1984-1985 related to falls of ground and crushing, and many accidents and injuries due to being "struck by falling objects" causing "crushing/bruising", "cut/puncture", and "scratch/abrasion" injuries. The potential for fatalities in LHD operators should be an area of more detailed analysis.

CHAPTER V

VIBRATION MEASURES

Introduction

Studies of WBV measured in off-road vehicles (tractors, construction machinery, forestry equipment) all report levels exceeding the ISO standards for decreased proficiency (Wasserman *et al.*, 1978; Hansson & Wikstrom, 1981; Crolla *et al.*, 1984). Preliminary investigations of mining equipment used in Noranda Mines revealed high levels of WBV in underground mining equipment as well (personal communication), however, there were methodological and equipment problems associated with testing. LHD operators are very aware of the vibration and jolting in the LHD vehicles and complain of back problems to management. The incidence of back injury was found to be similar in LHD operators compared with other underground workers even though LHD operators are seated and driving the vehicle for the majority of the workshift. Management and workers were interested in determining typical WBV levels from LHD vehicles and comparing these levels with the ISO Standards (2631, 1978) for WBV. If WBV levels were found to exceed the standards then methods could be considered for reducing the WBV.

In order to test the hypothesis that LHD operators are exposed to WBV within the frequency range of 1–10 Hz which exceeds the ISO Standards (2631) daily exposure limit, it was decided that WBV measurements would be taken in two separate mines. This would allow consideration for different rock and road variables which may affect WBV levels. Management from two of the larger Ontario mines volunteered to participate in this investigation. Both mines have a large population of LHD operators (Mine A=71 and Mine B=100) with a combined total of approximately 30% of LHD operators in Ontario. The mines were in different geographical locations and in different rock types. The mines also varied with respect to mining technique, road design and road terrain. At Mine A the roads were loose gravel which was regularly graded, while at Mine B some roads were cemented with a crushed rock slurry. Measuring WBV at two different sites would give a representative view of the overall WBV levels to which LHD operators may be exposed.

Three different LHD vehicles of different capacity and structural size were found in use at each of the mines. The bucket capacity distinguished the size of the LHD vehicle. At Mine A there were 3.5 cubic yd 'Wagner' LHD vehicles (145 horsepower), 6 cubic yd 'Jarvis Clark' LHD vehicles (215-230 horsepower), and 8 cubic yd 'Wagner' LHD vehicles (240 horsepower). At Mine B there were similar 'Wagner' 3.5 yd and 8 yd LHD vehicles and also 'Wagner' 5 cubic yd LHD vehicles (200 horsepower). The particular vehicles tested were chosen by management, based on their availability. In order to look for differences between machine sizes an attempt was made to measure the vibration in a sample of each LHD vehicle size. Where possible, two machines were measured over the same road conditions. In order to minimize operator variables the same two operators, where possible, drove each of the LHD vehicles at each mine site.

Methods

At Mine A vibration measures were recorded on two separate LHD machines in each of the following machine sizes; 3.5 yd, 6 yd, and 8 yd. The same two operators drove each of the six machines and the same underground test area was used in each of the trials. At Mine B, vibration measures were recorded on two separate machines in each of the following machine sizes; 5 yd, and 8 yd. Only one 3.5 yd machine was available and the tape recorder malfunctioned the day this machine was tested. The tape recorder had to be returned to the manufacturers for repair and was not available for a number of weeks. It was impractical to return to the mine for testing of only one vehicle. No recorded measures were therefore available for frequency analysis on the 3.5 yd machine but vibration meter levels were intact. Each of the five machines were driven by two operators, but a total of six different operators were utilized. The same test area was not available for each trial, and hence measurements were made in similar work areas on three different underground levels. Table 11 summarizes the test machines and operators at the two mines.

Tire pressures on each machine were measured by a mechanic and maintained within normal ranges during testing, and the seating/suspension designs were similar. The operators were all experienced drivers and were chosen by management. The operators' weight, height, age, and years of experience were recorded prior to the test. The vehicle speed, which depends mostly on road conditions, was recorded during the analysis. Operators were instructed to drive the LHD machines as they would on a normal workshift. The test areas chosen in each mine were similar, and typical, with respect to road conditions. Vibration measures were sampled for the full duration of each of the following five task conditions;

1. idling (with operator in seat)
2. mucking (loading the machine)
3. driving full (hauling ore)
4. dumping
5. driving empty

The average daily exposure times for each of the above five task conditions were obtained from the Industrial Engineering Department at each Mine site. In addition, exposure times were recorded during vibration testing for each of the five tasks.

Table 11. Whole body vibration vehicle test design.

MINE SITE	LOAD-HAUL-DUMP (LHD) VEHICLES TESTED Vehicle size (cubic yardage)*							
	8 yd		6 yd		5 yd		3.5 yd	
MINE A								
Machine	A	B	C	D			E	F
Operator	1, 2	1, 2	1, 2	1, 2			1, 2	1, 2
Mine B								
Machine	G	H			I	J	K	
Operator	3, 4	5, 6			7, 6	7, 6	8, 6	

*Bucket capacity typically depicted as cubic yardage (yd) in vehicle designation.

Vibration Measuring Equipment

A triaxial seatpan accelerometer (Bruel & Kjaer (B & K) type 4322) housed in a flexible rubber pad was strapped to the seat securely in accordance with the three perpendicular directions (see Figure 3) as described in ISO 2631 (1978). The seatpan simply sits between the seat and the operator. This apparatus does not interfere with driver tasks and complies with the ISO Standards 2631 (1978) for whole body vibration measurement from a seated posture. In an LHD machine, because of the operator's sideways orientation, the y-direction is the forward to reverse direction of machine travel (See Figure 3). The three accelerometers were connected to three Human Response Vibration Meters (B & K type 2512). The meters were calibrated for each of the three x, y, or z vibration axes. The vibration meters provided an instantaneous maximum peak vibration level over a chosen measurement period, and the root mean square (RMS) vibration average (Leq) over the same measurement period, expressed as a decibel ratio:

$$Leq = 20 \log \left[\frac{1/T \int a^2(t)\, dt}{10^{-6}} \right]^{1/2}$$

where Leq is in dB re 10^{-6} m.s^{-2}, T is the averaging time in minutes, and $a^2(t)$ is the square of the instantaneous frequency weighted acceleration in m.s^{-2}. The Leq is continuously calculated from the beginning of the measurement period and an updated level is displayed every eight seconds. The range of the vibration meter Leq calculator is from 104–134.5 dB (0.16–9.4 m.s^{-2}), and the accuracy is within $\pm$0.5 dB according to the manufacturer's specifications. The range for the peak detector is from 100–146 dB (0.1–20 m.s^{-2}), with an accuracy of $\pm$1.0 dB. The vibration meter incorporates two frequency weighting filters in accordance with the ISO 2631 (1978) which best approximates the human response to

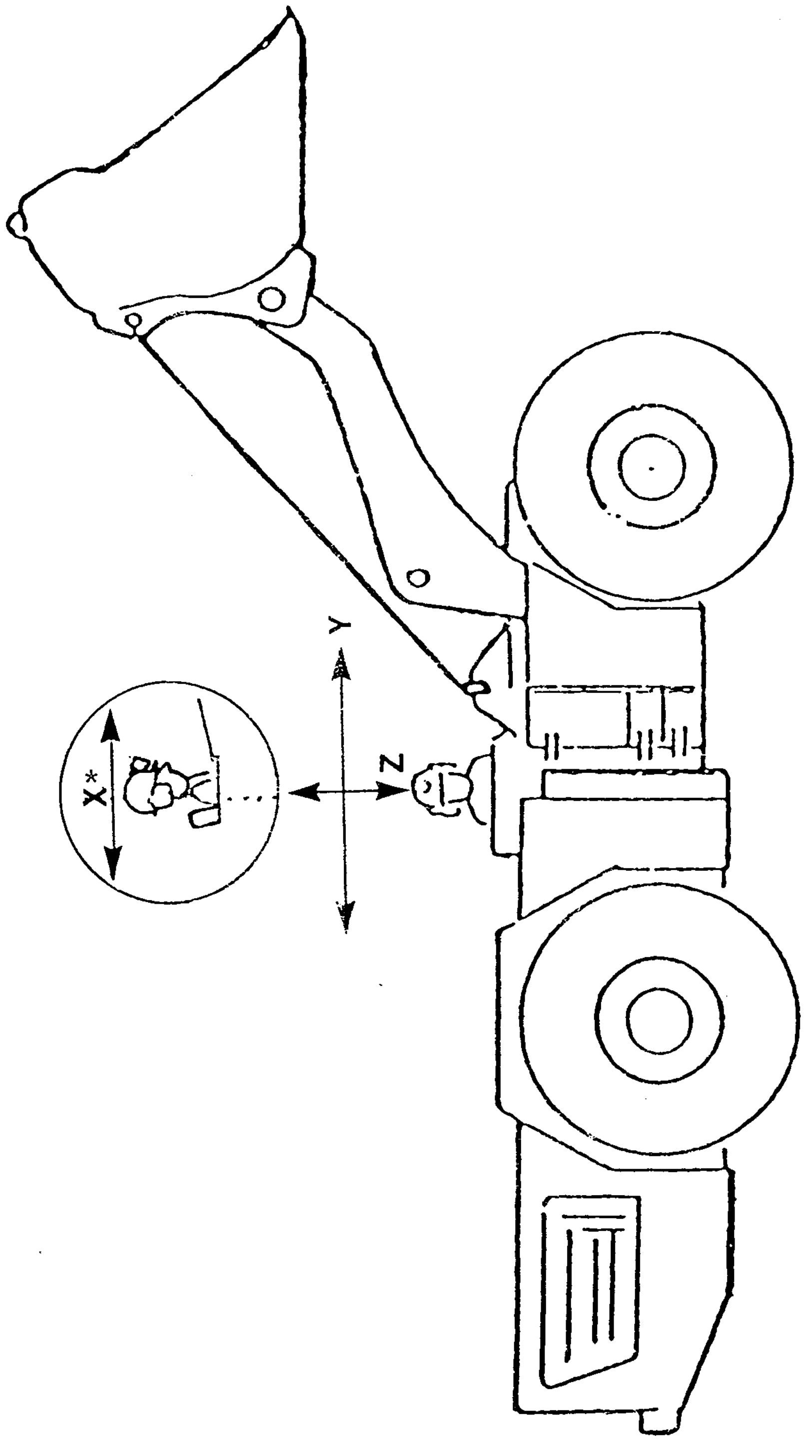


Figure 3. Three perpendicular directions in whole body vibration measurement in relation to LHD vehicle operation

*x-axis=longitudinal direction
y-axis=transverse direction
z-axis=vertical direction

vibration. The weighting factors relative to each frequency range are displayed in Table 12 for the x and y directions combined, and for the z direction.

The three weighted signals were routed to a four channel battery powered FM tape recorder (B & K type 7005F). A microphone was connected to the fourth channel and audio information corresponding to the vibration measurements was recorded during testing. The vibration meters and tape recorder were mounted in two padded metal boxes to prevent shock and movement (as described by Fraser, *et al.*, 1976). The boxes were bolted in turn to each LHD machine on the engine cover directly in front of the seated operator. In Appendix 1 details of the vibration measuring and analyzing equipment, as well as the calibration measures for each piece of equipment are provided.

Data Analysis

The data, stored on tape from the field, were later analyzed in the Ontario Ministry of Labour laboratory with a real time, one-third octave, digital frequency analyzer (B & K type 2131). This analyzer was capable of simultaneous analysis in each one-third octave frequency band. The weighted signal from the Human Response Vibration Meter, recorded on the FM tape recorder in the field was fed into the digital frequency analyzer where it was converted from analog to digital signals and sampled at a rate of 66,667 Hz (15μsec). The digital frequency analyzer split the signal into one-third octave frequency bands from 1.6–80 Hz using recursive filters. The signal in each one-third octave was passed through a squaring circuit, and a linear average was calculated according to the programmed equation:

$$A_I = A_{I-1} + T_I / K$$

where A_I is the linear average in each one-third octave band in $(m.s^{-2})^2$, A_{I-1} is the current sample, T_I is the new sample and K is the total number of samples. The time

Table 12. Weighting factors relative to frequency range*.

Centre frequency of 1/3 octave band (Hz)	Weighting Factors	
	Verticle vibration ('z'-axis) (dB)	Horizontal vibration ('x' and 'y' axes) (dB)
1.0	- 6	0
1.25	- 5	0
1.6	- 4	0
2.0	- 3	0
2.5	- 2	- 2
3.15	- 1	- 4
4.0	0	- 6
5.0	0	- 8
6.3	0	-10
8.0	0	-12
10.0	- 2	-14
12.5	- 4	-16
16.0	- 6	-18
20.0	- 8	-20
25.0	-10	-22
31.5	-12	-24
40.0	-14	-26
50.0	-16	-28
63.0	-18	-30
80.0	-20	-32

*Based on International Standards Organization (ISO 2631, 1978) averaging was set to one second; therefore a sample was averaged every second over the duration of the task. The linear averages were then fed through a lin/log conversion-square root unit. The linear average was converted to a logrithmic RMS output according to the equation:

$$Leq = \frac{20 \log A_T}{2}$$

where Leq is in dB, and A_T is the linear average in $(m.s^{-2})^2$. The digital frequency analyzer also computed an overall Leq level across all frequency bands by summing the linear averages prior to lin/log-square root conversion according to the equation:

$$\text{Overall } A = \Sigma \ A_T$$

where A and A_T are in $(m.s^{-2})^2$. This overall A was then put through the lin/log-square root unit to yield an overall Leq in dB.

The Leq computed by the digital frequency analyzer was usually slightly lower than that calculated by the human response vibration meter. There were three differences in the Leq calculation between the vibration meter and the frequency analyzer: 1. the vibration meter has a baseline of 90 dB, therefore any signal which is less than 90 dB was calculated as 90 dB; 2. the vibration meter was calculating a machine idling Leq for an average of 10 seconds at the beginning and end of each task as the experimenter got onto and off the machine to start or stop the meter. Using the digital frequency analyzer, only the task vibration was calculated into the Leq; 3. the minimal frequency for the vibration meter was 0.5 Hz, while the lower limit of the computer was 1.6 Hz.

A Hewlett Packard (HP) Microprocessor and disc drive (HP 300), monitor (HP 9122), and printer (HP 2122) with a software package (B & K 9177) was used to print out a frequency analysis graph of the vibration spectrum for every combination of direction, task, machine, operator, and mine (210 total). The vibration measuring and analyzing equipment are displayed in Figure 4.

The "Energraphics" Software Package was used to plot three dimensional bar graphs of the frequency spectrums. Individual plots were drawn for each task and direction at the two mines. Plotting the different machine sizes on each graph allowed for good visual comparison of dominant frequency bands and acceleration level differences in these bands.

Since the data from Mine B were incomplete, and different operators and test areas were measured, only the data from Mine A were statistically analyzed. A Repeated Measures Analysis of Variance (ANOVA) statistical design was used to analyze the data using the University of California, Department of Biomathmatics (BMDP 2V) statistical software program (Dixon, 1981) on Simon Fraser University's Michigan Terminal System (MTS) computer. Tasks 2, 3, 4, and 5[1] (mucking, driving full, dumping, and driving empty) represent the repeated measures across three machine sizes (3.5 yd, 6 yd, and 8 yd). The first null hypothesis states that there was no difference in the RMS Leq vibration levels measured among the four tasks. The second null hypothesis states that there was no difference in RMS Leq vibration levels measured among the three machine sizes.

The peak levels were recorded in the field from the human response vibration meters, and crest-factor ratios were calculated based on the ISO 2631 (1978) definition as follows:

$$F_C = X_{peak} / X_{RMS}$$

where F_C = Crest-Factor ratio, X_{peak} = the peak vibration in $m.s^{-2}$, and X_{RMS} = the average vibration in $m.s^{-2}$. Until more information is available, the ISO (2631) recommends a

[1]Idling measures were not included since vibrations were small and not measured in every situation.

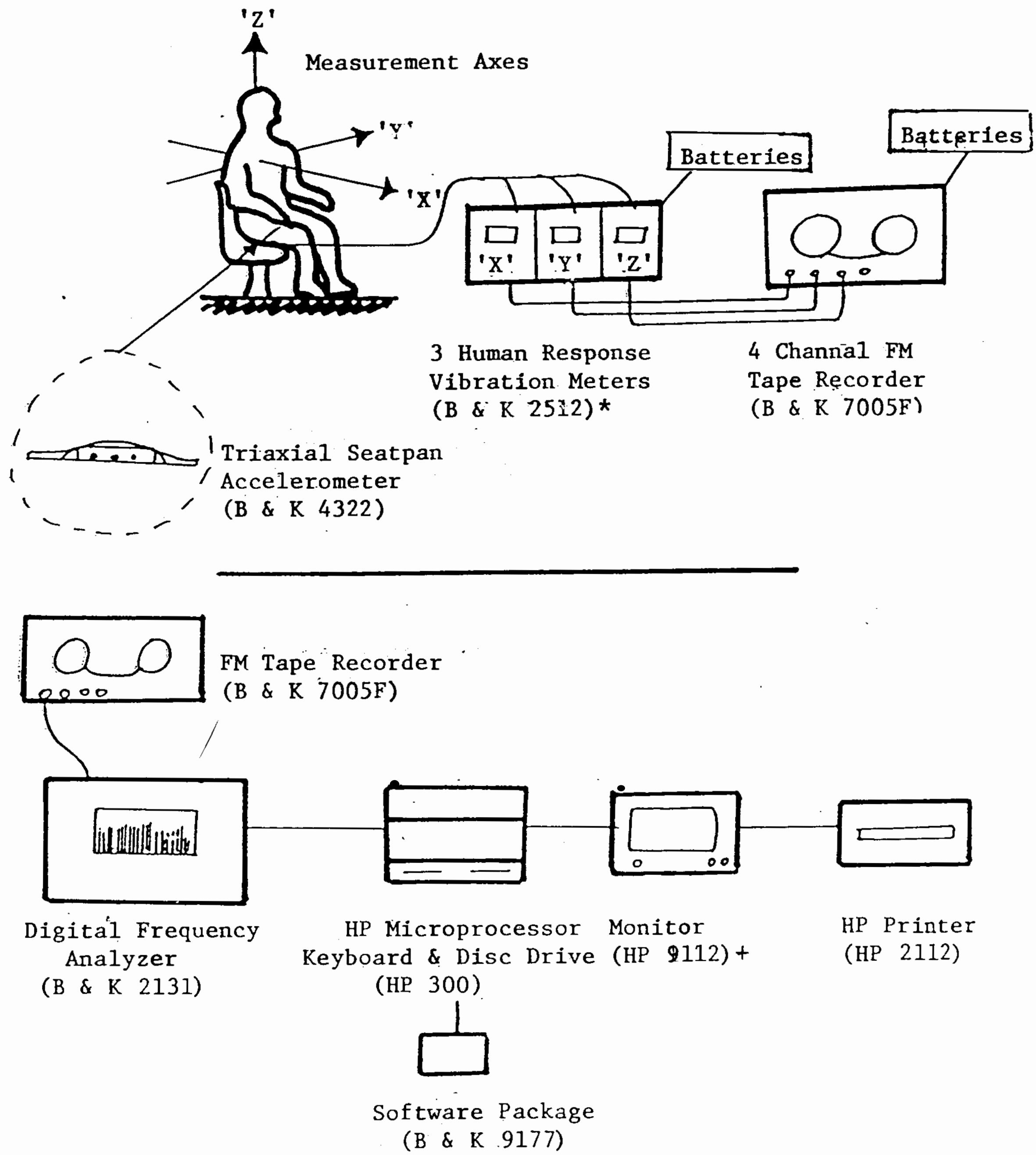


Figure 4. Vibration measuring and analyzing equipment

*B & K is Bruel and Kjaer, equipment manufacturers
+HP is Hewlett Packard, equipment manufacturers

minimum sampling period of one minute for evaluating crest–factors. The ISO also cautions that when a crest–factor ratio is greater than six, the effects of the vibration motion may be underestimated. With a minimum one minute sampling period, only tasks 3 (driving full), and 5 (driving empty) may be evaluated for crest–factors. Crest–factors in these two driving tasks were then compared with the ISO maximum of 6 (ISO 2631, 1978).

The exposure time data supplied by the Industrial Engineering Department in each mine and the RMS acceleration levels for each task were used to calculate Mean Daily Exposure Values (RMS, $m.s^{-2}$) for every machine and operator according to the following equation:

$$\text{Mean Daily Exposure} = [\Sigma(a_{RMS})_j^2 \times t_j \;/\; T]^{1/2}$$

where $(a_{RMS})j$ is the acceleration in ms^{-2} of the first task j; t_j is the time in minutes of exposure to that task j; and T is the total time in minutes exposed to all tasks (j=1,5) combined. This method of expressing total frequency–weighted acceleration from several exposures at different RMS accelerations is specified in the American Conference of Governmental Industrial Hygienists (ACGIH) standards for hand–arm vibration (ACGIH, 1986), and is routinely used by the Ontario Ministry of Labour for reporting vibration results. The mean daily exposure values were compared to the ISO 2631 standards (1978) for exposure levels in each of the three directions (see Figure 1). The ISO 1982 amendment recommends that if two or three vectorial components of a multiaxis vibration have similar magnitudes, the effects on comfort and performance of the combined motion can be greater than that of any single component. To assess the effects, the weighted vibration spectra in each axis are combined to give the vector sum A in $m.s^{-2}$ according to the following equation:

$$A = [(1.4\ a_{xw})^2 + (1.4\ a_{yw})^2 + a_{zw}^2]^{1/2}$$

where 1.4 is the ratio of the longitudinal to the transverse curves of equal response in the frequency ranges where humans are most sensitive. The vector sums were calculated for each task and permissible exposure times T_i found for each level of (A) according to the acceleration exposure limits in the ISO 2631 (1978). Expsoure ratios were then calculated for each level of (A) according to the equation:

$$r_i = t_i / T_i$$

where t_i is the actual task duration in minutes, and T_i is the permissible exposure time for the corresponding acceleration in minutes. The exposure ratios for the five tasks were summed to give the equivalent exposure ratio R, where:

$$R = \Sigma (t_i / T_i)$$

According to the ISO 2631 (1982), R must not exceed unity.

The Leq vibration levels, crest-factors and frequency spectrums were also compared with published reports (Wasserman *et al.*, 1978; Crolla *et al.*, 1984) that measured and analyzed WBV from heavy equipment in a similar way.

Results

The weighted vibration levels (RMS $m.s^{-2}$ and dB) from the Human Response Vibration Meters for each machine, operator, task, and direction are presented in Tables 13 and 14 for Mine A, and Tables 15 and 16 for Mine B. The operator demographic information, roadway maps and information, environmental measurements, and LHD tire pressures and seating suspension systems are presented in Appendix 2 for Mine A and Appendix 3 for Mine B. The exposure times obtained from the Industrial Engineering Departments at Mine A and Mine B are presented in Tables 17 and 18.

Table 13. Mine A Whole Body Vibration Levels ($m.s^{-2}$) in each of x, y and z-axes.

Task	Machine A						Machine C						Machine E					
	Operator 1			Operator 2			Operator 1			Operator 2			Operator 1			Operator 2		
	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
1. Idling	.1	<.1	.1	*			.1	.1	<.1									
2. Mucking	.45	.63	.53	.5	.59	.56	.67	.56	.56	.67	.63	.89	.75	.59	.84	.84	.71	.94
3. Driving Full	1.19	.84	1.33	.94	.47	1.19	1.5	.53	1.7	1.12	.56	1.8	1.8	.89	2.5	1.19	.71	2.11
4. Dumping	.32	1.19	.67	.53	.42	.35	.33	.53	.47	.42	.56	.63	.42	.63	.79	.56	.71	.84
5. Driving Empty	1.41	.59	2.11	1.19	.59	1.33	1.7	.67	2.24	1.12	.56	1.5	1.58	.71	2.8	1.5	.84	2.5

Task	Machine B						Machine D						Machine F					
	Operator 1			Operator 2			Operator 1			Operator 2			Operator 1			Operator 2		
	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
1. Idling										.1	.1	<.1	<.1	.11	.15			
2. Mucking	.75	.71	.71	1.58	1.12	.84	.79	.63	.75	.79	.59	.79	.94	.71	.94	.94	.71	1.0
3. Driving Full	1.26	.5	1.33	.84	.53	1.12	1.26	.5	1.5	1.26	.56	1.5	1.5	.47	1.99	1.12	.42	1.99
4. Dumping	.35	.79	.94	.47	.56	.59	.3	.53	.75	.5	.5	.47	.4	.63	.67	.63	.47	.79
5. Driving Empty	1.41	.67	1.68	1.26	.71	1.5	1.5	.59	1.5	1.26	.53	1.26	1.58	.53	2.5	1.58	.53	2.24

*Idling was not measured in every situation since acceleration magnitudes were low and varied minimally.

Table 14. Mine A Whole Body Vibration Levels (dB) in each of x, y and z-axes.

	Machine A						Machine C						Machine E					
	Operator 1			Operator 2			Operator 1			Operator 2			Operator 1			Operator 2		
Task	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
1. Idling	100	100	100	*			100	101	< 100									
2. Mucking	113	116	114.5	114	115.5	115	116.5	115	115	116.5	116	119	117.5	115.5	118.5	118.5	117	119.5
3. Driving Full	121	118.5	122.5	119.5	113.5	121.5	123.5	114.5	124.5	121	115	125	125	119	128	121	117	126.5
4. Dumping	110	121	116.5	114.5	112.5	111	110.5	114.5	113.5	112.5	115	116	112.5	116	118	115	117	118.5
5. Driving Empty	123	115.5	126.5	121	115.5	122.5	124.5	116.5	127	121	115	123.5	124	117	129	123.5	118.5	128

	Machine B						Machine D						Machine F					
	Operator 1			Operator 2			Operator 1			Operator 2			Operator 1			Operator 2		
Task	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
1. Idling										100	100	< 100	< 100	101	103.5			
2. Mucking	117.5	117	117	124	121	118.5	118	116	117.5	118	115.5	118	119.5	117	119.5	119.5	117	120
3. Driving Full	122	114	122.5	118.5	114.5	121	122	114	123.5	122	115	123.5	123.5	113.5	126	121	112.5	126
4. Dumping	111	118	119.5	113.5	115	115.5	109.5	114.5	117.5	114	114	113.5	112	116	116.5	116	113.5	118
5. Driving Empty	123	116.5	124.5	122	117	123.5	123.5	115.5	123.5	122	114.5	122	124	114.5	128	124	114.5	127

*Idling was not measured in every situation since acceleration magnitudes were low and varied minimally.

Table 15. Mine B Whole Body Vibration Levels ($m.s^{-2}$) in each of x, y and z-axes.

	Machine G						Machine I						Machine K					
	Operator 3			Operator 4			Operator 7			Operator 6			Operator 8			Operator 6		
TASK	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
1. Idling	.1	.1	.19	.1	.1	<.1	<.1	<.1	.1	*			.11	.1	.1			
2. Mucking	.56	.79	.94	.67	.79	.59	.47	.59	.71	.56	.56	.59	.89	.63	.67	1.41	.75	1.0
3. Driving Full	.4	.4	.5	.47	.63	.63	.71	1.19	1.26	.84	.75	1.12	+	..	..	.94	.53	1.41
4. Dumping	.53	.56	.53	.28	.32	.3	.4	.42	.5	.56	.47	.53	.18	.71	.71	.35	.53	.84
5. Driving Empty	.63	.71	.94	.59	.71	.94	.75	.84	1.0	1.0	.79	.84	1.0	.47	1.99	1.26	.63	2.23

	Machine H						Machine J					
	Operator 5			Operator 6			Operator 7			Operator 6		
TASK	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
1. Idling							<.1	<.1	<.1	<.1	<.1	<.1
2. Mucking	.71	.79	.89	.59	.75	.63	.84	.75	.89	.67	.89	.59
3. Driving Full	.75	.84	.94	.89	.89	1.41	1.0	.5	1.06	1.0	.53	1.0
4. Dumping	1.06	1.06	1.12	.45	.53	1.26	.4	.4	.4	.45	.5	.4
5. Driving Empty	.89	1.0	1.41	.89	.94	1.41	.79	.42	.53	1.06	.53	.84

*Idling was not measured in every situation since acceleration magnitudes were low and varied minimally.
+The human response vibration meter malfunctioned and data were not obtained for this task.

Table 16. Mine B Whole Body Vibration Levels (dB) in each of x, y and z-axes.

TASK	Machine G						Machine I						Machine K					
	Operator 3			Operator 4			Operator 7			Operator 6			Operator 8			Operator 6		
	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
1. Idling	100	100	105.5	100	100	<100	<100	<100	100	*			100	<100	<100			
2. Mucking	115	118	119.5	116.5	118	115.5	113.5	115.5	117	115	115	115.5	119	116	116.5	123	117.5	120
3. Driving Full	112	112	114	113.5	116	116	117	121	122	118.5	117.5	121		+		119.5	114.5	123
4. Dumping	114.5	115	114.5	109	110	109.5	112	112.5	114	115	113.5	114.5	105	117	117	111	114.5	118.5
5. Driving Empty	116	117	119.5	115.5	117	119.5	117.5	118.5	120	120	118	118.5	120	113.5	126	122	116	127

TASK	Machine H						Machine J					
	Operator 5			Operator 6			Operator 7			Operator 6		
	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
1. Idling							<100	<100	<100	<100	<100	<100
2. Mucking	117	118	119	115.5	117.5	116	118.5	117.5	119	116.5	119	115.5
3. Driving Full	117.5	118.5	119.5	119	119	123	120	114	120.5	120	114.5	120
4. Dumping	120.5	120.5	121	113	114.5	122	112	112	112	113	114	112
5. Driving Empty	119	120	123	119	119.5	123	118	112.5	114.5	120.5	114.5	118.5

*Idling was not measured in every situation since acceleration magnitudes were low and varied minimally.
+The human response vibration meter malfunctioned and data were not obtained for this task.

Table 17. Mine A Exposure times (minutes) for each of 5 LHD operator tasks.*

Task	Average Time (minutes)
1. Idling	16.9
2. Mucking	28.2
3. Driving Full	127.2
4. Dumping	7.2
5. Driving Empty	153.4
Total Exposure Time	332.9
Cleaning	8.3
Servicing	18.2

*Based on 14 time-motion studies conducted on random days with varying operators, machines and road conditions by Industrial Engineering Department, Mine A, 1981.

Table 18. Mine B Exposure times (minutes) for each of 5 LHD operator tasks.*

Task	Average Time (minutes)
1. Idling	27
2. Mucking	46
3. Driving Full	138
4. Dumping	20
5. Driving Empty	95
Total Exposure Time	326
Cleaning	not available
Servicing	not available

*Based on 20 time-motion studies conducted on random days with varying operators, machines and road conditions by Industrial Engineering Department, Mine B, 1984.

In all of the machines, at both mines, the accelerations measured in the x, y and z directions during idling were small (0.1 $m.s^{-2}$). In most cases the largest acceleration values were measured when driving full and driving empty. This was especially apparent in the x and z directions. High accelerations were measured occasionally during dumping and mucking. The highest accelerations were in the z direction, and usually occurred when driving empty. At Mine A in the x direction, a significant machine size effect was found (F = 4.67, df = 2/27, $\alpha \leq .05$). There was also a significant difference between the four tasks (F = 45.67, df = 3/27, $\alpha \leq .01$). The y direction acceleration values were random in pattern, and no significant differences were found either between machine sizes or between tasks. In the z direction, there was again a significant difference between machine sizes (F = 23.34, df = 2/27, $\alpha \leq .01$), and between the four tasks (F = 110.4, df = 3/27, $\alpha \leq .01$). There was also a significant interaction between machine sizes and tasks in the z direction (F = 4.7, df = 6/27, $\alpha \leq .01$). When the z direction data was graphed, the interaction was seen only between the 6 yd and 8 yd LHD machine, during task 4 and task 5.

Further statistics using Tukey's post hoc analysis (Kirk, 1968) determined which tasks and vehicles were different from the others, and which variables contributed to the significant interaction in the z direction. In the x-axis, when vehicle sizes were compared within each task, there was only one case of significance. In task 3 (driving full), the 3.5 yd was significantly different from the 8 yd vehicle. In the z direction during task 2 (mucking) and task 4 (dumping), there were no significant differences between the three machine sizes. In the two driving tasks, task 3 (driving full) and task 5 (driving empty), significant differences were found between the 3.5 yd and the 6 yd, as well as between the 3.5 yd and the 8 yd, with the 3.5 yd LHD recording the highest vibration levels. There were no differences between the 6 yd and the 8 yd LHD machines. One-way analyses of variance (ANOVA) were performed individually for each machine size and the Tukey's post hoc analysis (Kirk,

1968) was used with each ANOVA to determine which tasks were different from the others. In all three machine sizes, in both the x and z directions, the same results were found. There were significant differences between task 2 (mucking) and task 3 (driving full); task 2 (mucking) and task 5 (driving empty); task 4 (dumping) and task 3 (driving full); and task 4 (dumping) and task 5 (driving empty). There were no significant differences however between the two driving tasks (task 3 and task 5), or between the two non-driving tasks (task 2 and task 4). In each case of significance, the driving task produced higher vibration levels than the non-driving task. A summary of the statistical findings is presented in Table 19.

We cannot statistically compare the vibration levels between the two mines since there are a number of variables which are not controlled, such as road terrain and surface, operators, and machine maintenance. The overall Leq vibration levels at Mine A however seem higher than those measured at Mine B, especially in the x and z directions (see Tables 13-16). This was also apparent from the analysis of Mean Daily Exposure values.

Tables 20 to 23 present the Peak Acceleration values in $m.s^{-2}$ and dB. The peaks range from 1.2 to greater than 20 $m.s^{-2}$ but show no consistent pattern. The maximum peak a human response vibration meter records accurately is 20 $m.s^{-2}$ (146 dB). Many of the higher peak values lie in the z direction. On the average, there are more high level peaks measured at Mine A than at Mine B. However, at both locations the vibration signal is impulsive, containing peaks in every task and every direction.

Tables 24 and 25 present the crest-factors calculated for driving full and driving empty at Mine A and Mine B respectively. The ISO 2631 Amendment 1 (1982) states that crest-factor ratios greater than three often may be compared satisfactorily with the limits in the International Standard, but the importance of some motions containing occasional extremely high peak values may be underestimated by the ISO 2631 method. The crest-factors are very

Table 19. Summary of statistics

Direction	Finding	Test
x	-significant difference between machine sizes ($\alpha \leq .05$)	-Repeated Measures Analysis of Variance
	-significant difference between tasks 2-5 ($\alpha \leq .01$)	-Repeated Measures Analysis of Variance
y	-no significant differences between machine sizes or tasks	-Repeated Measures Analysis of Variance
z	-significant difference between machine sizes ($\alpha \leq .05$)	-Repeated Measures Analysis of Variance
	-significant difference between tasks 2-5 ($\alpha \leq .01$)	-Repeated Measures Analysis of Variance
	-significant interaction between machine and task ($\alpha \leq .01$)	-Repeated Measures Analysis of Variance
z Task 3 & Task 5 (driving full and driving empty)	-significant difference between 3.5 yd and 6 yd LHD -significant difference between 3.5 yd and 8 yd LHD	-Tukey's Post Hoc Analysis
z Task 2 & task 4 (mucking and dumping)	-no significant difference between 3.5 yd, 6 yd and 8 yd LHD	-Tukey's Post Hoc Analysis
3.5 yd, 6 yd & 8 yd machine size	-significant difference between: task 2 and task 3 task 2 and task 5 task 4 and task 3 task 4 and task 5 -no significant difference between: task 2 and task 4 task 3 and task 5	-Tukey's Post Hoc Analysis and One-way Analysis of Variance

Table 20. Mine A Whole body vibration peaks (ms^{-2}) in each of x, y and z-axes

Task	Machine A Operator - #1 X	Y	Z	Machine A Operator - #2 X	Y	Z	Machine C Operator - #1 X	Y	Z	Machine C Operator - #2 X	Y	Z	Machine E Operator - #1 X	Y	Z	Machine E Operator - #2 X	Y	Z
1. Idling	.17	.14	.28	+			.11	.63	<.1									
2. Mucking	2.98	>20 *	4.2	2.8	5.0	10.0	3.5	5.96	3.16	5.3	3.98	15.0	5.0	5.96	10.6	4.73	6.3	7.08
3. Driving Full	6.68	>20	8.9	7.5	4.2	7.9	9.44	10.0	11.2	7.08	7.9	5.96	16.8	7.5	> 20	9.44	9.44	> 20
4. Dumping	14.1	20	>20	4.2	2.23	1.88	2.37	3.76	3.98	2.5	2.8	5.96	1.7	3.35	5.0	4.73	4.73	11.89
5. Driving Empty	7.08	5.0	14.1	5.3	7.9	11.2	9.44	4.5	18.8	11.2	12.6	>20	10.0	7.9	> 20	9.44	8.9	> 20

Task	Machine B Operator - #1 X	Y	Z	Machine B Operator - #2 X	Y	Z	Machine D Operator - #1 X	Y	Z	Machine D Operator - #2 X	Y	Z	Machine F Operator - #1 X	Y	Z	Machine F Operator - #2 X	Y	Z
1. Idling										.13	<.1	.35	.1	.53	.53			
2. Mucking	2.66	3.5	6.68	>20	13.3	> 20	4.73	2.8	5.6	3.98	3.5	> 20	7.9	3.35	4.2	6.68	6.3	18.8
3. Driving Full	8.9	5.3	> 20	5.0	6.3	8.9	--	4.5	10.6	7.9	4.2	11.89	11.2	3.98	>20	6.68	3.35	> 20
4. Dumping	2.0	5.0	> 20	3.76	3.98	5.6	1.78	3.35	> 20	3.5	2.5	3.76	2.98	3.5	5.96	7.5	2.98	7.9
5. Driving Empty	8.9	4.73	>20	8.4	6.68	10.6	7.9	2.8	> 20	7.5	2.66	> 20	10.0	3.76	> 20	10.6	2.98	> 20

*The maximum peak recorded on the vibration meter is $20ms^{-2}$ (146dB) therefore all signals above this appear as >20.
+Idling was not measured in every situation since acceleration magnitudes were low and varied minimally.

Table 21. Mine A Whole Body Vibration Peaks (dB) in each of x, y and z-axes.

Task	Machine A Operator - #1 X	Y	Z	Machine A Operator - #2 X	Y	Z	Machine C Operator - #1 X	Y	Z	Machine C Operator - #2 X	Y	Z	Machine E Operator - #1 X	Y	Z	Machine E Operator - #2 X	Y	Z
1. Idling	104.5	103	109	*			101	115	<100									
2. Mucking	129.5	146	132.5	129	134	140	131	135.5	130	134.5	132	143.5	134	135.5	140.5	133.5	136	137
3. Driving Full	136.5	>146+	139	137.5	132.5	138	139.5	140	141	137	138	146	144.5	137.5	>146	139.5	139.5	>146
4. Dumping	143	>146	151.5	132.5	127	125.5	127.5	131.5	132	128	129	135.5	124.5	130.5	134	133.5	133.5	141.5
5. Driving Empty	137	134	143	134.5	138	141	139.5	133	145.5	141	142	>146	140	138	>146	139.5	139	>146

Task	Machine B Operator - #1 X	Y	Z	Machine B Operator - #2 X	Y	Z	Machine D Operator - #1 X	Y	Z	Machine D Operator - #2 X	Y	Z	Machine F Operator - #1 X	Y	Z	Machine F Operator - #2 X	Y	Z
1. Idling										102	<100	111	<100	114.5	114.5			
2. Mucking	128.5	131	136.5	>146	142.5	>146	133.5	129	135	132	131	>146	138	130.5	132.5	136.5	136	145.5
3. Driving Full	139	134.5	>146	134	131	139	--	133	140.5	138	132.5	141.5	141	132	>146	136.5	130.5	>146
4. Dumping	126	134	>146	131.5	132	135	125	130.5	>146	131	128	131.5	129.5	131	135.5	137.5	129.5	138
5. Driving Empty	139	133.5	>146	138.5	136.5	140.5	138	129	>146	137.5	128.5	>146	140	131.5	>146	140.5	129.5	>146

*Idling was not measured in every situation since acceleration magnitudes were low and varied minimally.
+The maximum peak recorded on the vibration meter is 146dB ($20 m.s^{-2}$) therefore all signals above this appear as >146.

Table 22. Mine B Whole body vibration peaks (ms^{-2}) in each of x, y and z-axes.

	Machine G						Machine I						Machine K					
	Operator - #3			Operator - #4			Operator - #7			Operator - #6			Operator 8			Operator 6		
TASK	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
1. Idling	.45	.6	.56	.3	.35	.32	.21	.47	.79	+			.13	.22	.42			
2. Mucking	3.35	4.2	5.0	2.23	2.8	2.37	2.23	4.2	4.5	3.16	2.66	5.6	4.73	3.76	11.2	7.1	3.76	>20 *
3. Driving Full	2.23	2.5	3.35	2.1	3.76	3.76	3.35	4.73	16.8	5.96	4.2	10.6	#	..	..	5.6	4.2	>20
4. Dumping	2.23	2.37	3.5	1.4	1.2	2.37	2.66	2.23	4.2	2.5	1.88	4.73	.79	4.2	5.6	2.5	3.98	12.6
5. Driving Empty	3.5	3.16	5.0	3.76	4.2	5.96	4.73	5.0	11.2	4.73	5.0	5.96	3.98	3.16	>20	6.68	3.35	>20

	Machine H						Machine J					
	Operator - #5			Operator - #6			Operator - #7			Operator - #6		
TASK	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
1. Idling							.18	<.1	.16	.1	<.1	.11
2. Mucking	4.5	4.5	9.4	2.8	3.16	11.89	3.98	2.8	5.3	2.23	3.76	2.8
3. Driving Full	3.35	2.98	10	4.2	4.2	>20	>20	2.0	–	4.2	2.1	7.9
4. Dumping	10.69	4.73	>20	2.0	2.5	5.6	5.6	2.23	2.98	3.76	3.35	3.98
5. Driving Empty	3.35	4.5	7.5	>20	3.5	20	4.2	2.1	4.2	4.2	3.5	10.6

*The maximum peak recorded on the vibration meter is $20ms^{-2}$ (146dB)therefore all signals above this appear as >20.
+Idling was not measured in every situation since acceleration magnitudes were low and varied minimally.
#The human response vibration meter malfunctioned and data were not obtained for this task.

Table 23. Mine B Whole body vibration peaks (dB) in each of x, y and z-axes.

	Machine G						Machine I						Machine K					
	Operator - #3			Operator - #4			Operator - #7			Operator - #6			Operator 8			Operator 6		
TASK	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
1. Idling	113	115.5	115	109.5	111	110	106.5	113.5	118	+			102.5	107	112.5			
2. Mucking	130.5	132.5	134	127	129	127.5	127	132.5	133	130	128.5	135	133.5	131.5	141	137	131.5	>146
3. Driving Full	127	128	130.5	126.5	131.5	131.5	130.5	133.5	144.5	135.5	132.5	140.5	#	...	...	135	132.5	>146
4. Dumping	127	127.5	131	123	121.5	127.5	128.5	127	132.5	128	125.5	133.5	118	132.5	135	128	132	142
5. Driving Empty	131	130	134	131.5	132.5	135.5	133.5	134	142	133.5	134	135.5	132	130	>146*	136.5	130.5	>146

	Machine H						Machine J					
	Operator - #5			Operator - #6			Operator - #7			Operator - #6		
TASK	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
1. Idling							105	100	104	100	<100	100.5
2. Mucking	133	133	139.5	129	130	141.5	132	129	134.5	127	131.5	129
3. Driving Full	130.5	129.5	140	132.5	132.5	>146	>146	126	-	132.5	126.5	138
4. Dumping	140.5	133.5	>146	126	128	135	135	127	129.5	131.5	130.5	132
5. Driving Empty	130.5	133	137.5	>146	131	146	132.5	126.5	132.5	132.5	131	140.5

*The maximum peak recorded on the vibration meter is 146dB ($20ms^{-2}$) therefore all signals above this appear as >146.
+Idling was not measured in every situation since acceleration magnitudes were low and varied minimally.
#The human response vibration meter malfunctioned and data were not obtained for this task.

Table 24. Mine A Crest-Factor Ratios ($\frac{\text{Peak Vibration}}{\text{RMS Average Vibration}}$) in each of x, y and z-axes.

	Machine A						Machine C						Machine E					
	Operator - #1			Operator - #2			Operator - #1			Operator - #2			Operator - #1			Operator - #2		
Task	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
Driving Full	5.6	>6*	>6	>6	>6	>6	>6	>6	>6	>6	>6	3.3	>6	>6	>6	>6	>6	>6
Driving Empty	5.0	>6	>6	4.5	>6	>6	5.6	>6	>6	>6	>6	>6	>6	>6	>6	>6	>6	>6

	Machine B						Machine D						Machine F					
	Operator - #1			Operator - #2			Operator - #1			Operator - #2			Operator - #1			Operator - #2		
Task	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
Driving Full	>6	>6	>6	6.0	>6	>6	--	>6	>6	>6	>6	>6	>6	>6	>6	6.0	>6	>6
Driving Empty	>6	>6	>6	>6	>6	>6	5.3	4.7	>6	6.0	5.0	>6	>6	>6	>6	>6	5.6	>6

*The International Standards Organization (ISO 2631, 1978) cannot be used to evaluate crest-factor ratios that are greater than 6.0 therefore any crest-factor ratios above 6.0 appear as >6.0.

Table 25. Mine B Crest-Factor Ratios $\left(\frac{\text{Peak Vibration}}{\text{RMS Average Vibration}}\right)$ in each of x, y and z-axes.

	Machine G						Machine I					
	Operator - #3			Operator - #4			Operator - #7			Operator - #6		
TASK	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
Driving Full	5.6	>6 *	>6	4.5	6.0	6.0	4.7	4.0	>6	>6	5.6	>6
Driving Empty	5.6	4.5	5.3	>6	5.9	6	>6	6.0	>6	4.7	>6	>6

	Machine H						Machine J					
	Operator - #5			Operator - #6			Operator - #7			Operator - #6		
TASK	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
Driving Full	4.5	3.5	>6	4.7	4.7	>6	>6	4.0	-	4.2	4.0	>6
Driving Empty	3.8	4.5	5.3	>6	3.7	>6	5.3	5.0	>6	4.0	>6	>6

	Machine k					
	Operator - # 8			Operator - #6		
TASK	X	Y	Z	X	Y	Z
Driving Full				5.6	>6	>6
Driving Empty	3.76	5.0	>6	5.6	>6	>6

*The International Standards Organization (ISO 2631, 1978) cannot be used to evaluate crest-factor ratios that are greater than 6.0 therefore any crest-factor ratios above 6.0 appear as >6.0.

high in both mines. At Mine A, 57.5% of the crest-factors in the 8 yd vehicle, 75% in the 6 yd and 96% in the 3.5 yd exceed the ISO (2631) maximum of 6. In total 76% of the crest-factors at Mine A exceed 6. At Mine B 41.5% of the crest-factors in the 8 yd, 54.5% in the 5 yd and 56% in the 3.5 yd machine are greater than 6. In total at Mine B, 43% of the crest-factors in the two tasks exceeded the ISO's maximum.

The Mean Daily Exposure Values are presented in Tables 26 and 27 for each operator, machine, and direction using the exposure data supplied by each mine's Industrial Engineering Department (see Tables 16 and 17). Table 28 presents the Acceleration Exposure Limits as a function of exposure time and direction from the curves in the ISO 2631 (1978). The Mean Daily Exposure levels measured were compared to the exposure limit of 0.6 $m.s^{-2}$ for 6 hours in the x and y direction and 0.8 $m.s^{-2}$ for 6 hours in the z direction (ISO 2631, 1978).

Based on the exposure time of 6 hours and the exposure limits for each axis, 17 of 24 or 71% of the mean daily exposure levels calculated in the x and y direction at Mine A exceeded the ISO limits. All of the vibration measures calculated to be within the ISO limits were in the y direction. All of the z direction mean daily exposure values exceeded the recommended ISO limits. This is shown graphically in Figures 5, 6 and 7. It should be noted that some of the levels measured in the z direction, especially in the 3.5 yd LHD machine (2.46 $m.s^{-2}$) comply with an ISO recommended exposure time for only 25 minutes (see Table 28). In the 8 yd and 6 yd LHD machines at Mine A, the recommended exposure limit in the z direction is exceeded in approximately 2.5 hours and 2 hours respectively. In the x direction, the recommended limit is exceeded in approximately 1.5 hours. At Mine B, 13 of 18 or 72% of the mean daily exposure values measured in the x and y direction were calculated to exceed the ISO exposure limits. In the z direction, 7 of 9 or 78% of the mean daily exposure values measured exceeded the recommended ISO exposure limits. Only one 8

Table 26. Mine A Mean daily exposure values (ms^{-2})

LHD Size	Axes				
	Machine	A		B	
	Operator	1	2	1	2
8 yd	x	1.22	1.01	1.25	1.10
	y	0.70	0.53	0.60	0.67
	z	1.66	1.18	1.43	1.26
	Machine	C		D	
	Operator	1	2	1	2
6 yd	x	1.49	1.05	1.30	1.18
	y	0.59	0.55	0.54	0.53
	z	1.86	1.53	1.40	1.28
	Machine	E		F	
	Operator	1	2	1	2
3.5 yd	x	1.56	1.28	1.45	1.31
	y	0.76	0.76	0.52	0.49
	z	2.46	2.16	2.12	1.98

Table 27. Mine B Mean daily exposure values (ms^{-2})

LHD Size	Axes				
	Machine	G		H	
	Operator	3	4	5	6
8 yd	x	0.50	0.51	0.78	0.79
	y	0.57	0.64	0.87	0.83
	z	0.71	0.69	1.07	1.26
	Machine	I		J	
	Operator	7	6	7	6
5 yd	x	0.65	0.81	0.85	0.91
	y	0.93	0.69	0.50	0.57
	z	1.03	0.90	0.82	0.83
	Machine	K			
	Operator	8	6		
3.5 yd	x	*	1.01		
	y		0.61		
	z		1.52		

*Due to incomplete data a mean daily exposure ratio could not be calculated.

Table 28. Acceleration limits as a function of exposure time and direction.*

Exposure time	Acceleration limit (ms^{-2}) x and y axes	z axis
8 hour	0.45	0.63
6 hour	0.60	0.80
4 hour	0.71	1.06
2.5 hour	1.00	1.42
1 hour	1.70	2.36
25 minutes	2.50	3.60
16 minutes	3.00	4.24
1 minute	4.00	5.60

*Based on exposure limits in the International Standards Organization (ISO 2631, 1978) Guide for the evaluation of Whole body Vibration.

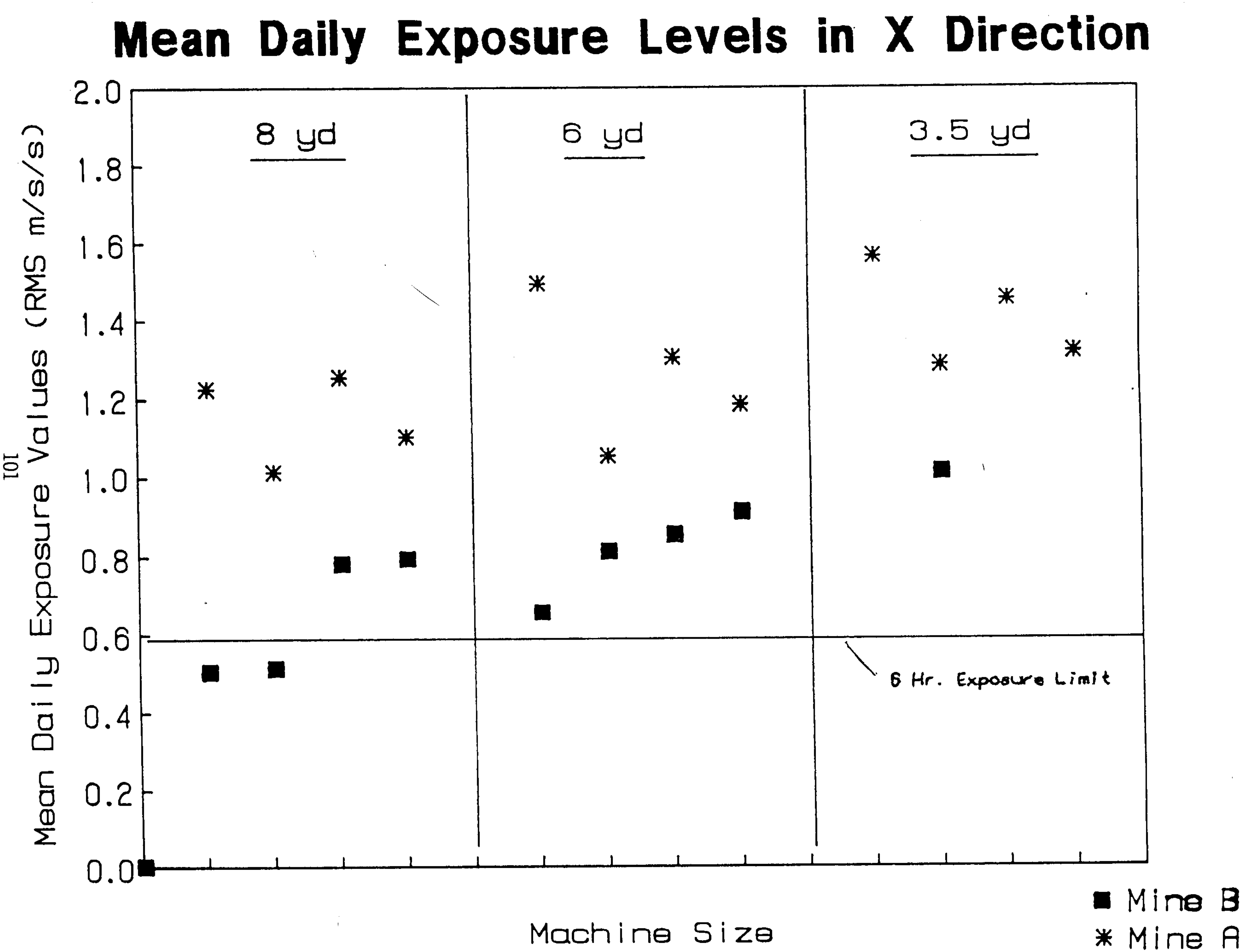

Mean Daily Exposure Levels in X Direction
8 yd
6 yd
3.5 yd
6 Hr. Exposure Limit
Mean Daily Exposure Values (RMS m/s/s)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Machine Size
Mine B
Mine A

Figure 5.

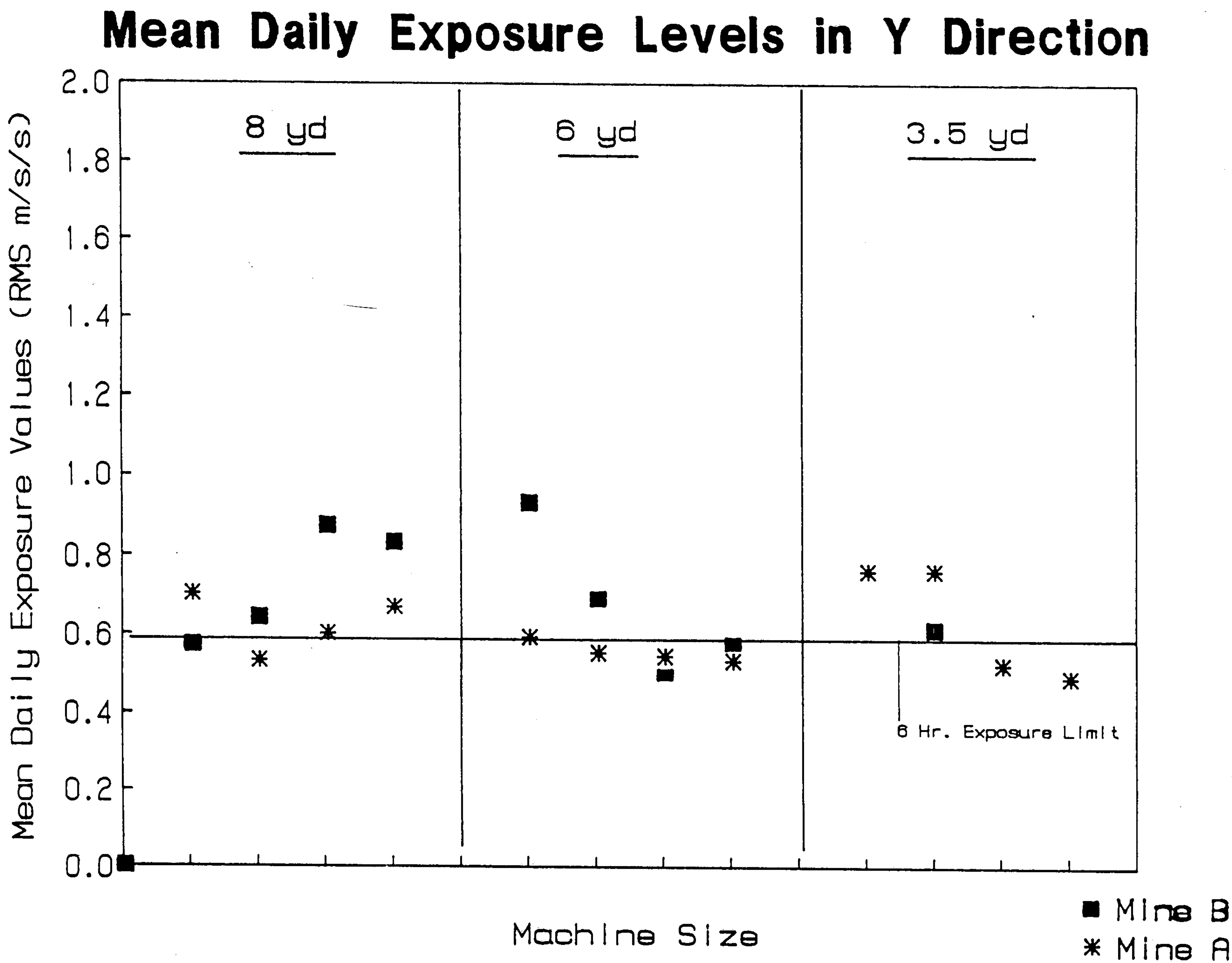

Mean Daily Exposure Levels in Y Direction
Mean Daily Exposure Values (RMS m/s/s)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
8 yd
6 yd
3.5 yd
6 Hr. Exposure Limit
Machine Size
Mine B
Mine A

Figure 6.

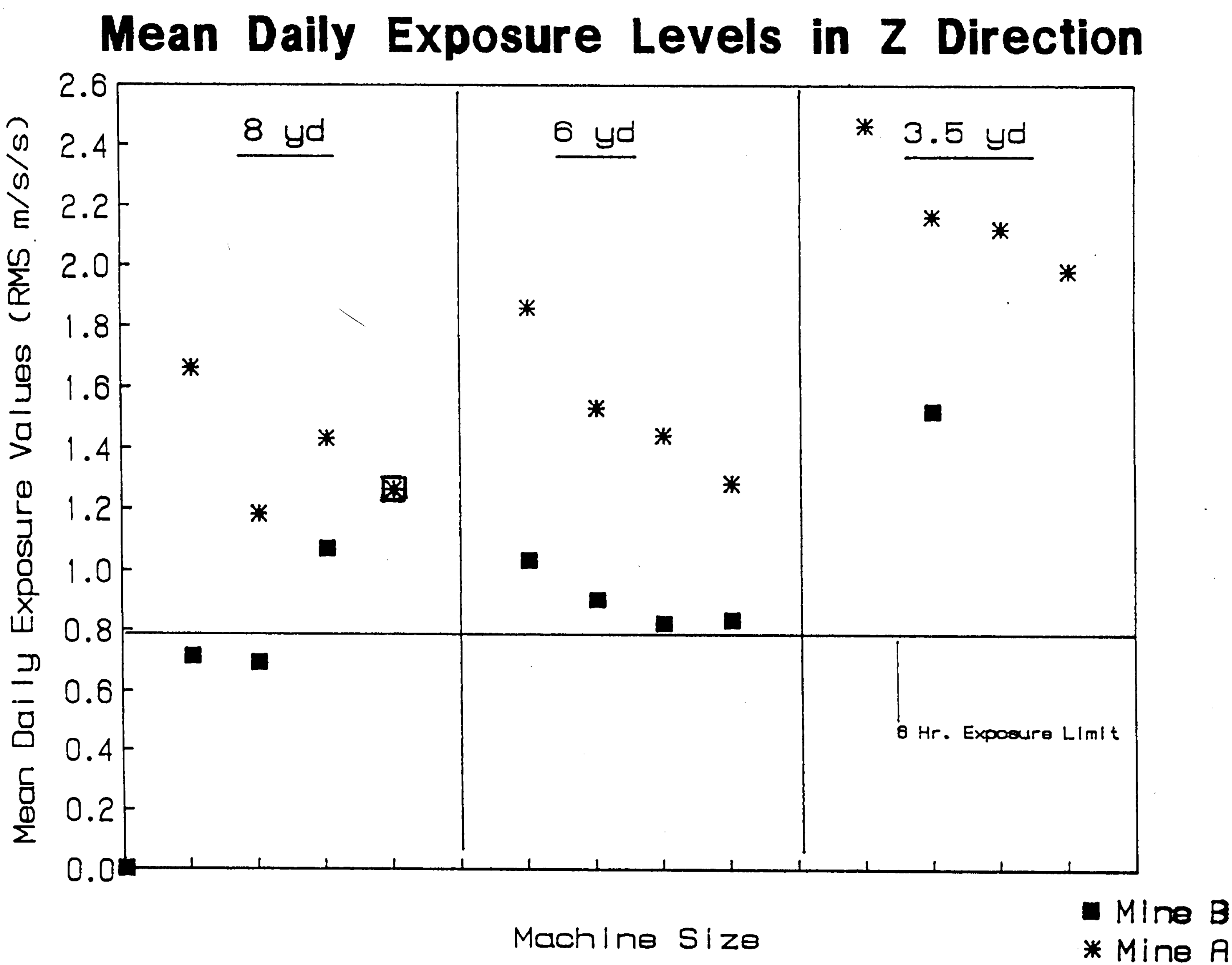

Mean Daily Exposure Levels in Z Direction
Mean Daily Exposure Values (RMS m/s/s)
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
8 yd
6 yd
3.5 yd
8 Hr. Exposure Limit
Machine Size
Mine B
Mine A

Figure 7.

yd LHD machine was within the ISO limits in all three axes, but only with one operator and not the other. All of the vehicles at both Mine A and Mine B exceeded the fatigue or decreased proficiency boundary.

The daily exposure ratios calculated using weighted acceleration vectors are presented for each vehicle and operator for both mines in Table 29. All of the vehicles exceeded the permissible ratio of unity. The ratios ranged from 1.7 to 12.0 with the higher values found at Mine A and with the 3.5 yd LHD vehicles. This is presented graphically in Figure 8.

Each of the weighted vibration signals measured from the Human Response Vibration Meter was recorded on the FM Tape Recorder and analyzed with the digital frequency analyzer at the Ontario Ministry of Labour laboratory (210 in total). A frequency analysis and hard copy frequency spectrum was derived for all of the recordings. Samples of frequency spectrums from the digital frequency analyzer, HP microprocessor and B & K 9117 software are shown in Figures 9 to 11. The frequency spectrums are summarized in three-dimensional bar graphs in Figures 12 through 17. The four graphs in each figure represent the four tasks respectively. Within each bar graph the different machine sizes were contrasted.

With the exception of idling, among all tasks, machines, and directions the dominant frequency band was 1.6, 2.0, 2.5, or 3.15 Hz with very few exceptions. The idling frequency ranged between 32 and 80 Hz, with 50 Hz being the average dominant band. Generally, the z direction dominant frequency bands were slightly higher ($\geq$3.15 Hz) and the vibration was spread more flatly across the spectrum (up to 32 Hz). In the x and y directions the dominant frequency bands were most often 1.6 or 2.0 Hz with the accelerations dropping off dramatically by 4 Hz.

Table 29. Daily exposure ratios using weighted acceleration vectors for Mine A and Mine B*

Mine A

Machine	A		C		E	
Operator	1	2	1	2	1	2
	6.12	4.0	8.9	5.1	12.0	9.0
Machine	B		D		F	
Operator	1	2	1	2	1	2
	5.5	4.8	5.5	4.7	8.6	7.6

Mine B

Machine	G		I		K	
Operator	3	4	7	6	8	6
	1.7	1.98	3.26	3.24	+	5.2
Machine	H		J			
Operator	5	6	7	6		
	3.68	3.85	2.66	2.45		

*Daily exposure ratio is the ratio of actual total exposure time to permissible exposure time given the acceleration values measured for each task. The daily exposure ratio must not exceed unity.

+Due to incomplete data a ratio could not be calculated for this situation.

DAILY EXPOSURE RATIOS FOR MINE A & B

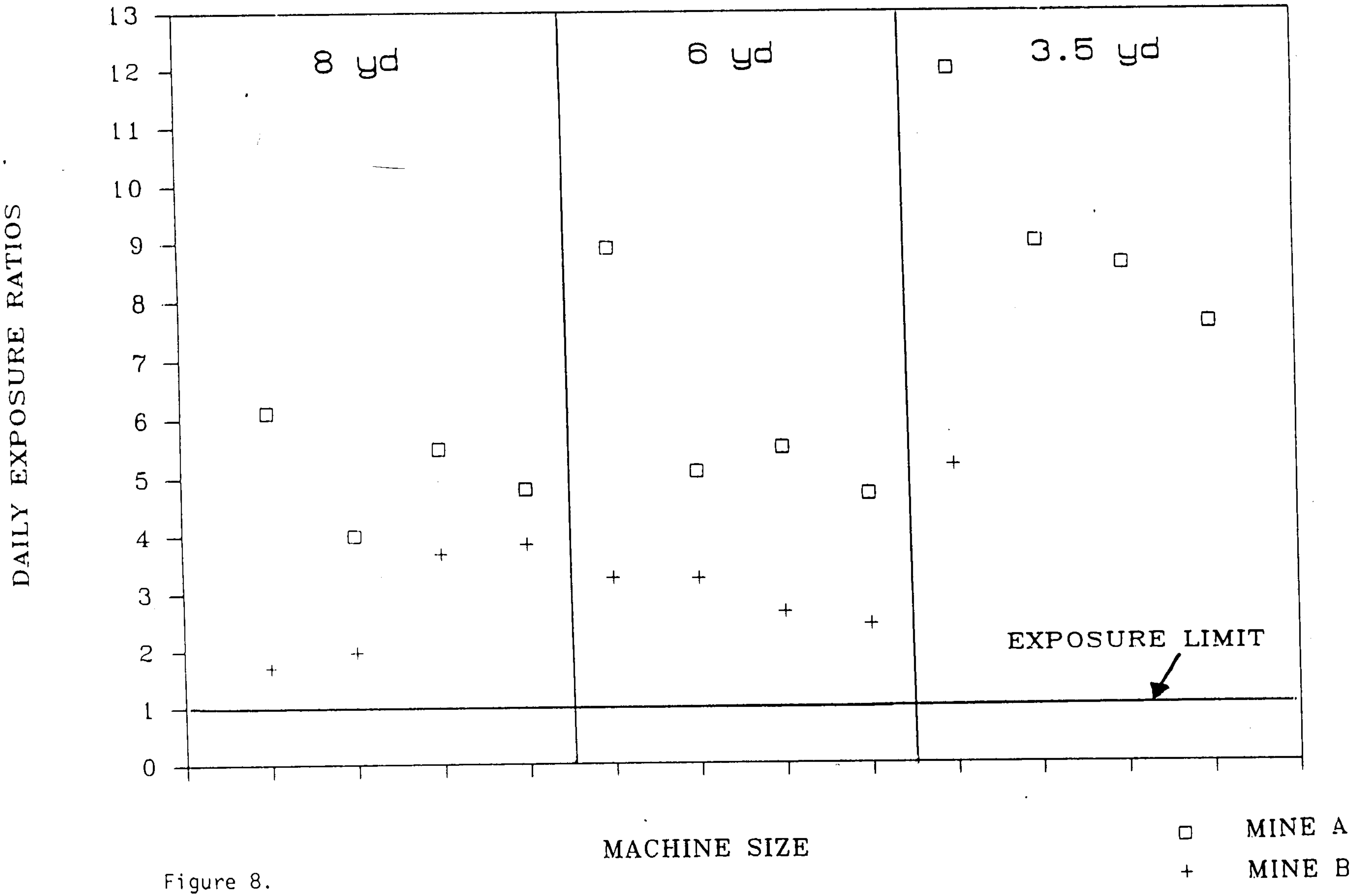
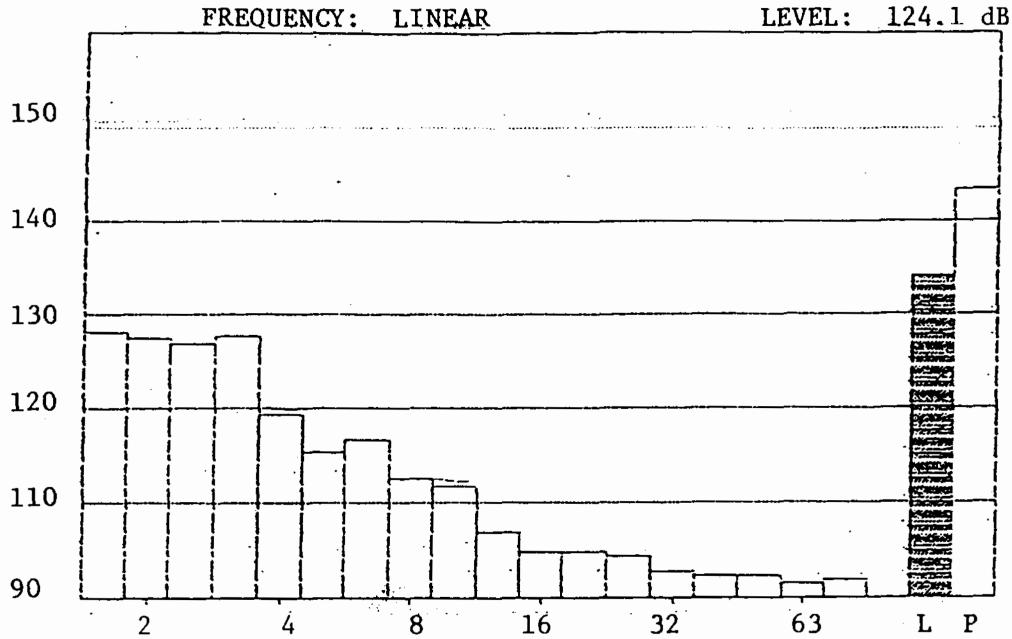


Figure 8.



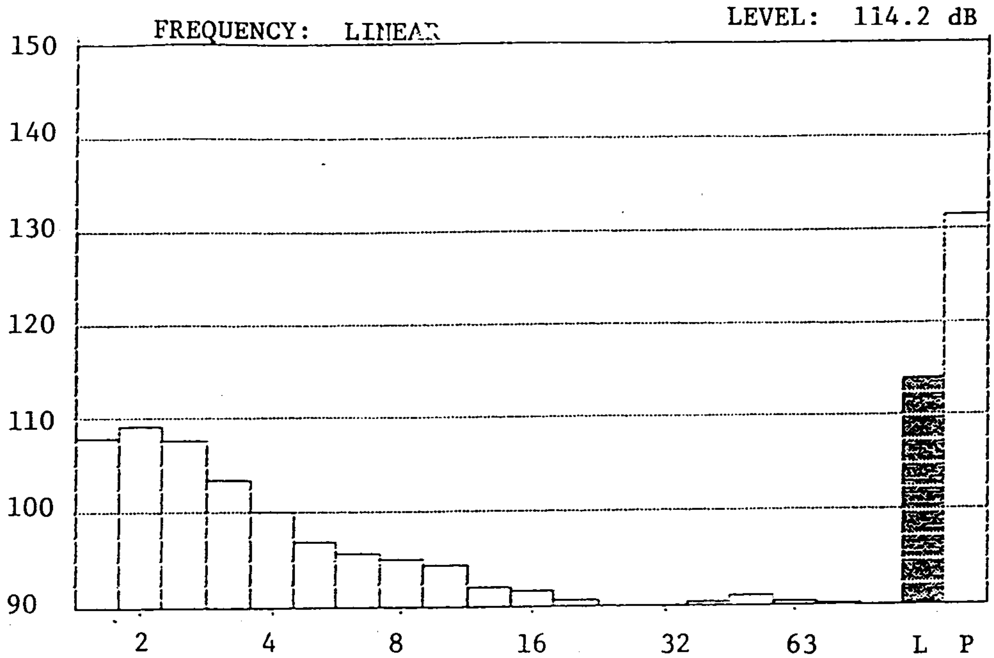
<u>Average Vibration Spectrum</u>

Frequency	Level
2 Hz	118.2 dB
2 Hz	117.6 dB
3 Hz	116.9 dB
3 Hz	117.7 dB
4 Hz	109.5 dB
5 Hz	105.4 dB
6 Hz	106.7 dB
8 Hz	102.5 dB
10 Hz	101.7 dB
13 Hz	96.9 dB
16 Hz	94.8 dB
20 Hz	94.8 dB
25 Hz	94.4 dB
32 Hz	92.6 dB
40 Hz	92.2 dB
50 Hz	92.2 dB
63 Hz	91.5 dB
80 Hz	92.8 dB

<u>Measurement Identification</u>

No. of Spectra	:	170
Averaging	:	Linear
Average time	:	1 second
Linear	:	124.1 dB
Peak	:	133.4 dB

Figure 9. Whole body vibration frequency spectrum at Mine A in the X-axis for a 3.5 yd LHD vehicle performing task 5 (driving empty).



<u>Average Vibration Spectrum</u>

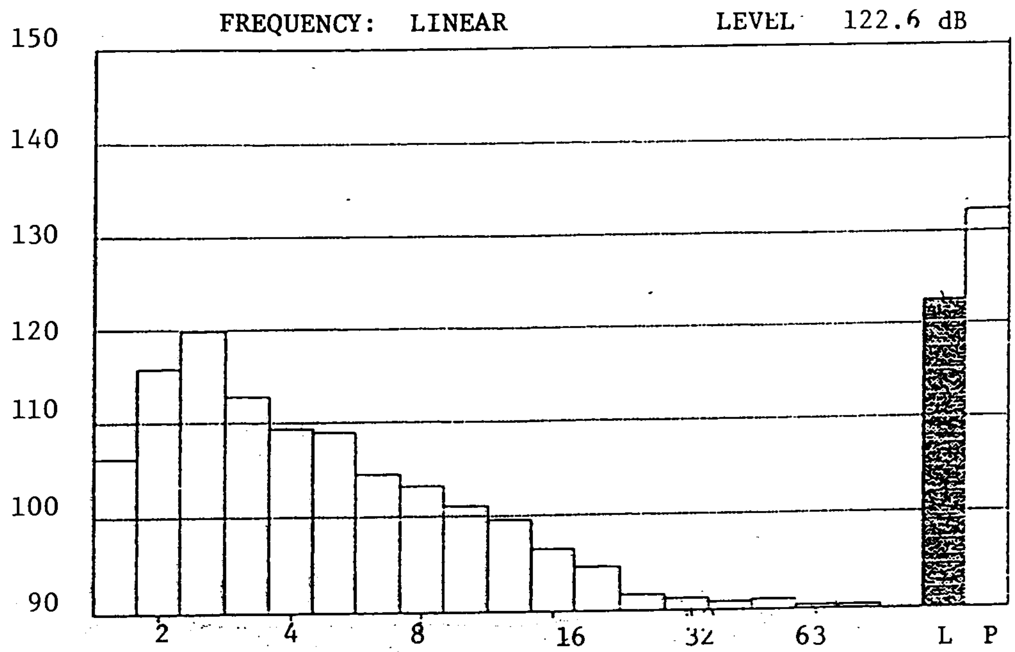
Frequency	Level
2 Hz	108.0 dB
2 Hz	109.3 dB
3 Hz	107.7 dB
3 Hz	103.4 dB
4 Hz	100.0 dB
5 Hz	96.9 dB
6 Hz	95.6 dB
8 Hz	95.0 dB
10 Hz	94.3 dB
13 Hz	92.1 dB
16 Hz	91.6 dB
20 Hz	90.5 dB
25 Hz	90.0 dB
32 Hz	90.0 dB
40 Hz	90.4 dB
50 Hz	91.0 dB
63 Hz	90.3 dB
80 Hz	90.1 dB

<u>Measurement Identification</u>

No. of Spectra: 80
Averaging : Linear
Average time : 1 second

Linear : 114.2 dB
Peak : 131.5 dB

Figure 10. Whole body vibration frequency spectrum at Mine A in the Y-axis for a 6 yd LHD vehicle performing task 2 (mucking).



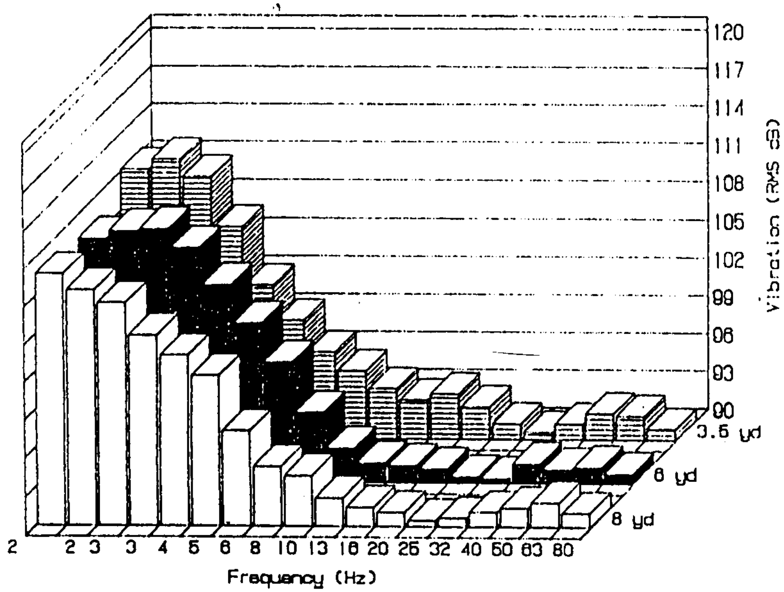
Average Vibration Spectrum

Frequency	Level
2 Hz	106.3 dB
2 Hz	115.7 dB
3 Hz	119.8 dB
3 Hz	112.9 dB
4 Hz	109.4 dB
5 Hz	109.0 dB
6 Hz	104.6 dB
8 Hz	193.2 dB
10 Hz	101.2 dB
13 Hz	99.6 dB
16 Hz	96.5 dB
20 Hz	94.5 dB
25 Hz	91.7 dB
32 Hz	91.3 dB
40 Hz	90.7 dB
50 Hz	91.0 dB
63 Hz	90.4 dB
80 Hz	90.3 dB

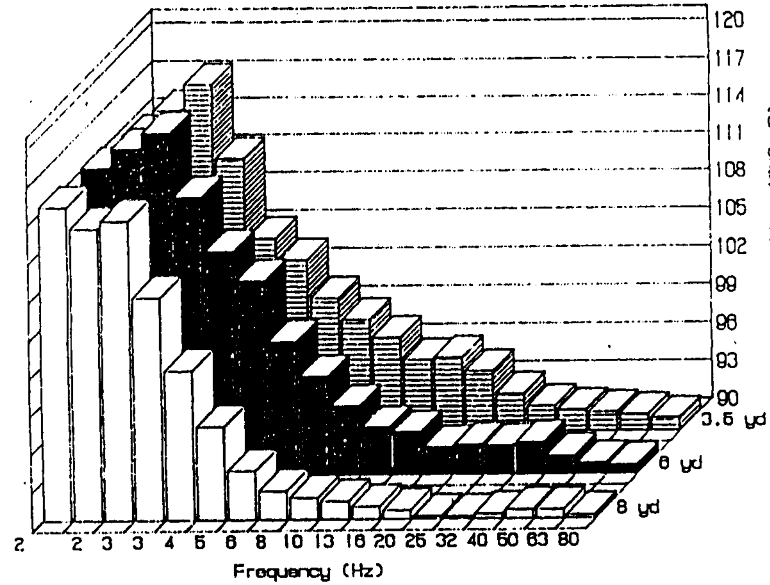
Measurement Identification

No. of Spectra	:	200
Averaging	:	Linear
Average time	:	1 second
Linear	:	122.6 dB
Peak	:	132.4 dB

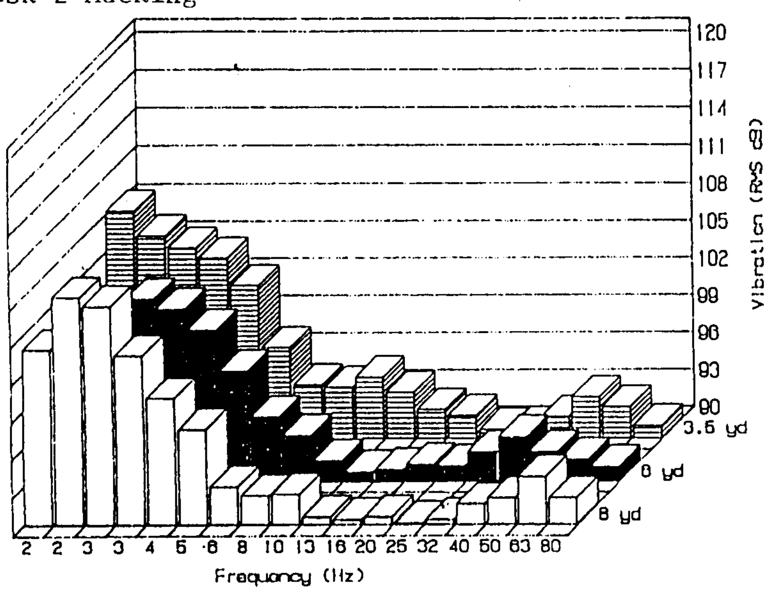
Figure 11. Whole body vibration frequency spectrum at Mine A in the Z-axis for an 8 yd LHD vehicle performing task 3 (driving full).



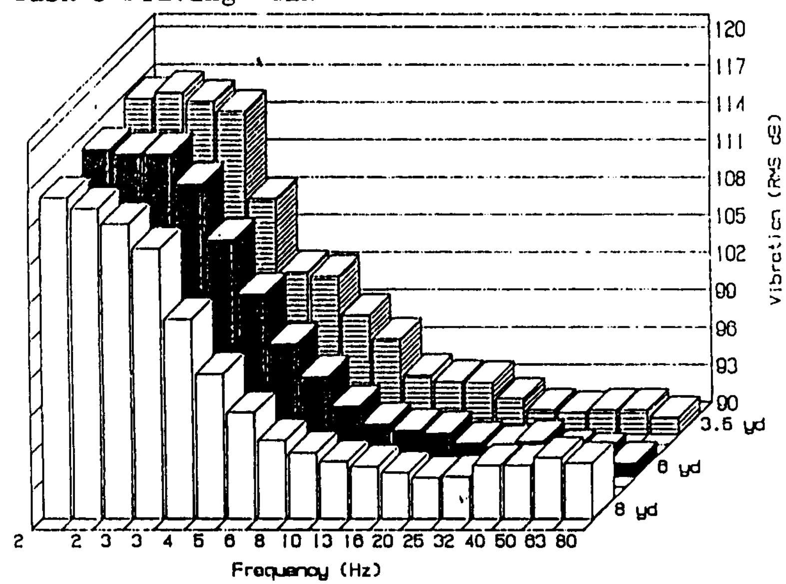
Task 2 Mucking



Task 3 Driving Full

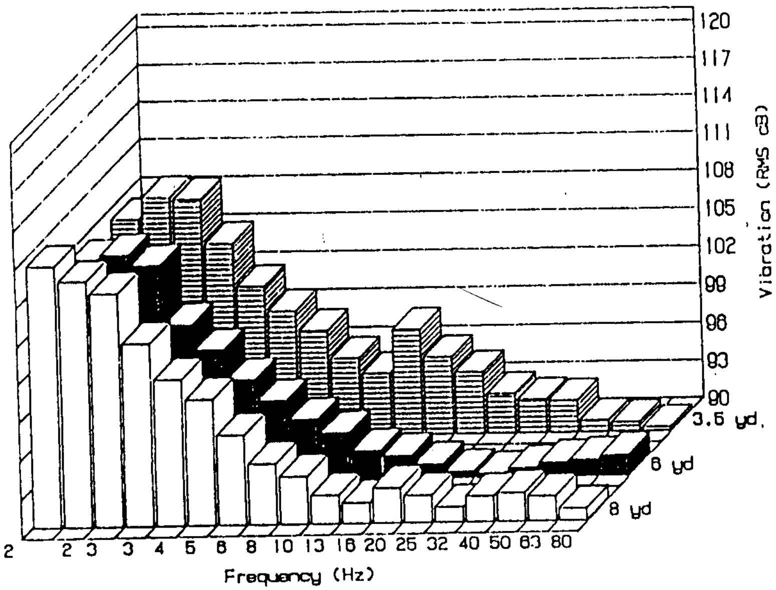


Task 4 Dumping

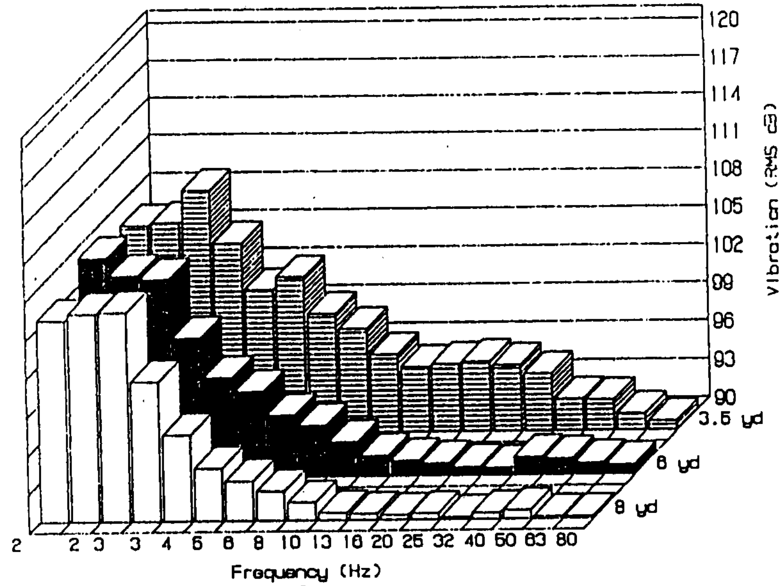


Task 5 Driving Empty

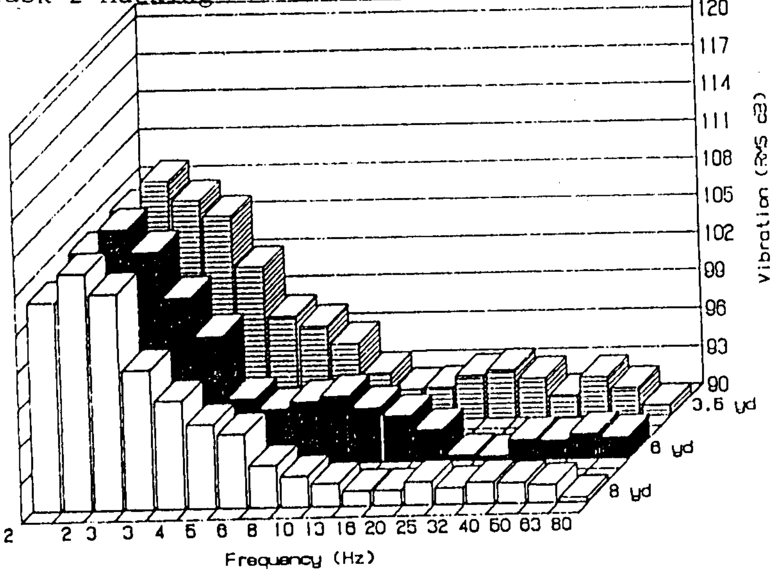
Figure 12. Whole body vibration frequency spectrums for Mine A in the X-axis for each of 4 tasks.



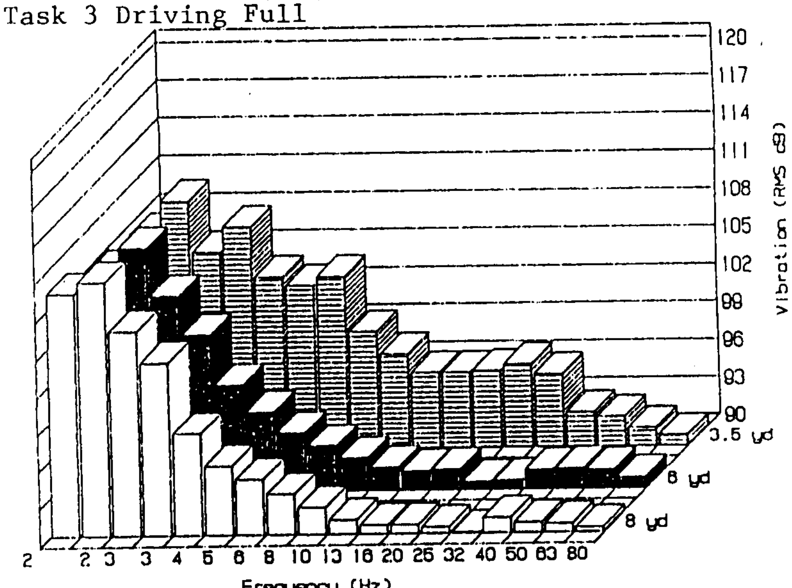
Task 2 Mucking



Task 3 Driving Full

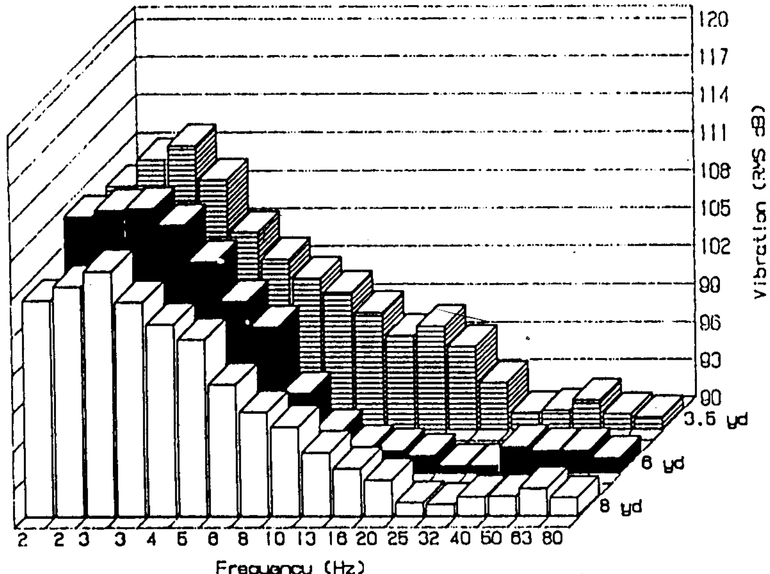


Task 4 Dumping

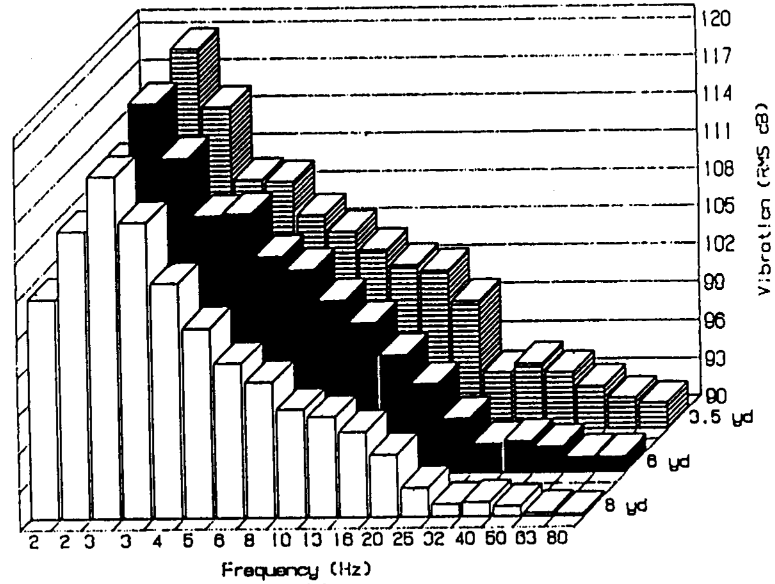


Task 5 Driving Empty

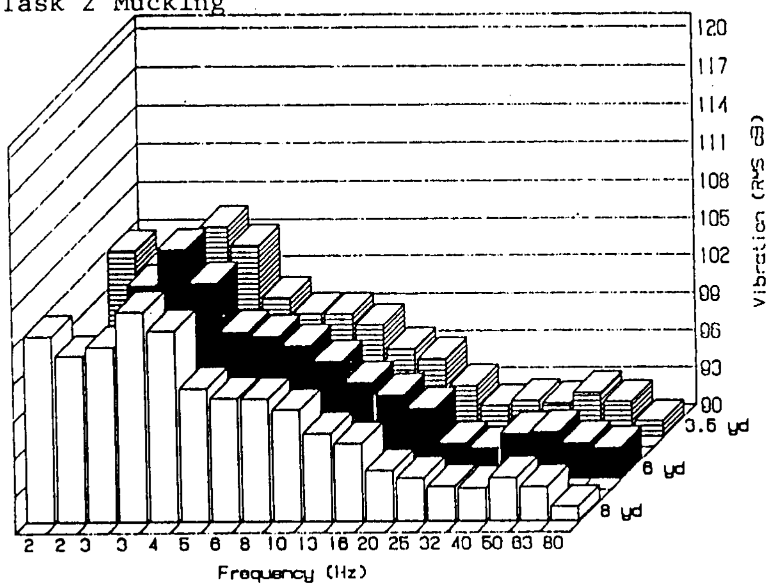
Figure 13. Whole body vibration frequency spectrums for Mine A in the Y-axis for each of 4 tasks.



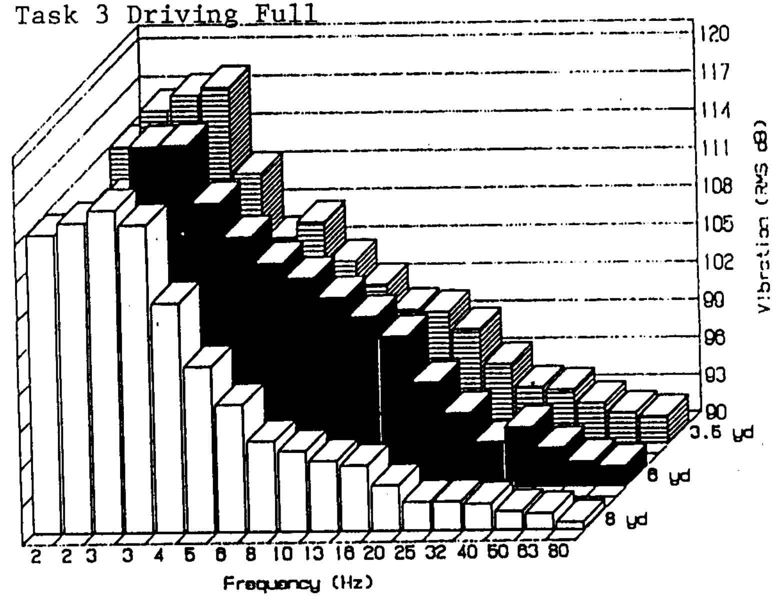
Task 2 Mucking



Task 3 Driving Full

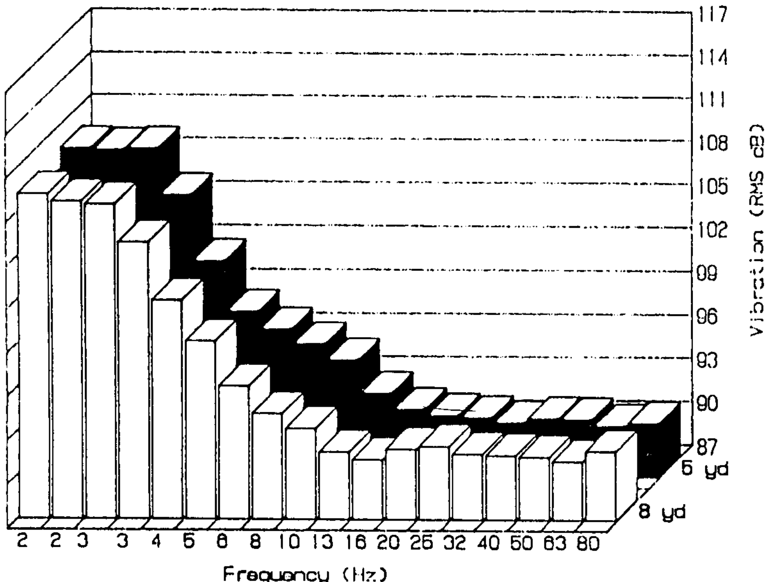


Task 4 Dumping

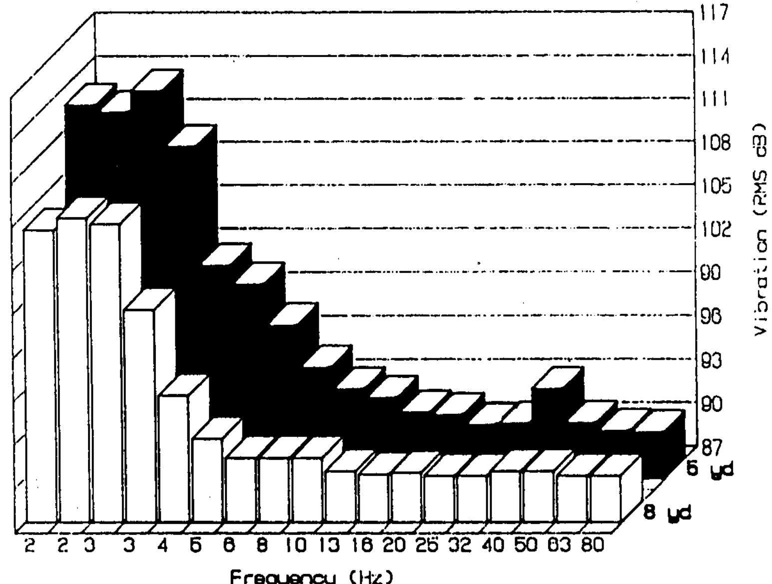


Task 5 Driving Full

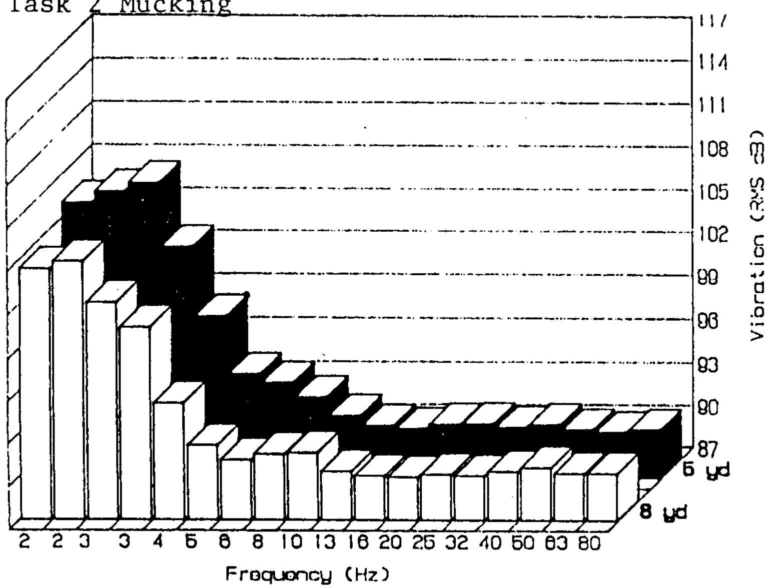
Figure 14. Whole body vibration frequency spectrums for Mine A in the Z-axis for each of 4 tasks.



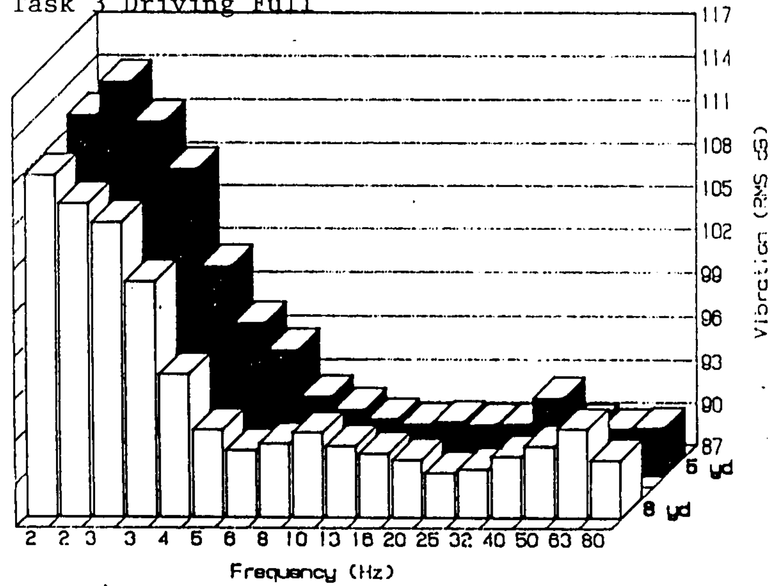
Task 2 Mucking



Task 3 Driving Full

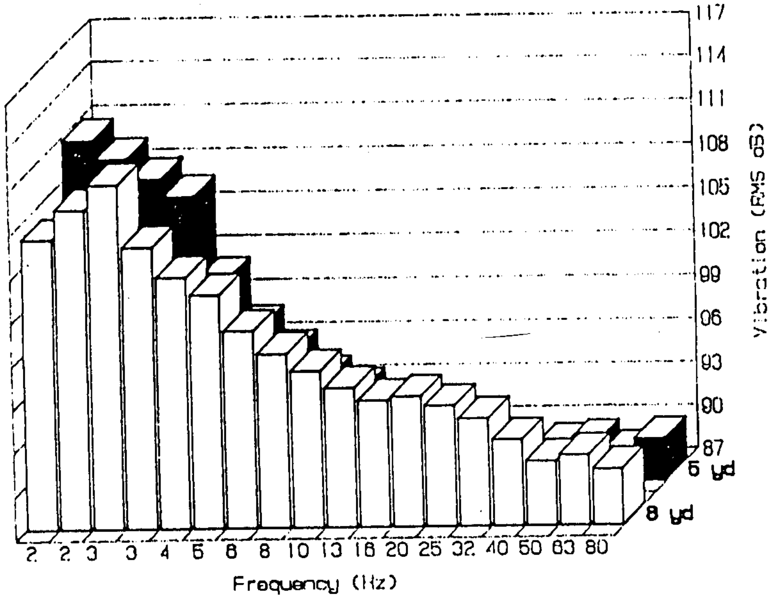


Task 4 Dumping

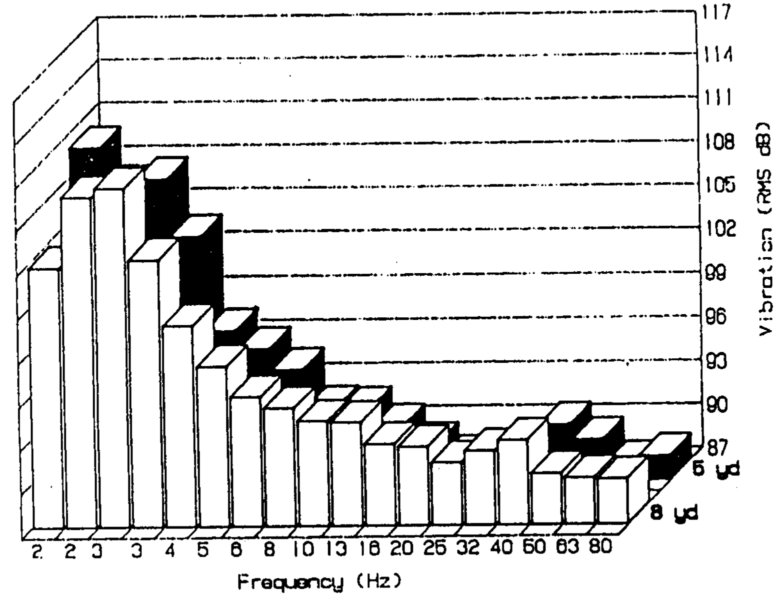


Task 5 Driving Empty

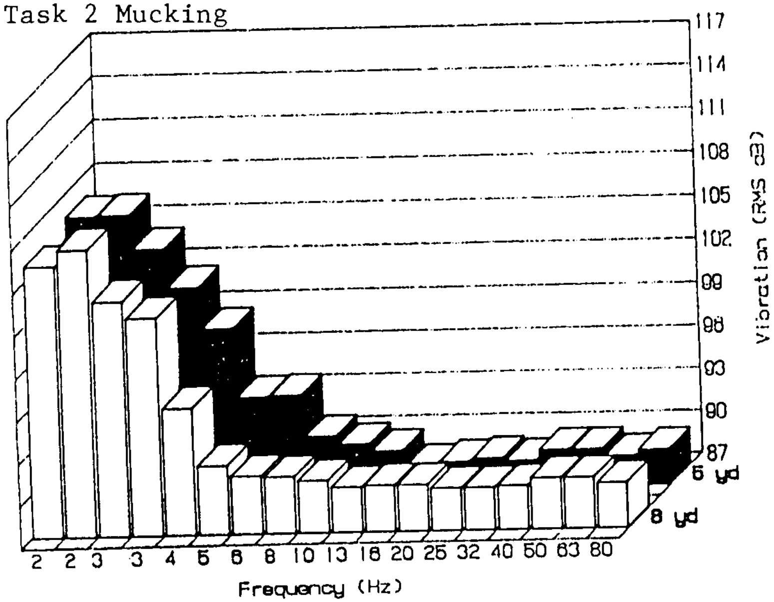
Figure 15. Whole body vibration frequency spectrums for Mine B in the X-axis for each of 4 tasks.



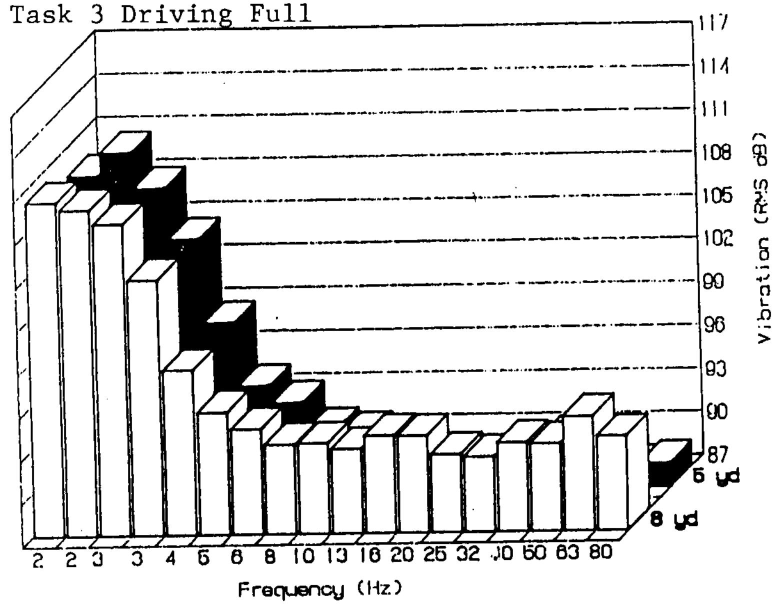
Task 2 Mucking



Task 3 Driving Full



Task 4 Dumping



Task 5 Driving Full

Figure 16. Whole body vibration frequency spectrums for Mine B in the Y-axis for each of 4 tasks.

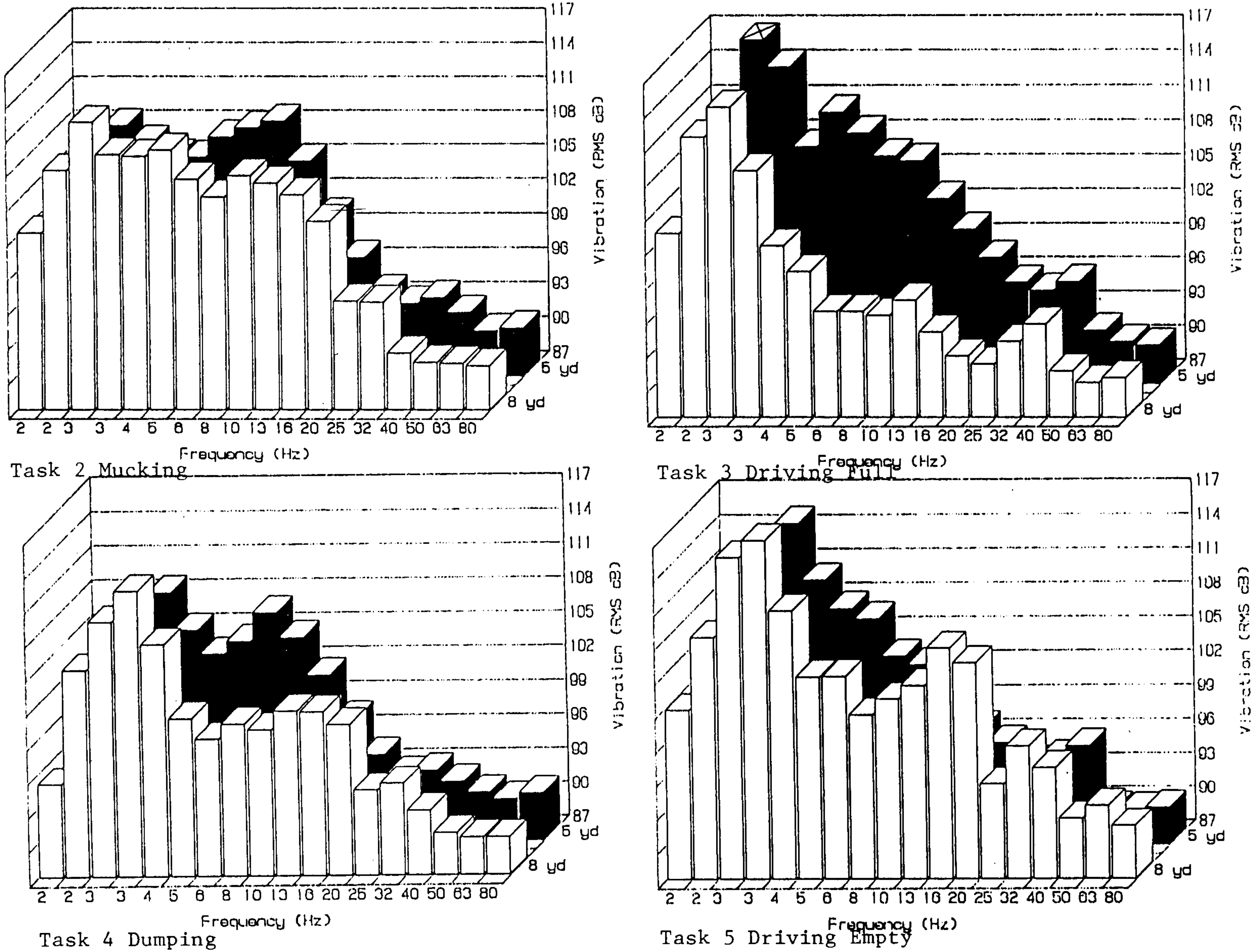


Figure 17. Whole body vibration frequency spectrums for Mine B in the Z-axis for each of 4 tasks.

Discussion

It is postulated that the statistically significant difference found in vibration accelerations between vehicle sizes is due in great part to the mass difference between the three vehicles. The 3.5 yd vehicle produced higher Leq acceleration levels and peak levels than either the 6 yd or 8 yd machines. It is a much smaller, lighter machine and gives a visibly rougher ride than the other two machine sizes. Also, the tires on a 3.5 yd LHD machine are smaller and hence more susceptible to road irregularities. Informal discussions with some operators indicated bias concerning sizes. Several operators reported severe discomfort while operating the 3.5 yd machine, and call the 8 yd machine the "Rolls Royce". The jolting in the 3.5 yd machine often causes the operators to leave the seat, making the operation of controls difficult. The cab space is smaller in the 3.5 yd machine which frequently causes the operators to hit their knees and legs against the frame when driving over bumps in the road.

The difference in acceleration between machine sizes in the z-axis was only significant during the two driving tasks; driving full and driving empty. When driving, as opposed to mucking or dumping, the speed of travel is greater, and the task duration is longer, therefore the road surface and machine mass become important factors. The mucking and dumping tasks were short in duration and involved very slow machine speeds. The majority of LHD motion is due to the bucket hitting the rockpile in mucking and to releasing the load of ore in dumping. These two tasks were seen to produce high peaks in many instances.

The statistically significant difference among the four tasks occurred between the driving tasks and the non-driving tasks. There were no differences in vibration acceleration found between mucking and dumping, or between driving full and driving empty. In most situations, the driving empty task produced slightly higher acceleration levels than driving full (although not statistically significant). This may be due to the lower mass and consequently greater acceleration in response to an applied impulse when unloaded. Also, although the LHD machines are locked in second gear, the travel time when driving empty is slightly faster; see Appendix 2 and 3.

The peak acceleration levels, although random, were very high with many cut off at the 20 $m.s^{-2}$ limit of the vibration meter. The majority of crest-factors were found to exceed the ISO (2631) limit of 6. The vibration to which an LHD operator is exposed may not only be characterized by a high level of low frequency whole body vibration induced by the tires, terrain and the road surface, but compounded by occasional repetitive high level jolts and impacts likely induced by road irregularities as well. "According to the present state of knowledge, one can presume that from the point of view of chronic injuries a vibration with weighted accelerations (crest-factors) of less than or equal to 6 probably lead to no stronger biological reactions whereas those greater than 6 may have stronger effects compared with non shock-type vibration" (Dupuis & Zerlett, 1986). Therefore, the presence of high level jolts in LHD vehicle vibration likely compounds the overall vibration, resulting in a more severe exposure.

A number of factors may be postulated to explain the higher crest factors found at Mine A compared with Mine B, including road design, road conditions, rock characteristics, machine maintenance, and operator training. None of these factors have been tested however. The literature is lacking with respect to the health and safety effects and subsequent recommended doses of high level short duration peaks. It has been shown, however, that vigorous muscle contraction appears to accompany large shocks and induces muscular fatigue (Chaffin & Andersson, 1984). It has also been observed that when the spine is subjected to strong vertical acceleration, compressive spinal fractures may occur (Chaffin & Andersson, 1984; Troup, 1978). In a series of studies where subjects were exposed to varying intensities and combinations of vibration exposure, vibration with higher crest-factors was subjectively rated as more severe than vibration with lower peaks having the same total RMS acceleration (Clarke *et al.*, 1965). In fact, the British utilize peak loads along with RMS acceleration when defining an environment in terms of crew performance ability (Clarke *et al.*, 1965).

The vibration measured while operating the LHD vehicles was predominately low frequency, with the majority below the 4–8 Hz range. The idling frequencies were higher (32–80 Hz) suggesting that engine vibration is not the major cause of vehicle vibration. The low frequency vibrations found in all tasks are probably due to: road conditions; vehicle path, or speed; steering through turns; and changing grades or side slopes in the road terrain. The LHD frequency spectrum was also similar to other rubber tire machines (scrapers, motor graders, and loaders) measured above ground by Wasserman *et al.* (1978). The major frequency bands reported by Wasserman *et al.* (1978) were 0.1–5.25 Hz with accelerations from 0.4–1.3 $m.s^{-2}$. Wasserman *et al.* (1978) reported that about 25% of the major frequency band peaks occur at $\leq$ 0.15 Hz, and 40% of the remaining vibration peaks occur in the 2.12–2.6 Hz frequency range.

The mean daily exposure levels calculated were found to exceed the ISO 6–hour exposure limits (2631, 1978) in both mines, with only one machine (with one operator only) complying with the ISO standards in all three directions. Although there are limitations associated with the ISO standards, the high level, long duration exposures of LHD operators warrant attention. Dupuis & Zerlett (1986) recommend that if there is high stress in more than one axis the situation should be taken particularly seriously. The potentially increased risk of WBV–related performance effects and health disorders when vibration magnitudes are high in all three directions, however, cannot be concretely estimated (Dupuis & Zerlett, 1986). The 1982 amendment to the ISO 2631 included a vector acceleration calculation to combine the effects of the three axes. This signified recognition that the effects of multi–axis WBV on the human body may be greater than that of any single axis motion. When exposure ratio values were calculated using the vector accelerations, all of the vehicles exceeded the permissible value, some by a factor of 12. The high level acceleration measured in the x-axis in LHD vehicles was often responsible for elevating the ratios to extremely high values.

During 1987, the ISO committee circulated a draft document including major revisions to the previous WBV standards. These revisions have not yet been agreed upon. The British Standards Institute have, however, adopted the standards (BS 6841, 1987). The new standard attempts to include the effects of high crest-factor ratios by using the fourth power of acceleration (i.e. $m.s^{-4}$). This gives the peak acceleration values more weight in the overall vibration calculation. The BSI (1987) also states that the severity of vertical axis exposure is increased by the addition of a horizontal exposure, and therefore all three axes should be summed. Since the vibration measured in LHD vehicles contained high crest-factor ratios and high x-axis acceleration, what is suggested by the BSI (1987) standards is that the overall comfort and performance effects on the operators are more severe than previously recognized by the ISO (1978). The results of LHD vibration exposure calculations, especially in light of the new British Standards, suggests that efforts should be made to reduce the duration or magnitude of WBV exposure in LHD operation.

In calculating the mean daily exposures, the two driving tasks had the highest acceleration values and also were performed for the longest proportion of time. An LHD operator at Mine A spends approximately 85% of his 5.5 hour operating day driving full or driving empty. At Mine B, the two tasks account for 72% of the 5.4 hours of operating time. An operator is also responsible for cleaning and servicing the vehicle and maintaining the roadway. This slight difference between the two mines in exposure time for the two driving tasks may be due to different average road distances to the dumping point. The exposure times for idling, mucking and dumping are longer at Mine B which may mean there were a greater number of cycles and shorter turnaround time. This difference in the amount of driving time between the two mines might account in part for Mine B having slightly lower acceleration levels.

According to Dupuis & Zerlett (1986), failing to comply with the ISO standards in any one of the three x, y, or z directions renders the WBV exposure as severe and capable of compromising worker safety and health. The exposure limit recommended is set at approximately half the level considered to be the threshold of pain (or limit of voluntary tolerance) for healthy human subjects (ISO 2631, 1978). The ISO guidelines are very similar to the German K Factor. Dupuis & Zerlett (1986) stress that according to the present state of knowledge, from the point of view of the intensity of vibration, these guidelines appear to be a valid foundation for the evaluation of the question as to whether a certain stress represents a risk to the health of the vertebral column. A recent critical review of the long term effects of whole body vibration by Seidel & Heide (1986) however concluded that the "data existing today do not permit the substantiation of a safe limit reliably preventing diseases of the locomotor and peripheral nervous system. Long term exposures below or near the Exposure Limit of ISO 2631 (1978) were not without risk" (Seidel & Heide, 1986). Their conclusions, based on a review of 78 papers with quantitative data, support the view that the Exposure Limit is a minimum requirement at all work-places, rather than a limit reliably protecting health. The authors recommend that in no cases should the 4-8 hour limit be exceeded at workplaces, and the z direction limit especially should be lowered. The results of this investigation revealed that 96% of the LHD vehicles tested exceeded the ISO limits in at least one direction. Many exceeded the limits in all three directions.

In their review, Seidel & Heide (1986) hypothesize a two-phase development of long-term effects with respect to the back. In the first phase, WBV causes a muscular weakness and reduction of intervertebral spaces. This results in increased spinal mobility and consequent instability in the motion segments. In the second phase, the long term strain of

WBV causes manifest degenerative changes in the vertebral structure, resulting in a decrease in mobility. The alteration of biochemical processes and blood supply may be a further factor (Seidel & Heide, 1986; Seidel *et al.*, 1986). The most common injury area for LHD operators was found to be the back, with "surface rough" and "sudden start/stop" as contributing factors. It is plausable that the high levels of WBV and jolts to which an LHD operator is exposed are contributing to this high incidence of back problems either directly, or by weakening structures thus pre-disposing them to injury. Also, LHD operators had an unusually high incidence of neck problems. It may be that the high WBV levels found in the x direction contribute to this. It may also be that the twisted neck posture assumed by the LHD operator leads to neck disorders. Seidel & Heide (1986) report a high incidence of neck disorders associated with a lower intensity of WBV, suggesting that non-vibration related conditions dominate as causes for this morbidity. Alternatively, the high neck injury incidence may be a combination of both poor posture and high WBV factors.

Preliminary medical examinations and regular medical check-ups have been recommended for workers exposed beyond the exposure limit (Seidel & Heide, 1986). The "Occupational Health Regulations for Prevention Against WBV" are presently being prepared in Germany to outline procedures for physical examinations for workers exposed to WBV (Dupuis & Zerlett, 1986). In the initial examination, a general examination, thorough work history and special examinations (for example, of spinal columns and stomach) would be administered. A list of medical disqualifications for people to be employed under exposure to WBV includes clear degenerative diseas of the spinal column, duodenal diseases (gastritis), and chronic stomach disorders. The regulations advise follow-up examinations in workers up to 50 years of age every 4 years, and in those over 50 years of age every 3 years.

In a review of WBV literature from forestry equipment, Rummer (1986) summarizes the main factors thought to affect vibration in forestry machinery:

1. Tire flexibility - stiffer tires cause more vibration
2. Tire size - larger tires bridge smaller objects, reducing vibration
3. Axle suspension - bogies and swing axles reduce vibration of the machine
4. Transmission - sensitive speed control can improve operator response to rough terrain
5. Location of operator - the greater the distance from the center of mass, the more vibration
6. Driving style - careful attention to driving can reduce vibration
7. Speed - the most important factor.

These variables were not isolated in this study. The difference in vibration between sizes of machine may be due to a combination of mass and tire size. Machines in underground mines historically have not been equipped with any type of suspension system. The likely reasons include the harsh environment, relatively poor maintenance of equipment, height and space restrictions, cab being open to the environment, additional costs for designing and installing suspensions, and a lack of emphasis on suspension systems or improved seating design on underground equipment either from the manufacturers, mine operators (management), or government regulatory agencies. Sealants and materials used for seat cushions, and mounts for isolating shock and vibration must comply with rigid requirements dealing with toxic fumes and fire hazards (Crolla *et al.*, 1984).

Conventional off-road vehicles use passive vibration methods (spring and damping element), but these actually amplify vibration at lower frequencies (Crolla *et al.*, 1984) In order to absorb vibration they must have a low natural frequency, but this corresponds to large static and dynamic deflections which may not be desirable for seat design or for operator control (Crolla *et al.*, 1984). A great deal of research has gone into the development of "active suspensions" for applications such as tractors (Gunderson & Wilson, 1981), with varying amounts of success. These seats simultaneously sense and compensate for vibration input. However, cost and reliability have limited their use. The seat/suspension system, to be effective, can either reduce the level of vibration acceleration across all frequency bands, or shift the dominant frequency band to one at which the human body is less sensitive. Where vibration levels are high in greater than one direction, this becomes more difficult (Crolla *et al.,* 1984).

Remington (1984) analyzed a number of common seating and suspension systems for vibration reduction. Four seats were "high performance" seats and the fifth had a mechanical spring suspension. Three of these "high performance" seats are commonly found on LHD machines. In ratio comparisons between seat vibration and floor vibration, Remington found substantial vibration in all directions. The "high performance" seats were not notably better than the standard spring seats. All of the seats provided from 5–100 dB of isolation in the vertical direction, but none of the seats reduced the vibration in the 1–2 Hz range in the x or y directions. To be effective, a seat must isolate in all three directions.

There are few jurisdictions with preventive regulations regarding WBV in Occupational Safety and Health Documents. In the Federal Republic of Germany, general guidelines exist for agricultural tractors stating that the "noise and mechanical vibration affecting the driver in the driving cab or driver's space is not allowed to surpass what can be reasonably avoided, according to the present status of technology", and "the seat must be sufficiently suspended, upholstered, and damped" (Dupuis & Zerlett, 1986). The German Agricultural Injuries Insurance Institute has a work protection regulation for agricultural vehicles (1970) which has also been standardized for the European Common Market, including a testing procedure. The highest threshold corresponds to a frequency-weighted RMS acceleration of 1.25 $m.s^{-2}$ in the z direction. When this threshold is compared to the LHD mean daily exposure values measured in the z direction, 11 of 12 LHD vehicles at Mine A and 2 of 9 vehicles at Mine B surpass the 1.25 $m.s^{-2}$ threshold. In some LHD vehicles measured, the x direction vibration was higher than the z direction. It is therefore important that thresholds be incorporated for the x and y directions as well. The preventive regulation "Vibration" is in preparation in Germany with instructions regarding the occurrance and sources of vibration risk as well as measures for protection from vibration (Dupuis & Zerlett, 1986).

The use of engine damping to solve both noise and vibration problems has increased in recent years with the new regulations on highway vehicle noise levels. Engine damping requires the identification and ranking of magnitudes of all the major vibration contributing components, for example, oil pans, valve covers, timing gear, etc.. All sheet metal components have resonances excited by engine forces under typical operating conditions. Some success has been reported with sandwich configurations to dampen the sheet metal components (Nashif, 1983). This approach is less costly than building enclosures to isolate components which may lead to undesirable leakage at the joints and adds to product weight, cost, handling and serviceability costs. The most common engine damping approaches include source modification, stiffening modification, mass modification, isolation, damping and/or barriers or enclosures. The effectiveness of damping material is evaluated on the basis of its ability to dissipate vibrational energy into heat, noting temperature, frequency and other environmental factors.

When a vehicle travels over a road, resonance may be produced by the vehicle system as described, but also by the road profile. A road profile is described by its surface roughness. Resonance is undesirable for the operator, but it also affects the road surface, the vehicle suspension system, and the engine (Farah, 1982). Farah (1982) found that road roughness correlated with human ratings of ride quality and he used a biomechanical model to predict the absorbed power. The model was found to be a good indicator of road serviceability. Clearly more work is needed in the area of road design and road surface improvement to lesson vibration exposure in off-road vehicles. In an unpublished study of underground mining vehicles sponsored by Noranda Research (Personal Communication with

Mr. Guy Nollet), the vibration levels and crest-factors of LHD machines were found to be extremely high (actual values were not made available). It was felt that the most important factor in reducing the vibration levels was the road condition. The authors report 30% reductions in RMS vibration with well-graded roads. A great deal more quantitative investigation is required to determine which factors are most important, effective, and economical for LHD machines in underground environments.

CHAPTER VI

PERFORMANCE MEASURES

Introduction

The purpose of this phase of the research was to examine the effects of WBV on selected indices which may be important for worker safety, health, and comfort. Subjects were the LHD operators from the two previously described mine locations. Inclusion was based on a minimum of two years experience driving LHD machines. A brief health questionnaire was used to screen operators for prescription medications or visual, circulatory, muscular and nervous system diseases or injuries (see Appendix 4). Two performance tests were chosen to measure vibration effects on visual acuity, and manual dexterity. Each test is discussed in greater detail below.

Visual Acuity

Rationale for Choice of Visual Acuity

Visual acuity was chosen as a performance measure for a number of reasons. It has been identified as a sensitive performance measure of vibration (Griffin, 1975), and the loss of visual acuity is proportional to the amplitude of vibration exposure (Ramsey, 1975). It is not affected by noise, temperature change or many of the other stresses of the underground environment (the effect due to poor lighting underground was controlled). Visual acuity has important implications for the safe driving of LHD machines, and a decrement in visual acuity may be a contributing factor in underground accidents. Also, increased disorders of the eye are a documented chronic effect of WBV, particularly narrowing of the arterial vessels (ILO, 1976). The acute effects of WBV on visual acuity of LHD operators may be measured immediately after a shift of driving. It could be reasoned that frequent episodes of acute exposure could eventually lead to chronic visual disorders.

Methods

Visual acuity is commonly measured by the Snellen fraction V = d/D, where: V=visual acuity, d=the distance at which a standardized symbol can be discriminated, and D is the distance at which that symbol subtends one minute of arc (Grusser, 1983). The symbols are letters in a Snellen chart. For far-sightedness, the chart was held a standardized distance from the person to be tested (20 ft.) and D was calculated from the size of the smallest letter the person could read. For people with normal vision, D is the same as the test distance, so the Snellen fraction is 20/20. For near vision, the chart was held at a close, standardized, distance from the subject (32 in.), and the test was repeated. In a routine examination, each eye is tested individually with the other eye covered, during both the near-and far-sighted tests. In this study the subjects were tested in a near-and far-sighted test with eyes uncovered as in normal viewing. Driving an LHD vehicle requires near visual acuity in control operation and monitoring of machine dials, as well as far visual acuity for driving tasks such as negotiating corners. If corrective lenses were normally worn, they were worn during the testing.

To prevent subjects memorizing the order of the letters on the chart, four different charts were constructed for the four conditions of pre/post shift, and near-and far-sighted tests in which they participated. However, each line contained the same letters, (as some are more difficult to discriminate than others) in a random presentation. As a subject proceeds through the chart not only does the size of letters decrease, but the number of letters per line increases. The D = 30 line contains 6 letters, D = 20 contains 7 letters, and D = 15 contains 8 letters. For a subject to move on to a new line on the chart, he/she must successfully identify all the letters on the current line. If one or two errors are made, this was reflected in the acuity score such that a finer score breakdown was possible. For example, one error at the D = 20 line yielded a score of 21.4, two errors yielded 22.8 and so forth. If all 7 letters were in error, the score would be 30 which is the test score of the previous line which is completed correctly (see Appendix 5).

In an underground environment where the lighting is limited mostly to a caplamp, the lack of illumination itself may lead to decrements in visual acuity over the course of a shift. Because of this complication, a control group of male underground workers in similar lighting levels were measured for visual acuity. This group included foremen and labourers not exposed to whole body, or hand-arm vibrations. The second control group were surface workers who were not exposed to whole body, or hand-arm vibrations, or to an eight-hour lighting decrement. The lighting decrement may have a negative effect on visual acuity. The surface group were male and female seated office workers.

Environmental measures were taken at each testing site, both underground and on the surface, of: lighting (luminance, or light coming from the chart (cd/m^2), general area illumination (lux), and illumination (lux), or light falling on the chart; noise (dBA); temperature and relative humidity (wet bult; dry bulb). Noise and temperature were monitored and maintained within normal ranges for the particular environment. Extreme environmental conditions may act as a generalized stressor and affect performance test results. The lighting levels underground were found to be similar, while the lighting on surface was much improved. The lighting, noise and temperature data and measurement equipment information may be found in Appendices 6 and 7.

A pre-test with 15 male and female subjects at Simon Fraser University failed to show a statistically significant difference in pre/post visual acuity scores for near-or far-sighted vision following a normal day of office and VDT work. Some of the subjects reported tired eyes at the end of the day, but eye fatigue should not alter a visual acuity score. The variance in the pre-test subjects (SD = 3.72) was used to determine the minimum sample size. In order to distinguish a difference of 2.0 in a visual acuity score (approximately 1 letter in error out of 7 at the 20:20 line) with a 95% power of confidence, a sample size of 13 was required. A total of 16 LHD operators, 14 underground workers and 17 office workers from both mines participated in the visual acuity measures. A health questionnaire was filled out with participants prior to the tests to identify any eye or visual disorders, injuries or medications which may affect visual acuity testing (see Appendix 4).

The above ground control group was tested for visual acuity prior to and following their work shift, in their normal ambient lighting. The LHD operators and the underground control group were tested prior to shift and at the end of shift in a haulage turn-around area underground. This area was outside the path of LHD vehicle traffic but had similar lighting conditions. The workers came directly to the test area prior to beginning work underground. At the end of their shift the LHD operators drove directly to the test area so the measurements were taken within three minutes after exposure cessation. The near and far visual acuity tests required approximately five minutes to administer. The same testing site was used for both LHD operators and underground workers in both the pre and post measurements. However, due to the transient location of operators, the sites changed from day to day. As seen in Appendix 7 however, the environmental conditions were similar.

A 2 x 3 Repeated Measures Analysis of Variance (ANOVA) statistical design was used to compare the difference in visual acuity scores from pre to post shift for the three groups. The pre and post scores were the repeated measures across the three groups. Data were analyzed by the Michigan Terminal System (MTS) Computer at Simon Fraser University using the University of California, Department of Biomathmatics (BMDP 2V) Statistical Software program (Dixon, 1981).

Manipulation and Dexterity

Rationale for Choice of Manipulation & Dexterity

Inhibition of isotonic feedback during co-ordinated manual tracking has been reported as an effect of WBV exposure resulting in overshooting and undershooting of discrete movements (Lewis & Griffin, 1976). Decrements in reaction time and steering ability in simulated driving tasks under various combinations of frequencies and amplitudes of WBV are also well documented (Hornick, 1961; Matthews, 1966; Ramsey, 1975; Khalil & Ayoub, 1976). Manual dexterity, as well as speed of movement and accuracy, is an important function in the use of LHD vehicle controls. A driver may have to respond quickly with discrete hand/arm movement in a driving situation, and degradation of this movement control may play a role in accidents and injuries, especially in emergency situations.

Methods

A Purdue Pegboard was used to test the effect of vibration exposure on manual dexterity. The pegboard measures gross movements of the hands, fingers and arms, in terms of speed and accuracy. The test was first developed in 1948 and standardized after extensive experimentation in numerous plants, testing several thousand employees in a wide variety of industrial jobs (Tiffin, 1948). Test-retest reliabilities were obtained by correlating scores for one trial on the test with one-trial scores obtained two weeks later. Reliabilities ranged from 0.6 to 0.76 for one-trial scores, and between 0.82 and 0.91 for three-trial scores (Tiffin, 1948).

The administration and scoring is standardized. After instructions, demonstration, and a practice trial, scores are normally recorded for right hand, left hand, both hands, a composite (right + left + both), and an assembly task (for finger dexterity). For this study, only the two–handed test was used for time expediency and since LHD operators are most often required to continuously use two hands in operation of their vehicle. The score was determined by the summation of properly placed pegs at the end of the 30 second timed task duration. The norms for male industrial applicants were used for comparison (Tiffin, 1948). Typical scores range from 9 (1st percentile) to 18 (100th percentile).

The test was given to the LHD operators prior to and at the end of shift in the same environmental conditions as the visual acuity tests were administered. The health questionnaire (see Appendix 4) was used to screen out any operators on medication or suffering circulatory, muscular or nervous system diseases or injuries which may have altered test scores, such as vibration white finger disease and rheumatoid arthritis. The same control group of underground foremen and labourers, who are not exposed to heavy manual labour but had worked a full shift in the same lighting and other environmental conditions, were used for comparison. A shift of heavy manual labour may have fatigued subjects and caused a poorer manual dexterity test score at the end of the day. Control subjects were tested prior to and at the end of the shift in the same conditions as the LHD operators.

A pre–test was conducted at Simon Fraser University with 15 student subjects. A learning curve was drawn with the mean results of six consecutive trials. The curve plateaued and there was no significant difference in scores between the fifth and sixth trial as tested in a one–way analysis of variance. The workers underground therefore performed five consecutive learning trials in the pre–exposure condition to reach the plateau of the learning curve for the task.

The University students were re-tested at the end of a day of typical office and computer work. There was no statistically significant difference between the sixth pre-test score and the post score. The variance between the scores among the students (SD = 1.36) was used to estimate the minimum sample size. In order to detect a difference score of 1 in the manual dexterity test pre to post shift with a 95% power of confidence, a sample size of 7 subjects was required. The same subjects participating in the visual acuity tests participated in manual dexterity test, yielding a total of 16 LHD operators and 14 underground workers from both mines. Since it is the pre-post difference that is important rather than the actual test score, lighting is not a complication. The office workers were not required as a third group.

A 2 x 2 Repeated Measures Analysis of Variance (ANOVA) statistical design was used to analyze the differences in pre and post manual dexterity test scores between the two groups. The pre and post test scores were the repeated measures across the two groups. Data were analyzed by the MTS Computer at Simon Fraser University using the BMDP 2V Statistical Analysis program (Dixon, 1981).

Results

The demographic data for the underground subjects is found in Appendices 8 and 9. The mean age among underground workers was slightly higher than that for LHD operators; 38.9 and 33.7 years respectively. The mean weight and height among both groups were very similar.

The results for the Visual Acuity Near and Far tests for the three occupation groups are presented in Tables 30 to 32. In the Visual Acuity Far tests the pre-shift means for office workers, underground workers, and LHD operators were 19.5, 26.28 and 27.38, respectively. The post-shift visual acuity scores improved slightly in office workers (17.9) and

Table 30. Visual acuity test data for LHD operators in near and far tests, pre and post shift.

	FAR VISUAL ACUITY (20')		NEAR VISUAL ACUITY (32")	
	PRE	POST	PRE	POST
Subject				
1	30.0	30.0	30	24
2	31.7	28.6	26	30
3	31.7	31.7	30	25
4	24.3	33.3	20	30
5	21.4	20	18.3	20
6	24.3	31.7	26	35
7	30	44	32.5	30
8	48	35	30	52
9	15.6	21.4	21.4	35
10	31.7	20	20	32.5
11	31.7	31.7	30	30
12	25.8	27.2	30	30
13	25.8	24.3	28	22
14	25.8	30	30	32.5
15	17.5	21.4	22	22
16	22.8	17.5	20	30
Sum	438.1	447.8	414.2	480
Mean	27.38	27.99	25.89	30.0
Standard Deviation	7.5	6.9	4.8	7.5

Table 31. Visual acuity test data for underground miners in near and far tests, pre and post shift.

	FAR VISUAL ACUITY (20')		NEAR VISUAL ACUITY (32")	
	PRE	POST	PRE	POST
Subject				
1	22.8	27.2	32.5	48
2	31.7	31.7	30	15.6
3	17.5	30	17.5	17.5
4	42	30	30	30
5	31.7	24.3	32.5	30
6	24.3	16.3	28	24
7	21.4	21.4	30	30
8	16.9	17.5	26	20
9	16.9	16.3	20	20
10	42	30	30	30
11	35	42	30	30
12	21.4	22.8	30	24
13	24.3	21.4	22	20
14	20	20	30	22
Sum	367.9	350.9	388.5	361.1
Mean	26.28	25.06	27.75	25.79
Standard Deviation	8.7	7.2	4.7	8.1

Table 32. Visual acuity test data for office workers in near and far tests, pre and post shift.

	FAR VISUAL ACUITY (20')			NEAR VISUAL ACUITY (32")	
	PRE	POST		PRE	POST
Subject					
1	21.4	16.3		20	15
2	22.8	21.4		20	20
3	11.1	10.5		15	15
4	24.3	22.8		17.5	16.6
5	15.0	16.9		20	20
6	12.7	15.6		15	16.6
7	15.0	15.6		15.8	15.8
8	21.4	21.4		18.3	20
9	21.4	16.3		15.8	15.8
10	15.6	15		15.8	15.8
11	31.7	22.8		20	16.6
12	15	15.6		16.6	16.6
13	16.3	16.3		20	20
14	22.8	21.4		22	24
15	22.8	20		15.8	16.6
16	16.9	15.6		15.8	15.8
17	25.8	21.4		20	15
Sum	332.1	304.9	Sum	303.4	295.2
Mean	19.5	17.9	Mean	17.8	17.4
Standard Deviation	5.4	3.5	Standard Deviation	2.3	2.5

underground workers (25.06) but worsened slightly in LHD operators (27.99). When tested with an analysis of variance, a significant difference was found between the three groups (F = 10.2, df = 2/44, $\alpha \leq .01$), but no significant pre/post effect or interaction between trials and groups were found. The office workers scored better on the tests. The difference is likely due to the better lighting conditions on surface (see Appendix 7). A Tukey's post hoc analysis (Kirk, 1968) revealed that the significant difference between groups was found between office workers and LHD operators, and between office workers and underground miners. There was no significant difference between the two underground groups.

In the Visual Acuity Near tests the pre-shift means for office workers, underground workers and LHD operators were 17.8, 27.75 and 25.89, respectively. The post-shift scores improved in office workers (17.4) and underground workers (25.79), but worsened in LHD operators (30.0). An analysis of variance revealed a significant between groups effect (F = 28.06, df = 2/44, $\alpha \leq .01$) and a significant interaction between trials and groups (F = 3.64, df = 2/44, $\alpha \leq .01$). This is displayed graphically in Figure 18. A one-way analysis of variance with the pre to post difference scores in the LHD operator group showed non-significance. A one-way analysis of variance with the pre to post difference scores in the underground control group also showed non-significance. The LHD operators and the underground miners seemed to respond differently when tested post-shift which resulted in a significant interaction effect. Neither group on its own however had a strong enough pre to post difference score to eliminate the variance due to chance. A Tukey's post hoc analysis (Kirk, 1968) on the three groups showed a significant difference between office workers and LHD operators and between office workers and underground miners in both the pre test scores and the post test scores when analyzed separately.

The results for the Manual Dexterity Purdue Pegboard test are displayed in Tables 33 and 34. From the tables it may be seen that the average score of the fifth trial for LHD

VISUAL ACUITY-NEAR TEST RESULTS PRE TO POST SHIFT

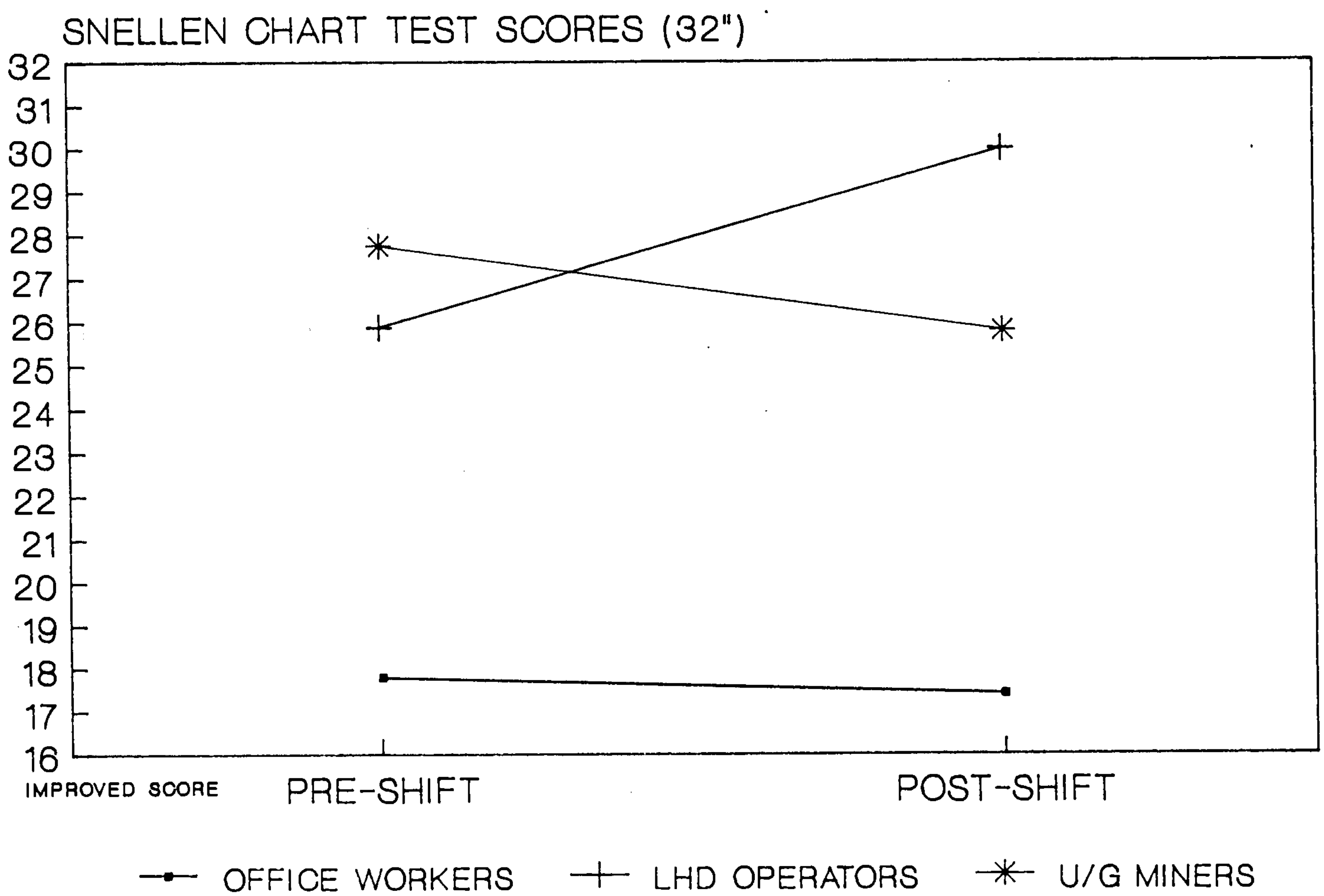


Figure 18.

Table 33. Purdue pegboard test data for LHD operators pre and post shift.

Subjects	Pre-Shift Learning Trials					Post-Shift
	1	2	3	4	5	
1	14	16	15	15	16	15
2	10	11	12	11	11	11
3	12	10	10	11	13	10
4	12	11	10	12	11	11
5	12	14	13	13	13	11
6	13	12	13	13	14	12
7	12	10	11	12	11	11
8	14	14	13	12	13	12
9	10	10	10	10	11	11
10	10	12	12	13	12	10
11	11	12	12	13	13	13
12	10	11	13	12	12	13
13	12	13	14	14	14	14
14	11	13	14	13	13	12
15	10	11	11	11	11	12
16	12	14	13	14	15	15
Sum	185	194	196	199	203	193
Mean	11.56	12.125	12.25	12.44	12.69	12.06
Standard Deviation	1.36	1.75	1.53	1.31	1.24	1.57

Table 34. Purdue pegboard test data for underground miners pre and post shift.

Subjects	Pre-Shift Learning Trials					Post-Shift
	1	2	3	4	5	
1	11	11	12	12	12	12
2	11	12	13	13	13	14
3	11	13	13	13	13	13
4	11	11	10	12	11	9
5	11	11	11	12	12	11
6	11	12	12	13	11	13
7	10	10	12	11	12	11
8	9	11	12	9	10	11
9	11	12	10	13	13	14
10	11	11	12	10	11	13
11	12	12	12	12	12	13
12	8	10	10	10	11	11
13	12	12	12	13	13	13
14	12	10	11	12	11	11
Sum	151	158	162	165	165	169
Mean	10.79	11.3	11.6	11.79	11.79	12.07
Standard Deviation	1.12	.91	1.02	1.31	1.68	1.44

operators and other underground workers were 12.69 and 11.79 respectively. These results correspond to a 65th and 50th percentile when compared with the norms for industrial applicants (Tiffin, 1948). LHD operators have typical manual dexterity scores when compared with other industrial workers. In the post-shift measures, the mean for LHD operators dropped to 12.06, while the mean for other underground workers rose to 12.07. The analysis of variance revealed no significant differences between the two groups (LHD operators and underground miners). There was also no significant difference between the pre and post measures. However, there was a significant interaction between trials and groups ($F = 5.27$, $df = 1/29$, $\alpha \leq .05$). These results imply that although there was no difference in manual dexterity test scores between underground miners and LHD operators, a different test response resulted following a day of work. The possibility that these results could have occurred by chance is only 5%. The average scores are displayed graphically in Figure 19. A one-way analysis of variance with the difference scores in the LHD operators group revealed significance. Therefore, the difference between pre and post scores is significantly different from zero at the 5% level, and not likely to have occurred by chance. A one-way analysis of variance with the difference scores in the underground miners revealed non-significance. The positive interaction was therefore due mainly to the LHD operator's experience. The LHD operators scored lower following a shift of driving, while the underground miners scored the same following their shift.

Discussion

The results of the visual acuity tests showed no significant difference in visual acuity scores between the LHD operators and the underground miners. No conclusions may be drawn about the chronic effects of WBV on the visual system. The better scores among office workers were expected, as these workers were tested in improved lighting conditions. There

MANIPULATION & DEXTERITY TEST RESULTS PRE TO POST SHIFT

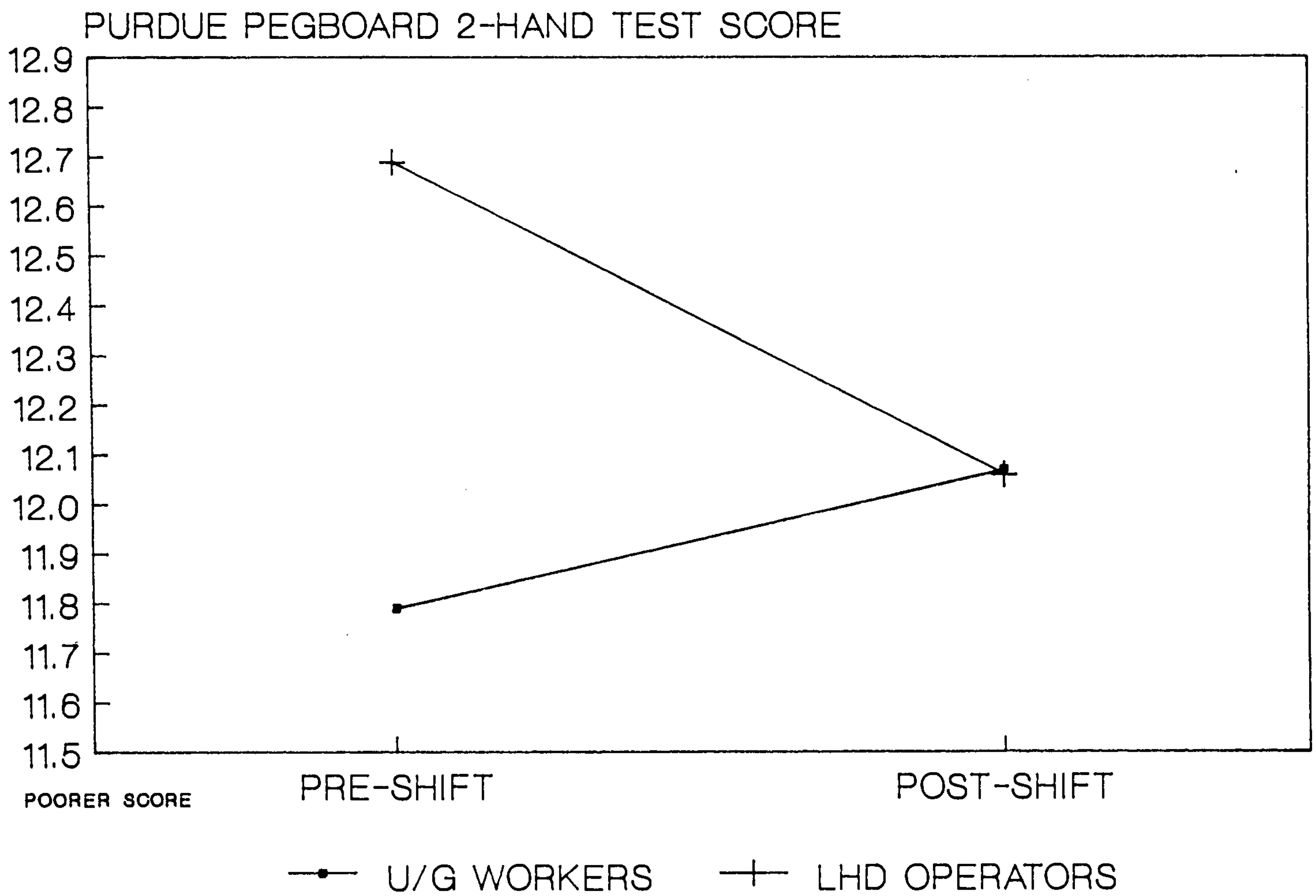


Figure 19.

was also no significant alteration in visual acuity among any of the groups over the shift. Unfortunately, it was impractical to test visual acuity during the vibration exposure of normal LHD operation. This would have allowed for a better understanding of the actual effects of vibration on visual acuity in an actual vibration environment. The significant interaction effect measured in the near-visual acuity scores suggests that the two underground groups responded differently to a work shift. The near-visual acuity scores of LHD operators tended to decrease pre-to-post shift while those of other underground workers tended to improve. However, when considered separately, the pre-to-post shift scores of the two groups did not show any significant differences. The standard deviations of the visual acuity scores of both underground groups were large, and were almost twice the standard deviations of subjects used in a preliminary test to determine sample size. The larger standard deviations may have resulted from poor underground lighting conditions. It is possible that testing a greater number of LHD operators and underground workers would have resulted in significant differences of pre-to-post shift visual acuity scores.

There are many studies in the literature reporting the vibration effects on visual acuity (Matthews, 1966; Khalil & Ayoub, 1976; Moseley & Griffin, 1986; Moseley & Griffin, 1987) however most are conducted in lab-controlled environments and under only one direction of sinusoidal vibration. It may be that the level of vibration measured and characterized from LHD operation causes decrements in visual acuity during machine operation. Visual acuity during WBV exposure was not measured with this test design. However, the results of this study do not show a residual decrement upon vibration cessation. Because an operator may adjust his posture consciously or unconsciously to modify the vibration input, it may be preferable to measure the vibration in the vicinity of the eye (Dupuis & Zerlett, 1986). This would be the best way to relate visual impairment to the physical stress.

A recent report by Moseley & Griffin (1987) demonstrates a non-linear decline in visual acuity with increasing duration of vibration. They found the greatest loss to occur about 70 minutes after exposure begins, after which visual acuity gradually improves. This provides evidence for some physiological adaptation to vibration of a long duration. In order to understand the practical effects of vibration on performance measures, field studies are essential. This is especially relevant when the vibration exposure has been measured and analyzed. It cannot be concluded from this study that there is no effect on the visual acuity of LHD operators due to vibration exposure. However, it can be concluded that there seems to be no significant decrement upon vibration cessation following a daily exposure.

The Purdue Pegboard manual dexterity scores for underground workers and LHD operators were average and slightly above average respectively when compared with male industrial workers. No chronic manual dexterity impairment due to WBV seems to have affected the LHD operators. Their scores were, on the average, higher than those of the other underground workers. The manual dexterity test scores for LHD operators worsened following a shift of driving. This did not occur among the other underground workers. The absolute value of the difference in test scores pre to post shift was, for practical purposes, not large. Among the 16 LHD operators, 6 had no change in scores pre to post shift, and 2 operators improved their score by 1 point. Therefore, half the LHD operators worsened, from 1 point to 3 points in one case. The functional importance of this difference in terms of operator safety and performance is difficult to assess.

There are more differences in the work tasks between the two underground groups than simply vibration exposure. We cannot assume that the WBV alone caused the post-shift decrement in LHD operators' manual dexterity. Also LHD operators are exposed to a certain amount of segmental vibration from the steering wheel of the LHD machine. This may cause temporary tingling, numbing or a decrement in sensitivity similar to a temporary threshold shift in hearing. We did not measure the vibration from the steering wheel, but it may separately be affecting factors such as grip strength, precision and reaction time.

The Purdue Pegboard test was chosen since it is a composite test of co-ordination, speed and accuracy. It does not however reproduce any of the skills required in LHD operation. It may be that the decrement in the Purdue Pegboard test results has no relation to the skills involved in LHD operation. Alternatively, however, if a small decrement is found in a simple manual dexterity task it may be postulated that a more complex series of hand-eye co-ordination tasks under situations of speed and accuracy could be affected even more. A similar limitation exists in this test as in the visual acuity tests. It was impractical to actually measure the manual dexterity skills while exposure to WBV was occurring. There are a variety of studies which cite performance effects under various vibration conditions (Khalil & Ayoub, 1976; Ramsey, 1975; Grethier, 1971; Matthews, 1966, Buckhout, 1964; Hornick, 1961; Guignard & Irving, 1960). The effects are most prevalent at the 3 to 12 Hz frequency range in the z direction and the 1 to 3 Hz frequency range in the x and y directions. As with visual acuity, most of these studies, however, are conducted in a lab using one direction sinusoidal vibration for a short duration.

A 1973 German study by Christ (reported by Dupuis & Zerlett, 1986) utilized simulated random farm-tractor vibration at a RMS value of 1.55 $m.s^{-2}$ for a two hour duration. There were no performance decrements measured in a tracking task with a steering wheel. During low vibration stress, the effects of fatigue may be compensated for by motivational factors. The authors suggested that with increasing vibration intensity, especially in the whole body resonance region, a decrease in performance must be expected (Dupuis & Zerlett, 1986). The same authors noted that where possible, the control movement and vibration movement should not follow the same direction. Although the manual dexterity decrement following exposure to WBV among the LHD operators is small, it may be that the decrement during WBV is much greater. The measure of ultimate practical significance, which will result in improved understanding of the safety and performance implications, would be manual dexterity during exposure to LHD vehicle WBV.

The manual dexterity after–effect measured may be similar to a temporary threshold shift in noise–induced hearing loss. The small decrement following WBV exposure could indicate a shift of system properties or strain induced by a prolonged stressor. As with noise the strain reaction may be related to a gradual accumulation of permanent chronic damage. If this were the case performance measures may be an effective way to indicate the presence or absence of such a strain in response to vibration stress.

CHAPTER VII

CONCLUSIONS

Accident and Injury Analysis

1. From the records of 584 LHD operators, 2,071 office workers, 743 underground supervisors and 10,357 underground miners the accident and injury pattern for LHD operators was found to be different from that for the three other occupations.
2. The majority of LHD accidents and injuries occurred during "mucking" or "operating the LHD" tasks. The most frequent accident types were "sudden stop/start" and "falls from a stationary vehicle", with "surface rough" as a contributing factor.
3. The part of body most frequently injured was the back followed by the eye, neck, finger, hand and multiple injuries. Injuries to the neck were more prevalent among LHD operators than in other groups. The most common nature of injury was "ache/pain/swelling".
4. Although the injury pattern is different, the incidence per 1,000 workers of overall injury among LHD operators was similar to that of other underground miners (180 and 183.5, respectively) and was similar between 1984 and 1985. However the relative risk for LHD operators compared to underground supervisors for overall injury was 2 and for office workers was 5.4.
5. A disproportionate amount of compensation funds were paid to LHD operators based on the percentage of LHD operators at a mine. At Mine B in 1985, 10.6% of compensation dollars were paid to LHD operators who made up 3.6% of the mine's workers. In 1984 at Mine A, 53% of the compensation dollars paid to injured LHD operators were for back injuries and in 1985, 42.5% of the funds were for back and neck injuries.

6. Data from the MAPAO Back Care Program in 1984 and 1985 were analyzed for Mine A and Mine B. Among LHD operators, 39% at Mine A and 41.5% at Mine B reported having had at least one lost-time back injury and 51% at Mine A and 55% at Mine B reported having back pain.
7. More carefully designed longitudinal studies are required to follow the health of vibration-exposed workers and relate it to the WBV characteristics.
8. Three fatalities occurred to LHD operators in 1984-1985. Two of these fatalities are related to falls of ground and crushing. The potential for fatalities among LHD operators should be an area of more detailed analysis.

Vibration Measures

1. Acceleration levels during machine idling were small (0.1 $m.s^{-2}$). There was a significant difference in vibration measures between tasks, with mucking and dumping being different from driving full and driving empty in the x and z directions. The highest measures were for driving full and driving empty (range = 0.4 – 2.8 $m.s^{-2}$).

2. There was a significant difference between vehicles of differing sizes at Mine A with the 3.5 yd being different from both the 6 yd and the 8 yd vehicle in the x and z directions. The 3.5 yd vehicle produced higher vibration levels, possibly due to its lighter weight and smaller tires.

3. The y direction vibration levels were random and inconsistent. Because of the operators' sideways orientation, this was typically the x direction in forward facing vehicles.

4. The vibration signals recorded were impulsive, containing high level random peaks in every task and direction. Many of the higher peaks lie in the z direction. The total proportion of crest-factors that exceeded 6 was 76% at Mine A and 43% at Mine B.

5. Mean daily exposure values were calculated using exposure data from each mine's Industrial Engineering Department. The two tasks with the highest vibration levels also made up the greatest proportion of exposure time (72–84%). In the x direction at Mine A, 71% of mean daily exposure levels exceeded the recommended ISO criterion of 0.6 $m.s^{-2}$ for 6 hours in the x and y direction, and 100% of the levels exceeded the recommended criteria of 0.8 $m.s^{-2}$ for 6 hours in the z direction. At Mine B, 72% of the mean daily exposure values calculated in the x and y direction, and 78% of the mean daily exposure values in the z direction exceeded the recommended level.

6. Some mean daily exposure levels (especially 3.5 yd – z direction) corresponded to a recommended exposure time of only 25 minutes. On average, in the 8 yd and 6 yd

LHD vehicles at Mine A, the exposure limit was exceeded in the z direction after approximately 2.5 hours and 2 hours, respectively. In the x direction, the recommended limit is exceeded after approximately 1.5 hours.

7. When exposure ratio values were calculated using summed vector accelerations, all the the vehicles exceeded the permissible value, one by a factor of 12.

8. All but one LHD (with one operator and not the other) exceeded the ISO exposure limits in at least one direction. Many exceeded the limits in all three directions. All vehicles exceeded the fatigue or decreased proficiency boundary.

9. The dominant frequency bands were found to be from 1.6 – 3.15 Hz, except for idling which ranged from 32–80 Hz. The dominant z direction frequency bands were generally higher (3.15 Hz) and the spectrum flatter until about 32 Hz. The dominant x–y direction frequency bands were 1.6 or 2 Hz and the majority of vibration signals drop off dramatically above 4 Hz.

10. The spectral pattern is similar to other published results in construction and forestry equipment. The acceleration levels however are higher.

11. A number of variables play a role in the amount of vibration transmitted to an operator; tire flexibility and size, vehicle suspension, vehicle transmission, location of operator, seating/suspension, driving style, speed of travel and road conditions. The importance of each of these factors in reducing WBV and jolts in LHD machines requires further quantitative investigation.

Performance Measures

1. In the Visual Acuity Far test, there was a significant difference in scores between the three groups with the office workers scoring better than the underground workers, presumably due to the betterlighting conditions in the office environment. There was no significant difference in visual acuity following a shift of vibration exposure for the LHD operators.

2. In the Visual Acuity Near test, there was again a significant between groups effect. A significant interaction between trials and groups was found; however, when each group was tested individually no pre to post difference in visual acuity scores was detected.

3. The exposure to WBV during LHD operation may affect the operators' visual acuity. However, there were no residual decrements measured in visual acuity post exposure.

4. In the Manual Dexterity test, there was a significant interaction between trials and groups. When the groups were tested separately a significant difference was found in pre to post test scores for the LHD operators. The LHD operators' test scores worsened following a shift of exposure to WBV, while the test scores for other underground miners stayed the same.

5. It cannot be concluded that WBV alone caused the decrement in a manual dexterity test score following a one day exposure since there are a variety of differences in the work tasks between the two groups. The LHD operators were also exposed to some segmental vibration from the LHD steering wheel.

6. The significant post vibration decrement in manual dexterity may indicate that an even greater decrement would be found during WBV exposure. The actual manual dexterity effects during LHD operation need to be clarified.

CHAPTER VIII

RECOMMENDATIONS

Accident and Injury Analysis

1. Carefully designed prospective epidemiological studies with improved accident investigation methods are required to ascertain whether in fact WBV plays a role in accident and injury to LHD operators.
2. A number of workplace design alternatives should be investigated with the aim of reducing the disproportionate incidence of neck injuries among LHD operators.

Vibration Measures

1. It is recommended that all feasible factors which may reduce the excessive levels of WBV in the x and z direction be investigated including: vibration damping; seating/suspension systems; improved road condition; road design; tire type, size, and pressure; and machine maintenance.
2. It is recommended that the use of the 3.5 yd machine be limited and the larger LHD machines be used.
3. Where possible, the amount of exposure time in the two driving tasks should be minimized. Mine design should incorporate shorter distances to the dumping points.
4. The speed of travel should be minimized and smooth driving practices enforced.
5. The practical implications of high level peaks are not well understood. More investigation into the effects of such excessive jolts and impacts is required.

Performance Measures

1. Field and epidemiological studies are required to;

   a. establish whether other aspects of performance are affected by vibration exposure

   b. determine if the performance changes occur during WBV exposure and whether they are "critical" for job performance and safety

   c. determine if the performance changes are purely temporary or if they are related to a gradual and chronic decrement.

APPENDIX 1 VIBRATION MEASURING AND ANALYZING EQUIPMENT

Equipment	Manufacturer	Other
1. Triaxial seatpan accelerometer	Bruel & Kjaer (B & K) Type 4322	
2. Human response vibration meter	B & K Type 2312	3 meters each calibrated separately for x, y, or z axes maximum level recorded: Leq 139.5dB (9.4ms^{-2}) Peak 146 dB (20 ms^{-2})
3. Calibrator	B & K Type 4291	
4. FM tape recorder	B & K Type 7005F	30 dB attenuation slow speed used
5. Digital Frequency Analyzer	B & K Type 2131	
6. Microprocessor	Hewlett Packard (HP) Type 300	
7. Software package	B & K 9117	

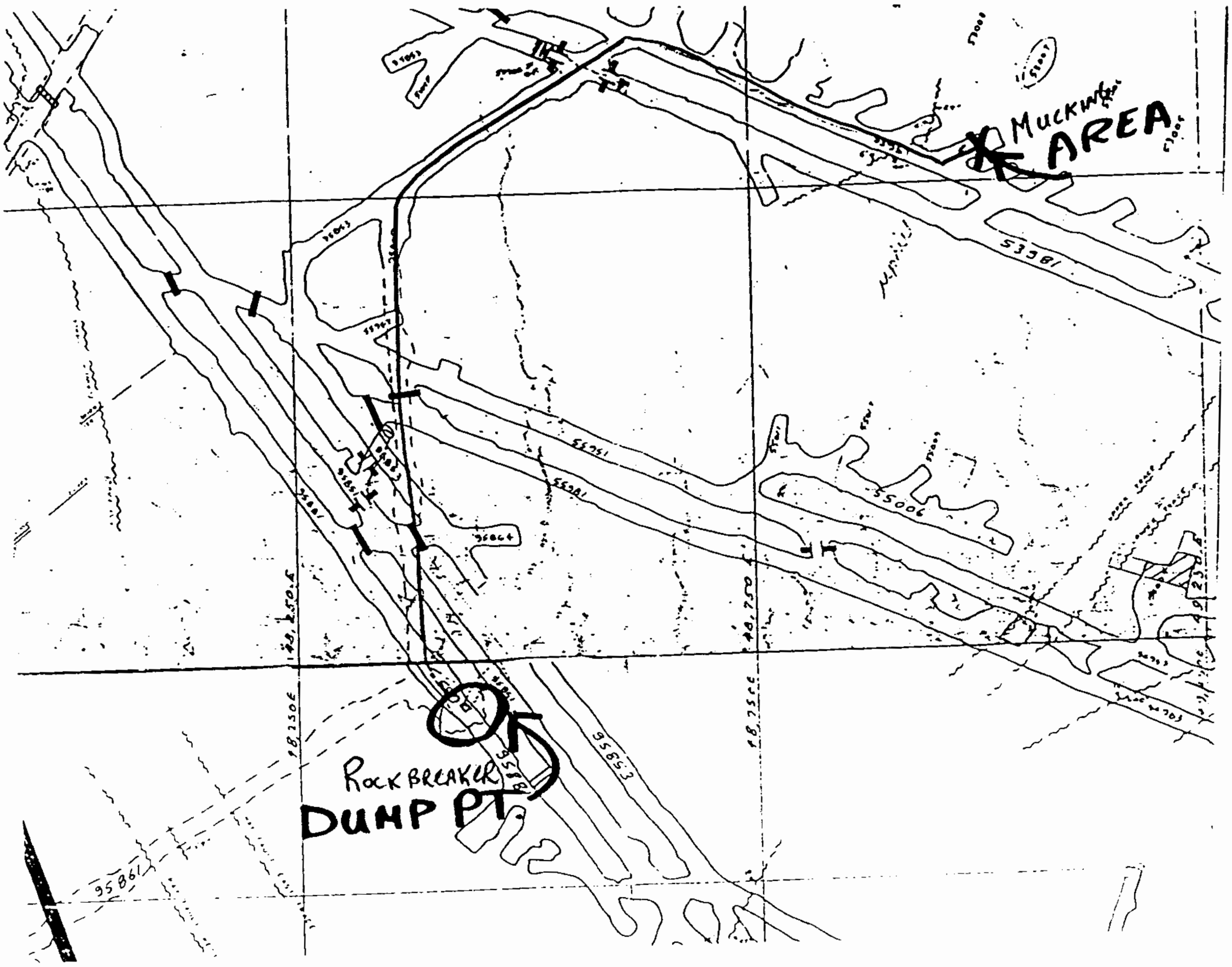
APPENDIX 1B CALIBRATION MEASURES

Mine	Axes	Calibration recordings and playback readings		
		Leq (playback) (dB)	Peak (playback) (dB)	Time (playback) (minutes)
Mine A	X	108 (108)	111 (116.5)	1.2 (1.2)
	Y	108 (108)	111 (118.5)	1.3 (1.3)
	Z	116.5(116.5)	120.5 (123)	1.0 (1.0)
Mine B	X	108 (108)	114 (115.5)	0.5 (0.5)
	Y	108 (108.5)	114.5 (117.5)	0.6 (0.6)
	Z	118 (118)	123.5 (124.5)	0.6 (0.6)

APPENDIX 2 MINE A LHD VEHICLE, OPERATOR AND ENVIRONMENTAL INFORMATION

Operator	Age (yrs)	Experience (yrs)	Weight (lbs)	Height (in)
1.	33	12	170	71
2.	40	4	180	68
Average	36.5	8	175	69.5

APPENDIX 2B MINE A TESTING SITE MAP



APPENDIX 2C MINE A AVERAGE TRAVEL TIMES

Distance Stope 53007 to rockbreaker 55D (miles)	Task 3 Driving Full Travel time (mpr)*	Task 5 Driving Empty Travel time (mpr)	Percent Difference (%)
0.25	3.9	4.3	10

*mpr = miles per hour

APPENDIX 2D MINE A ENVIRONMENTAL INFORMATION

Temperature:	
Wet bulb (degrees)	59
Dry bulb (degrees)	61
Relative humidity (%)	90%
Noise:	
Leq (dB_A)	96.7-100.7
Peak (dB_A)	125.8-129.6
Road Conditions:	
Stope 53007 to Rockbreaker 55D	gravel surface

APPENDIX 2E MINE A LHD VEHICLE INFORMATION

Machine	Manufacturer	Size (yd)*	Tire Pressure right front/rear (pounds per square inch)	left front/rear	Seating Suspension
A	Wagner	8	70/70	65/70	air
B	Wagner	8	65/60	70/60	air
C	Jarvis Clark	6	60/65	35/60+	spring
D	Jarvis Clark	6	65/65	65/65	spring
E	Wagner	3.5	65/65	65/65	air
F	Wagner	3.5	65/65	65/65	air

*cubic yardage capacity of bucket

+left front tire was pumped up in shop to 60 prior to testing

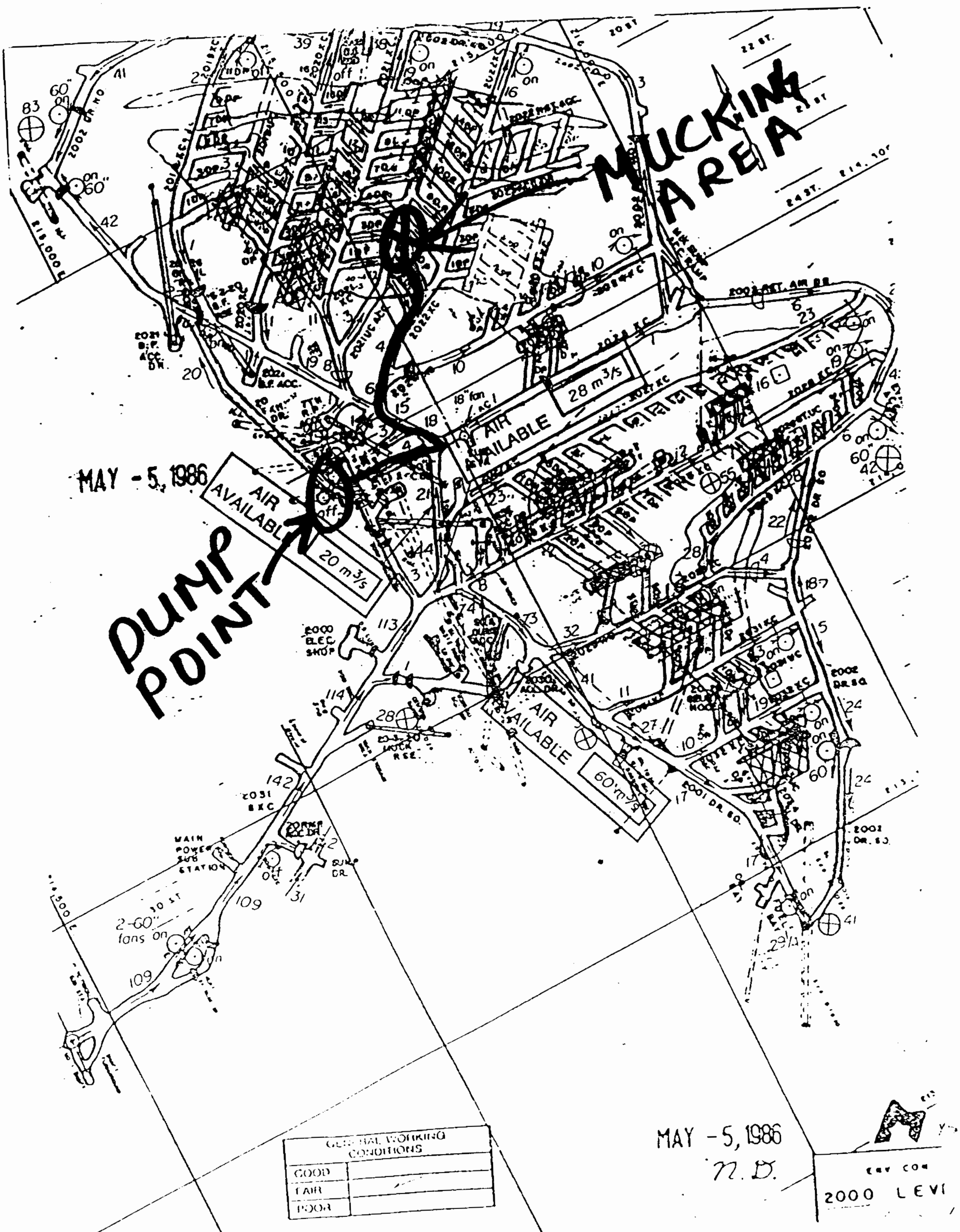
APPENDIX 3 MINE B LHD VEHICLE, OPERATOR AND ENVIRONMENTAL INFORMATION

Operator	Age (yrs)	Experience (yrs)	Weight (lbs)	Height (in)
3.	30	10	185	67
4.	41	11	140	67
5.	42	11	145	67
6.	39	*	180	71
7.	36	5	220	74
8.	38	+	170	69
Average (excluding 6 and 8)	37	9	172.5	68.75

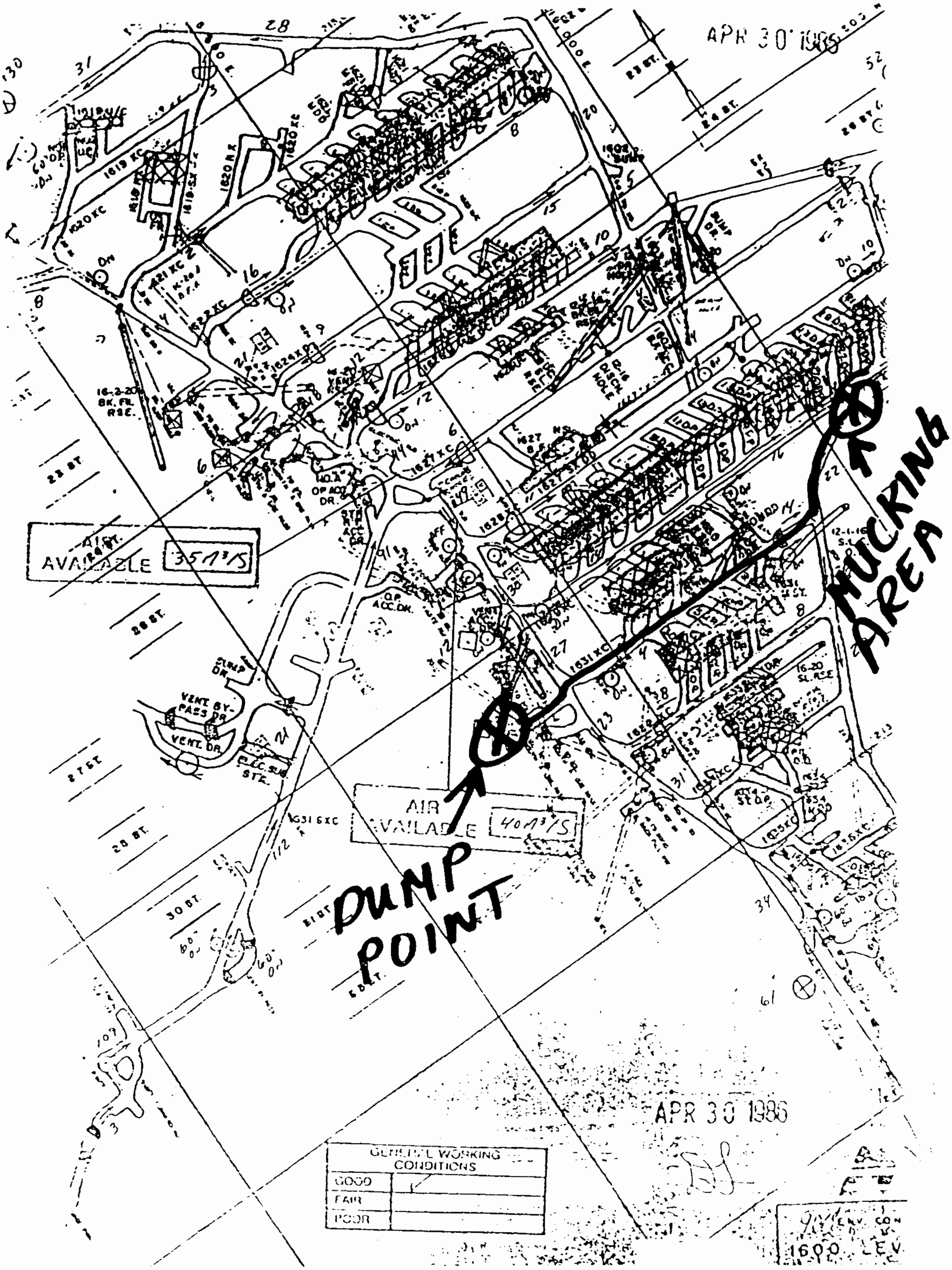
*operator 6 is assistant maintenance superintendent, not a full time LHD operator

+operator 8 is a timberman, he is sometimes assigned an LHD vehicle for clean-up work, but is not a full time LHD operator

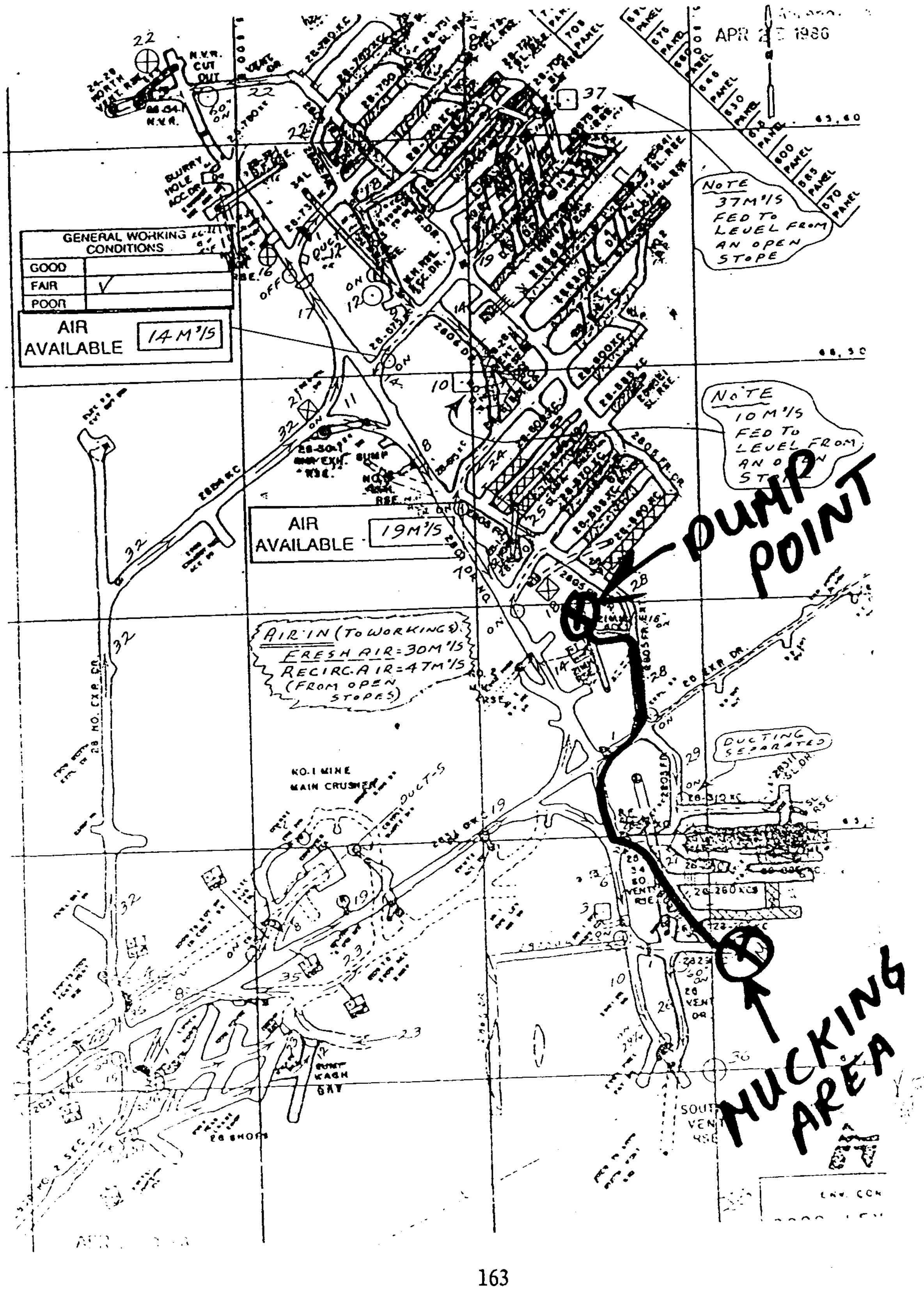
APPENDIX 3B MINE B TESTING SITE MAP (1)



APPENDIX 3C MINE B TESTING SITE MAP (2)



APPENDIX 3D MINE B TESTING SITE MAP (3)



APPENDIX 3E MINE B AVERAGE TRAVEL TIMES

Underground Level (feet)	Distance (Stope to Rockbreaker) (miles)	Task 3 Driving Full Travel time (mpr)*	Task 5 Driving Empty Travel time (mpr)	Percent Difference (%)
1600	0.17	3.95	5.15	30
2000	0.11	4.4	4.78	8.6
2800	0.15	2.88	4.84	68

*mpr = miles per hour

APPENDIX 3F MINE B ENVIRONMENTAL INFORMATION

Temperature:*	
Wet bulb (degrees)	59
Dry bulb (degrees)	62
Relative humidity	85%
Noise:	
Leq (dB_A)	94-100
Peak (dB_A)	103-120
Road Conditions:	
1600 level	cemented surface
2000 level	cemented surface
2800 level	gravel surface

*temperature readings were the same at each underground level

APPENDIX 3G MINE B LHD VEHICLE INFORMATION

Machine	Manufacturer	Size (yd)*	Tire Pressure right front/rear (pounds per square inch)	left front/resr	Seating Suspension
G	Wagner	8	70/72	72/70	air+
H	Wagner	8	78/78	74/76	air
I	Wagner	5	78/78	72/72	air
J	Wagner	5	70/70	70/70	air
K	Wagner	3.5	65/65	65/65	air

*cubic yardage capacity of bucket
+all had air seats, but they were chained down by operators to minimize bouncing.

APPENDIX 4 HEALTH QUESTIONNAIRE

PARTICIPANT INFORMATION SS #____________

1. LHD Operator ____ Office Worker ____ U/G Worker ____

Personal

2. Age ____
3. Years of Experience @ this Job ____
4. Weight ____
5. Height ____

6. Do you, or have you ever had any of the following injuries/ diseases to the fingers, hand, arm, shoulder or neck:

	YES	NO
a) bone fracture	____	____
b) ligament or tendon injury	____	____
c) severe cut or vessel damage	____	____
d) nerve injury	____	____
e) compound injury	____	____
f) frostbite	____	____
g) vibration white finger disease	____	____
h) Raynauds disease	____	____
i) amputation	____	____
j) joint fusion	____	____
k) surgical operation	____	____
l) Other - specify________________		

7. Has the disease/injury left any side effects?
Yes ____ No ____ If so, what?________________

8. Has a doctor ever told you that you suffered from:

	YES	NO
a) dupuytren's contracture	____	____
b) polyarteritis nodosa	____	____
c) systemic lupus erthematosus	____	____
d) dermatomyositis/polymyositis	____	____
e) scleroderma	____	____
f) takayasu's arthritis	____	____

9. Does it still affect you? Yes ____ No ____
If yes, what after-effects?________________

10. Have you ever been diagnosed as having:

	YES	NO
a) rheumatoid arthritis	____	____
If yes, where? ______		
b) disc union of the neck	____	____
c) cardiac catheterisation	____	____
d) embolism or thrombosis of hands or arms	____	____
e) coronary thrombosis or angina	____	____
f) pain in the calves of the legs while walking	____	____
g) migraine headache	____	____
h) high blood pressure	____	____

11. Does it still affect you? Yes ____ No ____
If yes, what after-effects? ______

12. Have you ever suffered from any of the following:

	YES	NO
a) polio	____	____
b) stroke	____	____
c) multiple sclerosis	____	____
d) peripheral neuritis	____	____
e) subacute combined degeneration	____	____
f) injury or operation to nerves of hands or arms	____	____
g) carpal tunnel syndrome	____	____
h) cervical rib	____	____
i) thoracic outlet syndrome	____	____

13. Does it still affect you? Yes ____ No ____
If yes, what after-effects? ______

Medications

14. Are you currently taking any prescription types drugs?
Yes ____ No ____

15. If yes, what prescription drugs are you taking?

1. Drug: ______
   Purpose: ______
2. Drug: ______
   Purpose: ______
3. Drug: ______
   Purpose: ______

APPENDIX 4C HEALTH QUESTIONNAIRE CONTINUED

Visual Problems

16. Have you ever been diagnosed as having any of the following eye or visual disorders:

		YES	NO
a)	phorias	____	____
b)	monocular vision	____	____
c)	conjunctivitis	____	____
d)	infections or cold sores in eyes	____	____
e)	glaucoma	____	____
f)	retinitis pigmentosa	____	____
h)	night blindness	____	____
i)	nystagmus	____	____
j)	macular degeneration	____	____
k)	Other - Specify ____________________		

17. Does it still affect you? Yes ____ No ____
If yes, what after-effects? ____________________

18. Have you ever had one of the following physical injuries to one or both eyes?

		YES	NO
a)	contusion	____	____
b)	hemorrhaging	____	____
c)	dislocation of lens, retina and other parts	____	____
d)	laceration of cornea, lid or conjunctiva	____	____
e)	cornial laceration	____	____
f)	foreign bodies in the eye	____	____
g)	thermal burn	____	____
h)	irradiation burn (ultraviolet infrared)	____	____
i)	chemical burn	____	____

		YES	NO
19.	Have you ever had a back injury?	____	____
20.	Was it a lost time injury from work?	____	____
21.	How many lost time injuries to the back have you had?	______	
22.	Do you still have back problems (pain episodes)	____	____

APPENDIX 5 VISUAL ACUITY TEST SCORE PROCEDURE

FAR VISUAL ACUITY

Test scores relative to number of errors

Test Scores
(total number of letters per line in brackets)

Number of Errors

0x	1x	2x	3x	4x	5x	6x	7x	8x
100(2)	150							
70(3)	80	90						
50(4)	55	60	65					
40(5)	42	44	46	48				
30(6)	31.7	33.3	35	36.7	38.3			
20(7)	21.4	22.8	24.3	25.8	27.2	28.6		
15(8)	15.6	16.3	16.9	17.5	18.1	18.7	19.4	
10(9)	10.5	11.1	11.6	12.2	12.7	13.3	13.8	14.4

APPENDIX 5B NEAR VISUAL ACUITY TEST SCORE PROCEDURE

Test scores relative to number of errors

Test Scores
(Total number of letters per line in brackets)

Number of Errors

0x	1x	2x	3x	4x	5x	6x
60(4)	75	90	105			
40(5)	44	48	52	56		
30(4)	32.5	35	37.5			
20(5)	22	24	26	28		
15(6)	15.8	16.6	17.5	18.3	19.1	
10(7)	10.7	11.4	12.1	12.8	13.5	14.2

APPENDIX 6 INSTRUMENTATION FOR ENVIRONMENTAL MEASURES

Equipment	Manufacturer	Other
1. Psychro-dyne wet bulb globe thermometer	Environmental Tectonics Company, Southhampton, PA	
2. Sound level metre	Bruel & Kjaer type 2205 Denmark	calibrated prior to use
3. Optikon light metre	Hagner Universal Photometer Model S2, Sweden	
Tripod	Optikon, Model S 95534 9	

APPENDIX 7 ENVIRONMENTAL MEASURES FOR PERFORMANCE TESTS

Environmental Measure	Mine A Test day 1	Test day 2	Mine B Test day 1	test day 2	office
Temperature:					
Wet bulb (degrees)	64	65	55	56	60
Dry bulb (degrees)	70	68	54	60	72
Relative humidity (%)	72	88	100	78	52
Noise:					
Leq (dB_A)	66-76	70-82	82-105	89-92	62-64
Lighting:					
Luminance on chart (cd/m^2)					
far test (20')	15.17	12.65	0.94	19.15	450
near test (32")	19.0	12.0	1.1	37.0	735
Illuminance (average) (lux)	132.0	390.0	32.3	132.5	5325
Illuminance from chart (lux)					
large chart	42.5	39.75	1.38	90.0	2233
small chart	60.0	33.0	1.40	90.0	2400

APPENDIX 8 DEMOGRAPHIC DATA FOR LHD OPERATORS

Subject Number	Age (yrs)	Experience (yrs)	Weight (lbs)	Height (in)
1.	42	22	155	67
2.	57	15	160	67.5
3.	32	11	165	73
4.	38	12	185	68.5
5.	46	16	250	74
6.	33	10	140	69
7.	46	5	150	65
8.	27	8	160	68.5
9.	34	9	138	66
10.	31	6	200	68
11.	31	11	150	69
12.	42	9	200	71
13.	35	7	155	66
14.	51	5	160	66
Mean	34.1	9.1	148	59.9
Standard Deviation	8.7	4.7	30.3	2.7

APPENDIX 9 DEMOGRAPHIC DATA FOR UNDERGROUND WORKERS

Subject Number	Age (yrs)	Experience (yrs)	Weight (lbs)	Height (in)
1.	33	10	180	71
2.	32	9	150	66
3.	38	10	195	68
4.	28	8	135	65
5.	40	15	150	68
6.	53	5	195	70
7.	26	8	196	71
8.	28	3	165	67
9	50	10	153	68.5
10.	35	11	135	66
11.	27	4	125	69
12.	28	6.5	160	68.5
13.	34	8.5	200	68
14.	37	3	200	66
15.	25	8	180	70
16.	25	5.5	170	69
Mean	33.69	7.47	168	68.19
Standard Deviation	8.9	2.6	25.2	1.8

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