University of Alberta

Human Vibration Monitoring System

by

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ABSTRACT

Research has shown that operators of heavy equipment in the mining industry are subject to whole-body vibration exposure that exceeds ISO 2631-1 (1997) guidelines. In particular operators of haul trucks are at high risk. Consequently an initiative was made to determine a solution to reduce the vibration exposure operators of haul trucks experience. The result was the creation of a visual onboard monitoring system that indicated to the operator when they were experiencing dangerous levels of vibration. In operation, when the operator was prompted by the system, they would try to change their driving patterns to avoid higher levels of vibration so that at the end of the shift they were below the ISO 2631-1 (1997) limit. The research of this project was to determine if the system was effective or not based on field testing of the vibration system. The results demonstrated that the system could potentially reduce vibration. This type of system could have significant impacts on the mining industry by improving health and safety of operators with more field data and further research.

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LIST OF NOMENCLATURE AND ABBREVIATIONS

A – Amplitude
WBV – Whole-body vibration
Wk – Frequency weighting list k
Wd – Frequency weighting list d
RMS – Root-mean-square
kS/s – kilo samples per second
a_w – weighted acceleration
W – weighting factor
a_i – RMS acceleration for the ith one-third octave
a_v – total cumulative vibration value
k_x – multiplying factor for x-axis
k_y – multiplying factor for y - axis
k_z – multiplying factor for z - axis
a_{wx} – frequency-weighted acceleration for the x - axis
a_{wy} – frequency weighted acceleration for the y - axis
a_{wz} – frequency weighted acceleration for the z – axis
Aeq – equivalent vibration magnitude
T_i – vibration exposure duration
VDV – vibration dose value
R_{eq} – equivalent rack

1.0 Introduction

In our everyday lives we are exposed to, or experience the effects of vibration. Most of our senses are stimulated by vibration giving us the ability to perceive our environment. Whether it is feeling the sensation of nerves from vibration of a car while driving on a poorly graded road or vibration of cilia in our ears giving us the ability to hear during a conversation, vibration has an overwhelming presence in our lives. Vibration is used to benefit us in many cases such as in the medical and exploration fields where principles of vibration are used in areas of imaging and diagnostics. However it is more common to recognize the damaging effects of vibration since these effects are more publicized and familiar to us such as earthquakes where high energy vibration sources cause tremendous destruction. On a personal basis many of us are familiar and have dealt with damaging effects of vibration when it comes to our vehicles where awkward vibrations serve as an indicator or the cause of damage, or with home appliances such as washing machines rumbling indicating an off balance load causing vibration damage to the mechanism of the machine.

Vibration has a strong presence in our lives, however the health effects of it are not widely realized by people in general. Many occupations expose people to unhealthy levels of vibration, commonly called whole body vibration (WBV), which until recent decades the effects of which have not been recognized. This increased knowledge about health and vibration has lead to this research to determine ways of reducing the source of vibration or means of reducing the effects of it. In particular, the research involved in this project has focused on the reduction of vibration exposure experienced by operators of haul trucks in the mining industry. This thesis discusses the creation of a system designed to help reduce vibration and the evaluation of the effectiveness of the system during field trials.

1.1 Mechanics of Vibration

Vibration is a phenomenon caused by the propagation of waves, which can be defined as disturbance or variation that transfers energy progressively from point to point in a medium. This energy transfer may take the form of elastic deformation, variation of pressure, change in temperature, and so on. Vibration is an oscillatory motion which causes particles in a medium to move during the propagation of the wave. Each particle is displaced away from its original position and then returns after the wave has passed, as long as there has been no deformation. There are two main categories of vibration: deterministic and stochastic (random). Deterministic motion refers to oscillations that can be predicted from knowledge of previous oscillations where as stochastic motion is less predictable and only displays some statistical properties (Griffin, 1990). Both categories can be further divided into sub-categories, however vibration encountered during haul truck operation can primarily be described by stochastic motion. Stochastic motion contains two sub-categories: stationary and non-stationary. Stationary random vibration occurs where an object is stationary and exposed to vibration from a source, such as, a bridge experiencing vibration from cars driving over it randomly. Non-stationary vibration occurs when an object is in motion and experiences vibration from a source. Random non-stationary vibration characteristics are present in haul truck vibration so for this reason the research is concerned primarily with this type of motion.

Vibration can be characterized by two properties: magnitude and frequency. The magnitude is the extent of the oscillation where frequency is the rate at which the oscillation cycles.

1.1.2 Magnitude

There are different methods to determine the magnitude of an oscillation. For this reason it is important to understand how each method works since standards for vibration and vibration analysis equipment use different ways of reporting or using magnitudes in evaluatios. The three typical methods of expressing vibration magnitude are: displacement, velocity, and acceleration.

1.1.2.1 Displacement

The first method is through the measurement of displacement during oscillations. Displacement can be measured from the datum to the maximum peak in one direction, referred to as peak displacement, or by the distance between the maximum peak displacement in opposite directions. Reporting displacement for magnitude is generally suitable for large-amplitude low-frequency motion.

1.1.2.2 Velocity

The second method is through the velocity of the oscillation. The common means of expressing magnitude through velocity is through the peak-to-peak velocity which is the difference between the maximum velocities of one direction and the opposite direction.

1.1.2.3 Acceleration

The last method, which is the most common, is through acceleration. As with velocity, acceleration magnitude is more related to the energy involved in the oscillatory movement. This can be expressed by the peak-to-peak acceleration or by peak acceleration. This method is most commonly used since instrumentation for measuring acceleration of oscillations are more convenient to use (Griffin, 1990). As a result, many standards regarding vibration and human vibration express magnitude in units of acceleration rather than velocity and displacement. The unit commonly used for acceleration is m/s^2 or in gravity units, g.

1.1.3 Frequency

The other component for evaluation of vibration is frequency of oscillation. The frequency is a measure of the number of cycles of motion occurring per second and is expressed in Hertz (Hz). Motions commonly contain multi-frequency vibrations (more than one frequency), therefore, it is necessary to determine the frequency content of vibration. This is accomplished through the use of a frequency spectrum (Figure 1.1) which separates the frequencies into bands. Each band represents a frequency that it is centered on, such as 1 Hz, 2 Hz, 4 Hz and so on. The resolution of frequency analysis is dependant on what type of octave band, is used. An octave refers to the interval between two frequencies, where for full octave bands the ratio is 2:1, so the spectrum of a full octave would be 1 Hz, 2 Hz, 4 Hz, etc. Another common octave scale that is used is the one third-octave, which have a ratio of ~1.25:1 (frequency spectrum 1, 1.25, 1.6, etc.). One third-octave bands are generally preferred where a smaller separation between bands (higher resolution) is necessary as is the case with the evaluation of whole body vibration where the response of the body can vary between small intervals of bands.

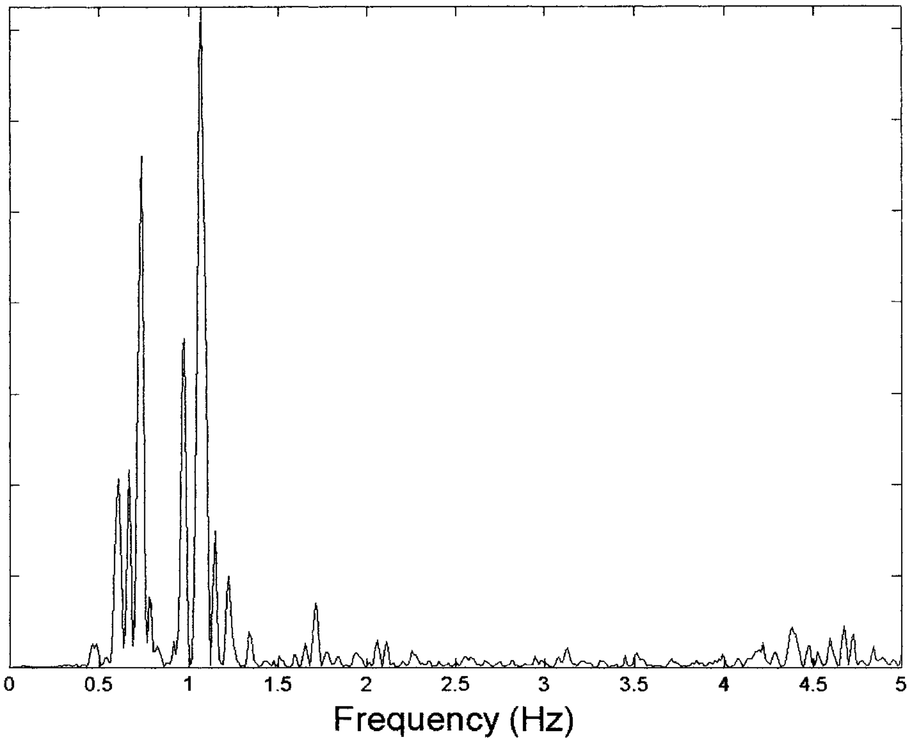


Figure 1.1 Sample frequency spectrum of a vibration sample

1.1.4 Quantifying Vibration

As mentioned earlier, acceleration of vibration is the most commonly used way of quantifying magnitude and can be expressed in terms of peak-to-peak or peak acceleration. This method works for motions that are consistent and simple, however most motions are complex and by using this method the severity of the vibration can be represented by an unrepresentative peak. For this reason vibration severity is represented by an "average" measure. The most common way of expressing the "average" of a motion is through the use of the root-mean-square (RMS). The RMS, is the square root of the average value of the square of the acceleration record (Griffin, 1990). For example, a motion having a peak magnitude of A would yield a peak-to-peak magnitude of 2A so the RMS value would be $A/\sqrt{2}$. When using the RMS, peak-to-peak or peak RMS must be specified since uncertainty (2.828 to 1, non-sinusoidal error can be much greater) can be introduced if it is not known which method is used.

1.1.5 Measurement

Vibration is measured through the use of vibration transducers, which are devices that convert one form of energy to another. More specifically vibration transducers convert mechanical energy (motion caused by vibration), to electrical energy. The most commonly used vibration transducer is the accelerometer which produces an electrical output proportional to acceleration when stimulated. The electrical output may be in the form of voltage, charge, current, or resistance change. When choosing the most appropriate type of accelerometer to use, the characteristics of the vibration motion must be coupled with the specifics of the accelerometer to provide a correct match. Choosing the wrong type of accelerometer for a certain vibration range can result in misinterpretation of the results. For example, some accelerometers are incapable of picking up the higher frequencies at an appropriate resolution so if the higher frequencies are targeted for study, the results will not be accurate. Manufacturers list the specifications for their accelerometers. As well there are often specifics given in standards and protocol for measuring vibration in certain applications that can assist the investigator.

2.0 Human Vibration

There are many aspects to the effects of vibration exposure to consider from a safety and loss management stand point. These are concerned with damage to people or property. In particular this study is more concerned with the effects to people, as a result the effects of investigations are discussed in more detail. The following chapter is intended to illustrate why it is necessary to investigate ways of reducing vibration exposure through the effects it has on humans. In general, this chapter is aimed at answering the question, why is it important to reduce vibration?

When discussing human vibration there are two main classifications. The first is hand-arm vibration which is shaking of one to two limbs particularly the hands and arms (more related to hand operated tools). The second is whole-body vibration (WBV) which is related to the shaking of two or more limbs. Whole-body vibration by definition is a result of the vibration of the supporting surface of a body (Bonvenzi, 1999). This could be a vibrating platform which someone is standing on, or a seat of a vehicle that is vibrating due to rough driving conditions...etc. For this reason the objective of this investigation is concerned with whole-body vibration and will be referred to as WBV.

The severity of WBV exposure depends mainly on four factors: the magnitude, frequency, direction, and duration (Griffin, 1990, Ozkaya et al., 1994, Bonvenzi, 1999). The magnitude and frequency are related to the vibration signal source. Magnitude refers to the energy of the motion with respect to WBV; it can be considered to be the amount of "force" capable of causing damage. The higher the magnitude of vibration the more damaging the vibration can be to the physiological structure of the body. The second component is the frequency which affects severity by determining the intensity of vibration or the period for which a magnitude is being applied. For example, a vibration having a high magnitude will not necessarily be damaging if the frequency is very low. The third factor, direction, is the location of where the vibration source is coming from in relation to the position of the body. This is based on a 3 dimensional (x, y, z) coordinate system. Different directional vibration will yield different results for severity (Wikström et al., 1994). For example, someone in a seated position driving will experience vibration primarily in the Z-direction moving parallel with the spine. Depending on how rough the road is in this situation the driver may also experience motion in the X and Y directions which are more dangerous to health than in the Z-direction. The final factor affecting severity is the duration, which is the length of time of exposure to vibration. Someone experiencing high magnitude jolts periodically can have similar damaging effects as another person experiencing very low magnitude low frequency vibration constantly for a longer length of time.

Different combinations of these factors can produce a variety of effects on health. Within these combinations, different organs of the body are affected by different combinations. The mechanics behind WBV is very complex; when vibration enters the body, soft and bony tissues begin to vibrate causing each type of tissue or organ to start vibrating at its own frequency. How a specific organ reacts to vibration depends on the mass, stiffness, and damping attributes (Thalheimer, 1996). As a result, when a vibration frequency of an external source matches the natural frequency of an organ or tissue, resonance can occur which is a serious condition and can cause the organ to vibrate at very high amplitudes (Dias and Phillips, 2002). This means that someone can be receiving damage to body organs and tissues when being exposed to vibration, even though the vibration amplitude is low but the frequency matches the natural frequency of the body part. The critical frequency for most of the body, based on research, has been found to be 4 to 8 Hz in the z direction and 1 to 2 Hz for the x and y directions. At these frequencies in a specific direction the most damaging effects will be seen (Tescke et al., 1999).

2.1 Health Effects of Whole-Body Vibration

Traditionally the effects of WBV were not recognized and therefore WBV was not a concern. With more and more people reporting health problems in occupations where there are high exposures to vibration, WBV began to come into focus. As a result, within the past few decades there have been numerous investigations into whole-body vibration and its effects on health. These investigations have shown an overwhelming presence of health problems for people exposed to WBV. Although each investigation was conducted independently, the results and health diagnosis are very similar.

Health problems that have been discovered can have physiological pathological, and psychological effects. Table 2.1summarizes the health conditions that have been found to occur as a result of WBV exposure. Of these health conditions the most prevalent are lower back problems which include diseases of the lumbar spine, disc degeneration and other pathological effects to the spine and skeletal structure.

Health Problems Related to Whole Body Vibration	
Phyisological	**Psychological**
lower back pain	Chronic Fatigue
Lumbago	Nervous Irritability
Sciatica	
Generalized Back Pain	
Intervertebral Disc Herniation	
Intervertebral Disc Degeneration	
Cardiovascular Disorders	
Osteoarthritis	
Gynaecological Disorders	
Male Sexual Disorders	

Table 2.1 Summary of health problems related to whole-body vibration

In a review conducted by Wikstrom et al. (1994) that compared a number of studies with a total of 18,000 exposed subjects and 29,000 control subjects not exposed to vibration, it was found that the subjects exposed to vibration had a much higher rate of lower back problems (LBP). The main conclusion was that WBV can contribute to the development of degenerative changes to the intervertebral discs and vertebrae (Wikstrom, 1994). Another review conducted from 1986 to1997, which took 43,000 subjects exposed to WBV in a number of different industries and compared them to 24,000 control subjects, concluded that subjects exposed to WBV had much higher incidences of LBP and degenerative changes in the spine. It also revealed on a lesser scale, that the subjects exposed to WBV also had a higher rate of adverse effects, compared to the control group, on the digestive system, female and male reproductive systems, and vestibular systems (Seidel and Heide, 1986). A third review prepared for the Workers' Compensation Board of British Columbia, showed that there is a link between back disorders and WBV (Teschke et. al., 1999). The most commonly noted were disc herniation and degeneration. It was also noted that consistent exposure to WBV after 5 years elevated the risk of developing back problems.

One of the most concerning aspects of WBV related to health is the development of pathological changes in the spine. A pathological change is considered to be physical damage or change to a body part. In many cases the physical damage is irreversible and conditions associated with the damage result in chronic pain or handicap. In particular, pathological changes due to degenerative processes caused by WBV can result in conditions such as: chondrosis, osteochodrosis, spondylosis, spondylarthrosis, and intertebral disc protrusion and prolapse (Dupuis and Zerlett, 1986). Pathological diseases like the ones previously listed were found to have a higher incidence in people exposed to WBV for many years compared to unexposed control groups (Miyashita et al., 1992).

There are additional effects that have been found relating to WBV. These effects are not physical or damaging to the body but can increase the risk of danger in working environments. Studies like the one conducted by the Australian Transport Safety Bureau have found that vibration causes changes to body metabolism and chemistry resulting in fatigue (Mabbott and Newman, 2001). This has serious implications in environments such as mines where fatigued truck drivers may not be able to focus at the task at hand, putting themselves and other's safety in jeopardy.

It is apparent that a consistent exposure to vibration can cause significant health effects and that the likely hood of developing health problems relating to WBV is inevitable for prolonged exposure. Many of these health effects are irreversible and people suffering from WBV disorders will experience pain or even worse a disability for the rest of their lives. Such pain and disabilities can prevent people from leisure activities as well as their jobs.

2.2 Standards for Whole-Body Vibration

As a result of the numerous studies linking WBV to health problems, standards have been developed by various partnerships between governments, physiologists, universities, and independent experts. The standards are aimed at defining guidelines for durations of vibration in an attempt to reduce the amount of vibration one can sustain. Although these standards are determined by the top experts in the world in this field, the standards themselves have limitations, as with any standard, due to the complexity of the subject and therefore debatable. However, WBV standards provide a metric for evaluating and provide guidelines for exposure limitations.

Standards for WBV have been developed by different organizations; the main ones are the International Standards Organisation (ISO) and the British Standards Institute (BS). The International Standards Organisation developed ISO 2631-1 (1997), *Mechanical vibration and shock-evaluation of human response to whole-body vibration* (a revision of the original 1985 version) and the British Standards Institute developed BS 6841, *Measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock.* Many countries have their own standards but are merely derivations of the ISO standard.

2.2.1 ISO 2631-1 (1997)

ISO 2631-1 (1997) is a modification of the original standard ISO 2631-1 (1985). This standard provides details on how to measure vibration and the evaluation of vibration with respect to comfort and health.

ISO 2631-1 (1997) uses a three dimensional coordinate system (figure 2.1) where each axis is orthogonal to one another. As a result, transducers used to measure vibration have to be placed in the direction of the corresponding axis of measurement orthogonal to one another. The standard requires that the location of measurement devices (location of transducers) should be placed at a point where vibration is entering the body. For someone that is seated this would be on the seat pan of the supporting surface.

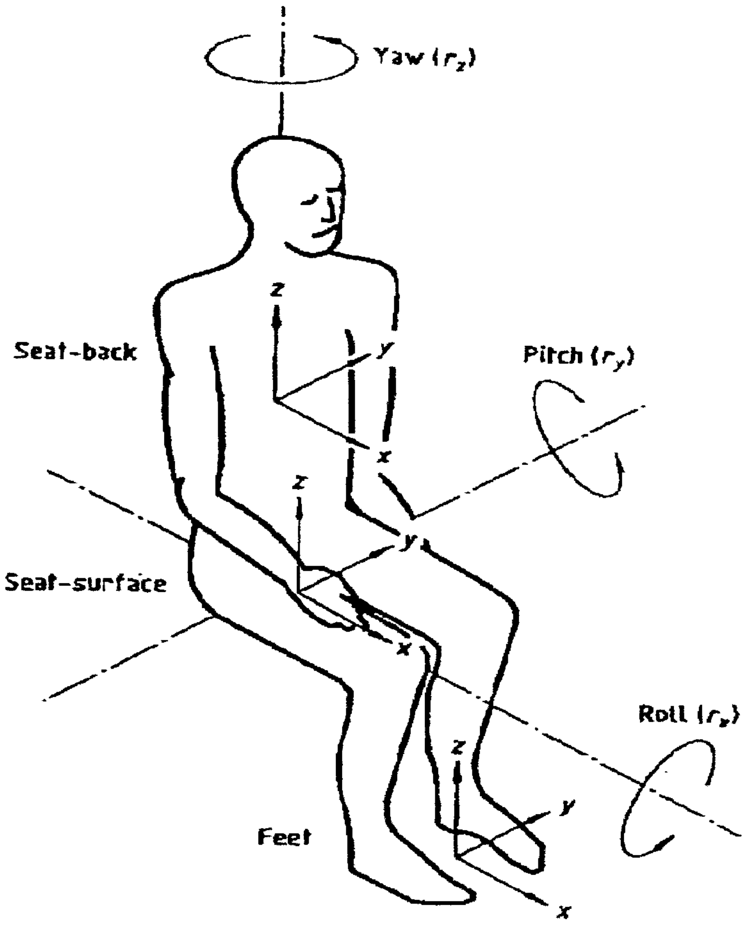


Figure 2.1 After ISO 2631-1 (1997) Coordinate System

To evaluate vibration the standard averages vibration over time and frequency bands so signal conditioning is required. The general requirements are that the frequency range to be considered is 0.5 Hz to 80 Hz. Therefore signal conditioning equipment must be adequate to accurately sample the highest and lowest frequencies. This requires band limiting filters with a high-pass filter at 0.4 Hz and a low pass at 100 Hz. Sampling rate of signals is to be 1.5 times the highest frequency of interest, termed the Nyquist frequency, in order to optimize signal to noise ratio. Specifics for creating required filters are found in IEC 1260: 1995 (IEC, 1995). Once the initial signal processing is fulfilled, the acceleration data (separated by each axis: x, y, z) is to be passed through another filter that separates the signal into 1/3 octave bands producing a frequency spectra (as described in section 1.13). Specifics for one-third octave band filters are also found in IEC 1260: 1995.

ISO 2631-1 contains two methods for evaluating exposure. The first is the basic evaluation method which uses the weighted root-mean-square acceleration; and the second uses the fourth power vibration dose method. To follow the basic evaluation method as set out by ISO, the next step would be to apply the frequency weightings to each a band of the spectra to yield the frequency-weighted acceleration (equation 2.1).

$$a_{eq} = \left[\sum_i (W_i a_i)^2 \right]^{1/2} \qquad (2.1)$$

where:

a_{eq} = weighted acceleration;

W_i = weighting factor for i th one-third octave band;

a_i = r.m.s acceleration for the i th one-third octave band.

The frequency weightings for the z-axis that are used in the standard are referred to as Wk and the weightings for the x and y axes are referred to as Wd. The weightings are shown in the ISO 2631-1 (1997) standard. The weighted acceleration is calculated for the measurement duration for each axis and the results are compared to the health caution guidance zones (figure 2.2). The health guidance caution zone chart has three distinct zones corresponding to the exposure duration and weighted acceleration. The first zone, referred to as "safe" zone, is located under the bottom line and it represents minimal effects to the body, the second is the “caution” zone where there are possible effects, and the third zone is the “danger” zone in which health effects are likely. For example, someone being exposed to WBV for 8 hours with an A_{eq} of 0.63 m/s^2 would be in the caution zone for health guidance.

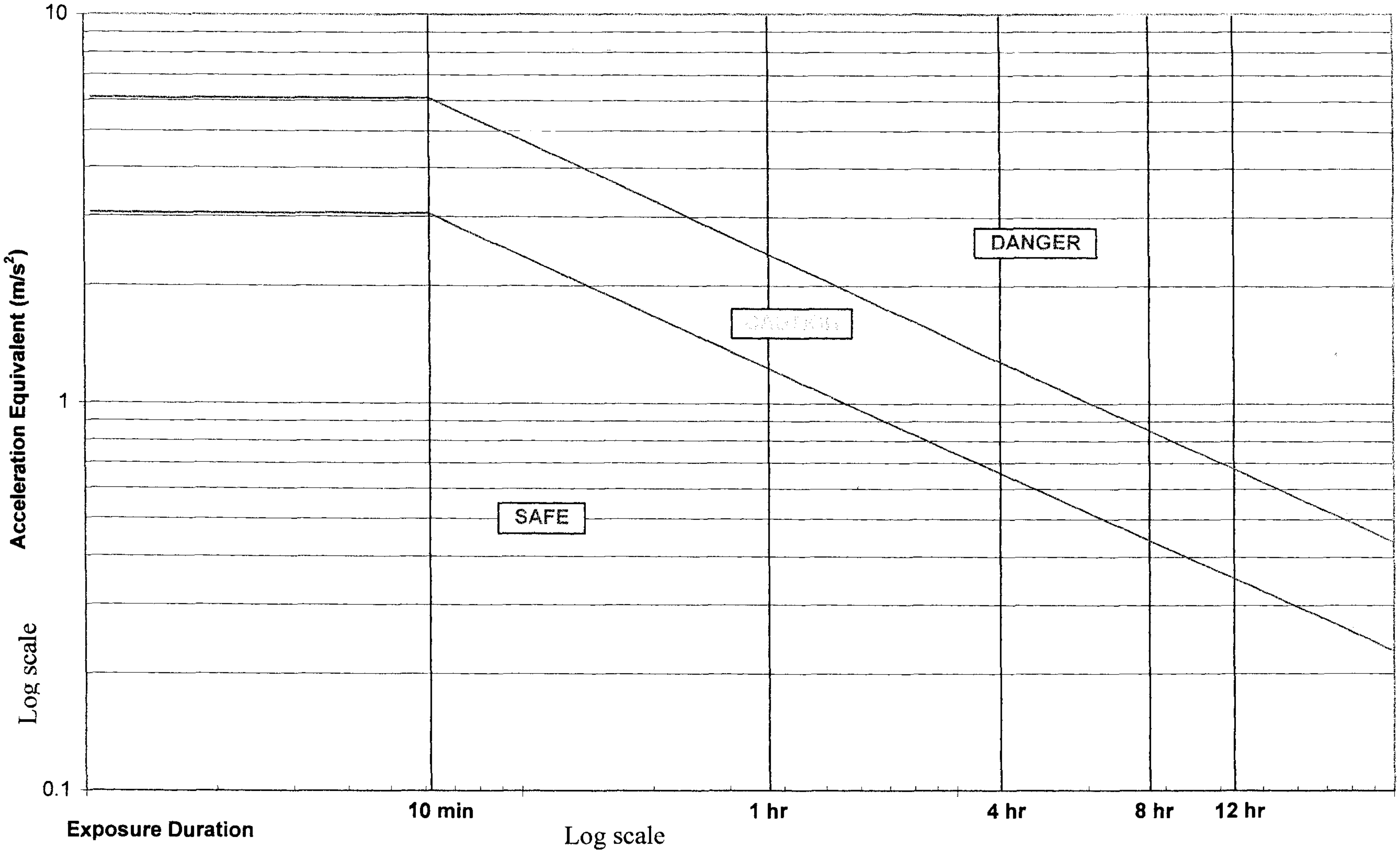


Figure 2.2 ISO 2631-1 (1997) health caution guidance zones

The total vibration value of weighted acceleration can be calculated to give the sum of vibration using equation (2.2) and then compare to the health guidance zones.

$$a_v = (k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2)^{1/2} \quad (2.2)$$

where:

k_x, k_y, k_z are the multiplying factors for each axis (1.4 for X and Y, 1.0 for Z);

a_{wx}, a_{wy}, a_{wz} are the frequency-weighted accelerations for each axis.

Equation 2.2 was developed to give the X and Y directions a higher weighting. This is based on studies that have found that vibration in the X and Y directions have been found to be more damaging to the body than the Z direction. In the standard it is unclear as to whether the sum is required to be used for health evaluation but it is suggested in the standard that when two or more axes are comparable, the sum can be used.

If there are two or more periods of measurement then the standards suggest using the equivalent vibration magnitude which can be calculated using the running root-mean-square (RMS), given by equation 2.3.

$$Aeq = \left[\frac{\sum a_{wi}^2 \cdot T_i}{\sum T_i} \right]^{1/2} \quad (2.3)$$

Where:

Aeq= equivalent vibration magnitude;

a_{wi} = vibration magnitude for the exposure duration of T_i.

The results for the equivalent vibration magnitude are also compared to the health caution guidance zones.

The other method for evaluation using the fourth power vibration dose method referred to as the vibration dose value (VDV), is slightly different. This method is more sensitive to peaks than the basic method by using the fourth power rather than the second power. It is suggested that the VDV method be used when the crest factor, which is the peak acceleration divided by the RMS acceleration, is above 9. However, the standard also mentions that the crest factor is an uncertain method for deciding whether RMS acceleration can be used to assess human response to vibration, providing confusion on what method to use. Therefore the user must interpret and decide what method is best based on the characteristics or their situation. The VDV method utilizes the same process and equations as the basic method, the only difference, as mentioned earlier, it that the VDV uses fourth power rather than the second power (equation 2.4).

$$VDV = \left[\sum_i (W_i a_i)^4 \right]^{1/4} \qquad (2.4)$$

As with the acceleration equivalent, the VDV equivalent (equation 2.5) remains the same but with fourth power.

$$VDVeq = \left[\frac{\sum a_{wi}^4 \cdot T_i}{\sum T_i} \right]^{1/4} \qquad (2.5)$$

The main difference between the basic and VDV methods exists in the evaluation of the health guidance. The VDV methods uses vibration dose values between of 8.5 $m/s^{1.75}$ and 17 $m/s^{1.75}$ for defining the health guidance caution zone. The same chart used for the basic method can be used for VDV. However, the VDV values must be converted to RMS values using the estimated vibration dose value (figure 2.3). The VDV equivalent health caution zones are shown by the dashed lines.

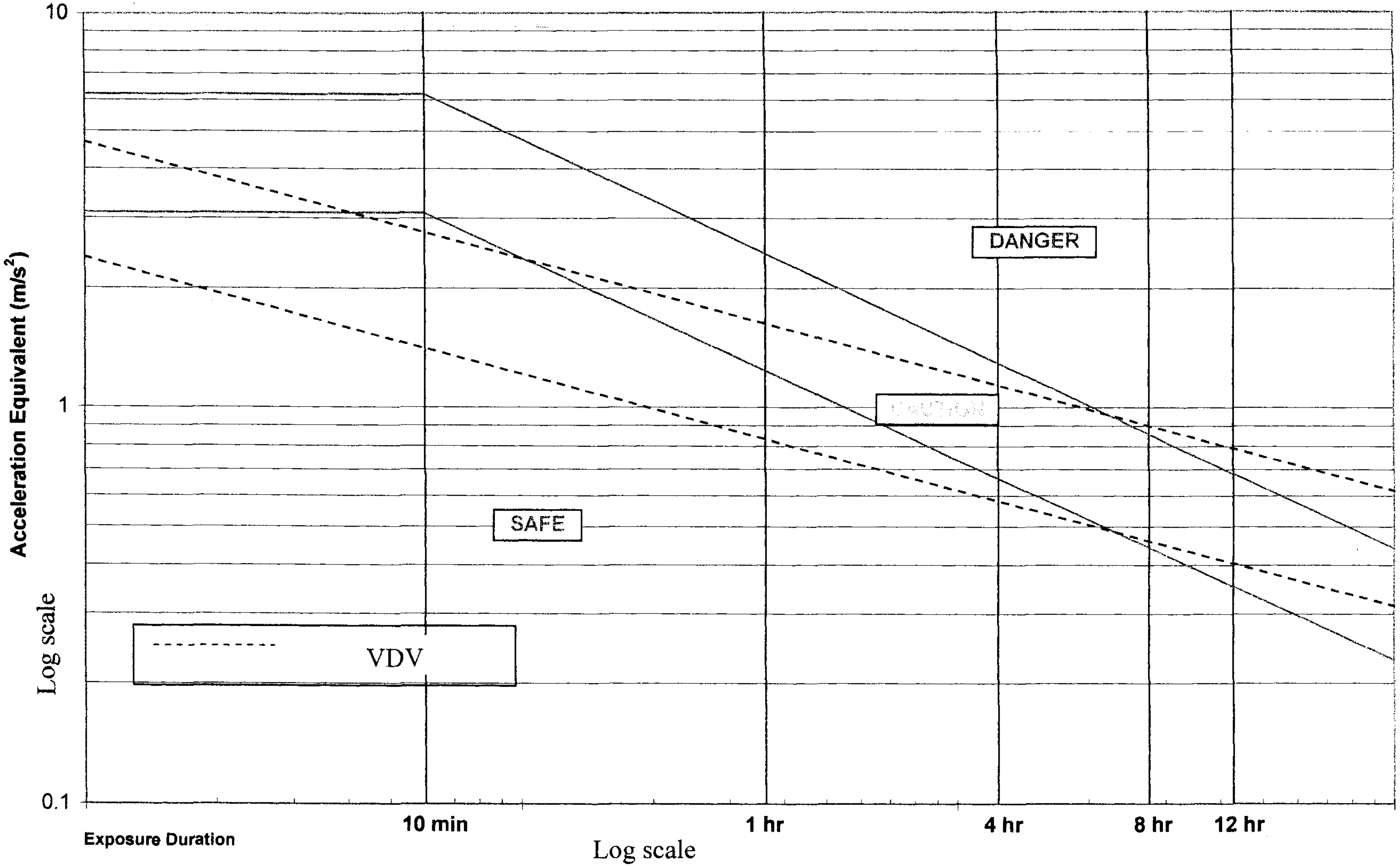


Figure 2.3 ISO 2631-1 (1991) health caution guidance zone VDV

2.2.2 BS 6841 (1985)

The British standard for whole-body vibration essentially follows the same procedure as indicated in ISO 2631-1, with a few differences. The first difference is the use of four measurements instead of three. BS 6841 suggests using a seat backrest measurement in the X direction in addition to the X, Y, Z measurements from the seat pan. The signal processing requirements are essentially similar to the requirements stated in ISO 2631-1. The second difference is the frequency weighting factors, which are the same for the X and Y direction as in ISO 2631-1, but differ for the Z direction. ISO 2631-1 uses a frequency weighting shape referred to as Wk, is sensitive to low frequencies (0.5 Hz - 5 Hz) where as BS 6841 uses the frequency weighting, Wb, which is more sensitive to higher frequencies (5 Hz – 8 Hz). As a result the Wk gives higher weighting than Wb in the 0.5 Hz – 5 Hz range and conversely Wb gives higher weighting to the 5 Hz – 8 Hz range.

The biggest difference between the two standards is through the choice of evaluation. As discussed earlier, ISO 2631-1 suggests two main ways of evaluating vibration. The first is through the use of the basic evaluation method, which is a RMS type calculation using the second power A_{eq}, and the second is the vibration dose value method which uses the fourth power. The difference is not in the calculation but which method to use. The British standard advocates the use of the VDV method since it suggests that the peaks encountered during vibration are the most damaging to health. The same equation used in ISO 2631-1 for VDV is used in BS 6841 (equation 2.4). The sum measure is not used in the British standard as it is suggested in the ISO standard.

For the evaluation of health on vibration exposure, BS 6841 does not use the health guidance system as used by ISO 2631-1 but rather uses an “action level”. The action level is the VDV value which vibration exposure is harmful to health and a reduction of vibration should be considered. The action level can be compared to the health guidance caution zone chart from ISO 2631-1 (1997) using the estimated vibration value (figure 2.4). The action level is indicated by the dash dot line.

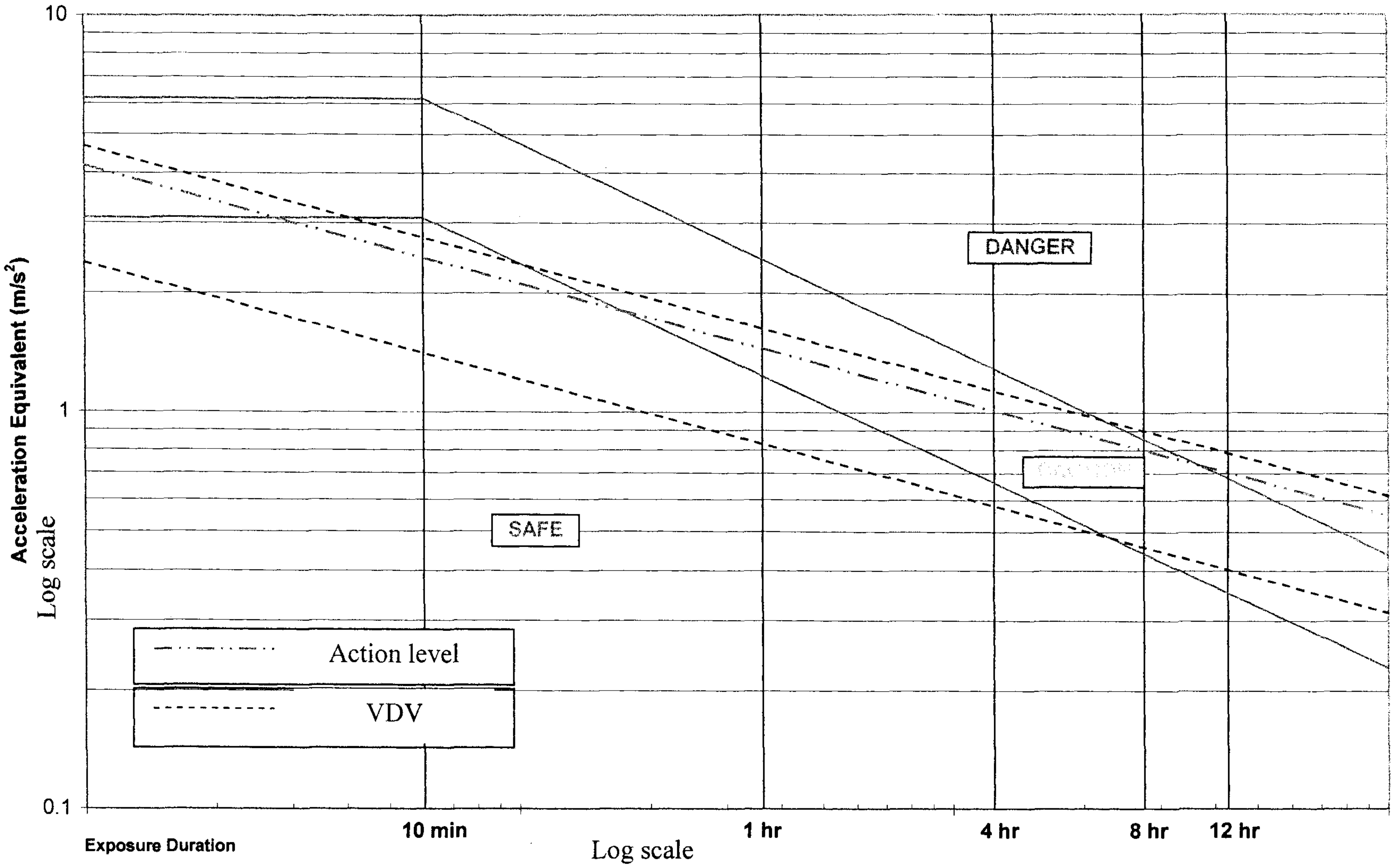


Figure 2.4 ISO 2631-1 (1997) health guidance caution zones comparison to BS 6841 action level

2.2.3 Worldwide Use of Standards

Both standards provide procedures for measuring and evaluating whole-body vibration but are different in this method. There are both positive and negative aspects to each standard making the decision difficult when choosing which one to use (Lewis and Griffin, 1998). Most countries use ISO 2631-1 as the standard of choice, or a derivative of it, for whole-body vibration. Canada, Australia, South Africa, the European Union, and other countries, all state ISO 2361-1 (1997) as being the standard of choice. The United States uses its own standard (SAE J1013, 1992) which is a derivative of the ISO standard. Based on general consensus, one would assume that using the ISO standard would provide a better platform for evaluating WBV due to its widespread use and making it easy to compare exposure studies to each other. To the best of the author's knowledge, Britain is one of the only countries that uses BS 6481 as the standard for WBV with few countries referring to it as an alternative method for evaluating WBV.

3.0 Occupational Exposure

It is estimated that between 4 – 7% of all workers in the United States, Canada, and some European countries are exposed to potentially harmful levels WBV; with more that 7 million workers in the United States alone exposed on a daily basis (Cann et al., 2003). Through the use of standards, particularly ISO 2631-1 (1997), there have been a number of studies that have measured the exposures encountered by subjects of a variety of occupations. Of all the occupations studied, driving occupations showed the greatest risk as a result of high vibration exposure. In particular, driving occupations involving earth moving machinery such as dozers, front end loaders, scrapers, haul trucks, etc…, where off-road travel is regular, show the highest risk (Teschke et al., 1999, van Niekerk et al., 1999). These high exposure driving occupations are a characteristic of the mining industry. Driving on very poor ground conditions is frequent making the mining industry a high exposure environment. One study conducted by Cann et al., showed that eight out of fourteen mining equipment types tested exceeded safe VDV as set out by ISO 2631-1 (1997). It was also shown that operators of certain equipment, such as haul trucks, were exposed to WBV levels with greater risk of developing adverse health effects.

3.1 Exposure Studies in the Mining Industry

There have been a number of research projects that have produced exposure results for mining equipment. A few of the studies have used the British Standard with a majority using the ISO standard. The common underlying theme with all the studies is that WBV levels experienced by operators of mining equipment are greater than the ISO health caution guidance recommendations. In fact one investigation revealed that all mining vehicle exposures were greater than ISO 2631-1 (Teschke et al.,1999).

Exposure measurements in the South African mining industry conducted on 135 ton payload haul trucks using ISO 2631-1 (1997) showed that the exposure levels (A_{eq}) for the x, y, and z directions were 1.23 m/s^2, 1.6 m/s^2 , and 1.15 m/s^2 respectively for a duration of 4 hours. Individually for each axial measurement the x and y axes are above the ISO danger limits while the z measurement is in the caution range for the 4 hour exposure. The sum for these results would produce an A_{eq} of 3.05 m/s^2, which is well over the safe limit. Operators continually driving under these conditions would be exposed to harmful levels of vibration that would likely lead to adverse health effects.

Another vibration exposure research project examined the levels of exposure for various types of construction equipment including haul trucks (size not mentioned). Vibration signals were averaged every 30 seconds for 20 minute testing periods. The results showed that the weighted acceleration (sum) ranged from 0.7 – 1.7 m/s^2 with a mean of 1.21 m/s^2. These ranges would not put a subject at risk for the 20 minute period since it is well below the caution guidelines. However, the 20 minute periods can be representative of the entire shift since haul trucks have cyclical operating routes that they travel on for a majority of a shift, the exposure encountered by the operators in this study would place them in the dangerous guidance zone in just one hour.

The results found in the previous studies were confirmed by a third study conducted in the oil sands industry in Ft. McMurray, Alberta, Canada. In this study a number of pieces of mining equipment were tested, including three haul trucks (Robinson, 1999). The Caterpillar 777 (163 tons), Caterpillar 789 (317 tons), and

Dresser (Komatsu) 830E Haulpak (385 tons) were the three types of haul truck tested. The exposure times were 11 hours for the Caterpillar trucks and 10.5 hours for the Haulpak trucks. The A_{eq} values obtained from each of the trucks were as follows: Caterpillar 777 0.5 m/s^2 (x), 0.3 m/s^2 (y), and 1.0 m/s^2 (z); Caterpillar 789 0.5 m/s^2 (x), 0.3 m/s^2 (y), and 1.0 m/s^2 (z); Haulpak 830E 0.2 m/s^2 (x), 0.2 m/s^2 (y), and 0.9 m/s^2 (z). Based on the results from this study all three trucks were below the caution region of the ISO 2631-1 health guidance caution zones in the x and y direction. However, the Caterpillar 777 and Dresser 830E were in the in the "danger" zone in the z direction and the Caterpillar 789 was in the "caution" zone but close to being in the "danger" zone. All three trucks are well into the "danger" zone for the sum of weighted acceleration with values of 1.29 m/s^2 for the Caterpillar 777, 0.939 m/s^2 for the Caterpillar 789, and 0.983 m/s^2 for the Dresser 830E. It is apparent that someone subjected to this type of exposure consistently is at risk of developing health problems.

3.2 Legislation

Due to increasing concern for whole-body vibration some countries have introduced legislation regarding exposure. However, when considering the problems of whole-body vibration it seems unreasonable that more legislation controlling exposure has not been introduced. In Alberta alone, the cost of vibration related injuries and incidences from mobile equipment has been \$1,703,119 from January 1999 to October 2004 (WCB, OCT.17, 2004). Another alarming statistic indicates that their have been 6,670 temporary disability days (days where work has been missed) as a result of vibration induced injuries from mobile equipment.

3.2.1 International

Internationally, whole-body vibration related problems are recognized but are largely not controlled. The United States and Australia do not have any regulations regarding WBV, but recommend using guidelines set out by each country's suggested standard of choice. Since it is only recommended that the standards should be followed, they are not enforceable by law.

Conversely, other countries have taken the opposite approach and made whole-body vibration standard legislation. It was estimated that 24% of workers in Europe are exposed to mechanical vibration, realizing the consequences the European Union decided to legislate whole-body vibration exposure limits, based on ISO 2631-1 criteria. The only deviation is that the European Union has set a daily exposure limit of value 0.8 m/s^2 and 14.6 $m/s^{1.75}$ (VDV) for an 8 hour reference period (EU, 2001). Since this is legislation by the EU, all the member states are required to comply.

Realizing the effects whole-body vibration can have, some countries have taken a step further and added vibration related illness to official occupational related diseases. Belgium, France, Germany and the Netherlands are among the countries that consider vibration related illness an occupational disease, which is compensable (Bonvensi, 1999 Dupis, 1994).

3.2.2 Canada

In Canada, occupational legislation is controlled by each province. Whole-body vibration legislation for the most part is negligible, with the exception of British

Columbia. In British Columbia it is law to comply with the guidelines set out by ISO 2631-1 (1997). Currently Alberta has no legislation to protect workers from whole-body vibration related disease but recommends compliance with ISO 2631-1 (1997).

4.0 Thesis Project

During the course of a shift, operators of haul trucks in the mining environment can be exposed to high levels of vibration. These high amounts of vibration can be attributed to aggressive driving patterns, rough and poorly maintained roads, poorly placed loads by shovels, and poorly maintained equipment. Subsequent to reported incidences of vibration induced injuries during operation of haul trucks, Syncrude Canada Limited decided to investigate exposure experienced by its employee's during operations. It was found that operators of haul trucks experienced levels of vibration that would be in the caution and danger zones of ISO 2631-1 (1997) health guidance caution zone (Radke and del Valle, 2002). These findings were consistent with the results of other investigations at other mines as discussed in previous sections. As a result of findings and commitment to health and safety, industry in partnership with the University of Alberta, took initiatives to develop ways of reducing whole-body vibration among operators of haul trucks.

There are three ways of reducing vibration of mobile equipment through the improvement of: driving surfaces, mechanical equipment, and operational practices. Each of the solutions have been examined or research is currently underway.

4.1 Driving Surfaces

The condition of the terrain that mobile machinery operates on, highly influences vibration exposure. It has been found that continuous surfaces along with regular maintenance of roads produce lower vibration exposure levels (Ozkaya, 1994).

As haul trucks drive on roads and loading areas, the weight of the machinery along with inconsistencies in road structure, produce ruts and hummocks that severely deteriorate the surface conditions. This rapid degradation of the operating surface can occur within a few truck cycles. Firm surfaces can produce these conditions making it even worse for soft ground conditions like oil sand. This is a tremendous challenge for oil sands mines where very soft underfoot conditions dominate. Persistent road maintenance to reduce road roughness would help reduce vibration exposure. However, in mine operations, equipment resources are often exhausted due to high demands within the mine site, making it extremely difficult for continuous maintenance. One solution to this problem is to improve the efficiency of haul road maintenance. In doing so, the maintenance effort may produce better and longer lasting results. To achieve better efficiency of haul road maintenance, a better understanding of the ground materials in the mining environment is necessary. Currently research is being conducted to gain a better understanding of the behaviour of oil sands when loading and unloading cycles occur (Joseph, 2002). It is believed that this work will inherently help reduce vibration exposure experienced by operators in this environment. This approach however will occur long term any may not completely eliminate the problem of operator vibration on its own.

4.2 Mechanical Equipment

Generally, there are two ways of reducing vibration in haul trucks. The first option involves the modification of the truck design to reduce motions that cause vibration. One method of achieving this is to reduce roll and pitch motions of the vehicle since both of these motions can cause severe vibration in the cabs of heavy haulers. By lowering the centre of gravity of the vehicle these motions would be reduced, improving the vibration characteristics. However this is not a very practical method since any design changes would require a complete change of the manufacturer's assembly line. In addition to this, the specifics and functionality of the vehicle could be compromised causing mines to drastically adjust mining methods as well as mining infrastructures such as maintenance shops, hoppers, etc... This is not to say that it is impossible for this change to occur, but rather a very long term change, if this direction is taken by equipment designers and manufactures.

The second solution involves a less drastic change in equipment design through modification of suspension. This is accomplished through suspension systems of the struts, cab, and seat. Under current practices suspension of the seat or vehicle do not necessarily reduce vibration exposure and in some instances the suspension systems are amplifying rather than attenuating vibration (Tescke, 1999). However, properly designed suspension systems tailored to the specific operating conditions can drastically reduce vibration exposure. It has been found that a combination of the three suspension systems (struts, cab, and seat) can result in a 50% reduction of vibration (Donati, 2002). To achieve such a reduction, the suspension system must be designed so that its highest cut-off frequency is less than the input frequency and should be sufficient enough so that bottoming and topping out at end stops does not occur. Therefore the frequencies and magnitude of vibration encountered during operation must be known to design a suspension system that will compensate for the specific conditions. Most suspension systems in haul trucks are designed for hard ground conditions which are encountered in hard rock mines, however for soft ground conditions such as in the oil sands there are little or no suspension systems that are designed for the conditions. To design a suspension system for specific conditions is very difficult in practice in the mining industry, since the conditions are constantly changing with weather and large equipment. This solution requires further research and is long term.

Another way of modifying suspension is through semi-active suspension where the suspension characteristics change to conditions rather than have the same reaction to all vibration. Semi-active suspension could provide a very effective way of reducing vibration however; each suspension system requires a specific algorithm for the conditions that will be encountered which is a very complex and costly process.

4.3 Operational Practices

The final solution considered here focuses on improving how the vehicle is operated. It has been shown that the vibration emission levels increase with travel speed and surface roughness (Author Unknown, Noise and Vibration Worldwide, 2002). By changing driving patterns vibration exposure might be decreased. This could be done in a number of ways, but the idea of an operator feedback system came about after the successful use of another feedback system in the mining industry. The feedback system previously used was put into practice to warn operators of high stress events on dragline booms during operation (Carroll,1997). This system provided operators with a visual screen that indicated to them that stress levels in the boom were reaching damaging levels. The premise behind this feedback system was that when the operators received an indication of high boom stress levels, they would ease off on operation to lessen boom stress. The dragline boom stress feedback system proved to be very effective in reducing boom damage.

It was thought of that the same idea used for dragline booms could be applied to reduce vibration in haul trucks. The same principle would be applied, where the use of a visual feedback system would indicate to operators when they are receiving harmful doses of vibration. During operation, when drivers were prompted that they are receiving harmful levels of vibration, they would ease off operation and/or change driving patterns to avoid such vibration. This would be a near future solution and could be implemented sooner than others if proven successful. In additional to this, the feedback system would be less costly than other solutions.

4.4 Operator Feedback Warning System

Based on the principles behind the vibration feedback system, it was decided that research be conducted regarding the use of a feedback system to reduce operator vibration exposure. It is hypothesized that a vibration feedback system could potentially reduce vibration which is the topic this thesis research will attempt to answer. It has been found that rack produces the most damaging effects to haul trucks frames (Joseph, 2002). Rack is defined as the sum of the strut pressure of the front right and rear left minus the sum of the front left and rear right. As a result, if a relationship can be established between rack and vibration equivalent, then any potential reduction in vibration would be reducing rack events that cause frame damage, and inherently those that are passed on to the operator. In general, the question to be answered here is: Can a vibration feedback system reduce vibration exposure experienced by the operators of mining haul trucks?

5.0 Methodology

To answer the thesis question the specifications of the feedback systems had to be determined. Details concerning how the system would work, what would the display look like, the development, the deployment and use, and the evaluation had to be answered.

5.1 Vibration Feedback System Criteria

In order to answer the question regarding a vibration feedback system's effectiveness of reducing vibration exposure, a firm plan of action for how the system would work had to be determined. For this project the focus was on the overall exposure for the entire duration of a work shift. To achieve an overall reduction of vibration exposure, each instant of a vibration event would have to be reduced. As a result, it was decided that two types of indicators would be used.

The first would be an instantaneous display showing the severity of vibration, based on threshold values, the operator was experiencing at a given moment. The intention of this type of indicator is to make the operator aware of any dangerous vibration events they received at any moment so that they in term could change driving patterns to obtain an acceptable vibration level which would also be indicated once the vibration levels dropped below the threshold.

For events where there would be quick jolts of high magnitudes of vibration, where they occur too quickly for the operator to react, the intentions of the feedback system in this case would be slightly different. In these circumstances, the operator would know the location where they received the high vibration indication and could change driving patterns to lessen the severity at that location or avoid it. If the location is still causing vibration problems after the fact, it would serve as an indicator to operation supervisors to repair the problematic ground conditions. This would also work when the trucks are being loaded, where a large number of jolts often occur, by the operators of haul trucks notifying the loader or shovel operators when they are receiving high vibrations while being loaded. This way the loader or shovel operator can make a conscious effort to place material into the truck gentler. However the vibration feedback system would only be applied for these cases once it was proven effective by this research project.

The second vibration indicator would be an overall vibration indicator or meter that would show the overall vibration the operator has experienced for the shift. This type of meter can be compared to a radiation exposure indicator that people wear that work near radioactive sources. As a person is exposed to radiation the indicator will "fill up" to the amount of radiation exposure reaches the recommended limit. At this point the person can no longer be exposed to radiation within a certain time period under the recommended limit for exposure duration. The vibration indicator would work in the same fashion. During the operation of the haul truck the overall vibration meter would fill up based on vibration levels and once the recommended vibration limit for the shift duration was attained the operator would have to be removed from the equipment to avoid further exposure.

The intention of the operator feedback system was for the two indicators to work together to help reduce vibration. The first indicator would help reduce vibration for increments of time (instantaneous), then the overall incremental vibration summed for the operation duration would be reduced, which would be displayed by the second indicator.

Once the logic behind how the system would work was defined, the actual system design had to be determined. An appropriate system would have to fit certain criteria in order to answer the question of this research. The first point that had to be satisfied was the ability to show the two displays, being the instantaneous and cumulative vibration, so that the operator could visually receive their vibration exposure so that they could react accordingly. The second was that the two displays had to be simple and easy to understand. If the display were difficult to understand or could potentially be misread, the whole point of the feedback system would be jeopardized. The third was that the system used ISO 2631-1 (1997) as a measurement and evaluation standard. There is debate as to what whole body vibration standard is best to use. For this project ISO 2631-1 (1997) was selected over other standards to be used for the measurement and evaluation of vibration for a number of reasons. This standard gives higher weightings to lower frequencies making it more appropriate for off-road vehicles due to its sensitivity to lower frequency vibration (Lewis and Griffin, 1998). It has been found that the model suggested by ISO 2631-1 (1997) better predicts subjective evaluation than other standards (Griefahn, 1999). The ISO standard for whole-body vibration is widely used making the results analogous for comparison to other studies. The final criterion was that the feedback system would have to record the vibration values for both instantaneous and cumulative vibration so that the data could be analyzed.

When selecting an appropriate system that could be used for the project the four criteria that had to be satisfied were taken into consideration. The first option for the selection process was to take at look at the commercially available units. Two commercial units were looked at. The first system that was examined was the SVAN 912A manufactured by SVANTEK. This system was capable of measuring vibration and providing RMS calculations. However the SVAN 912A was determined to be inappropriate for the purposes of the project since the system did not evaluate whole-body vibration according to ISO 2631-1 (1997), and failed to provide a simple display. The second system, the HVM100, manufactured by Larson Davis was better since it used ISO 2631-1 (1997) for whole-body vibration evaluation. The downfall with this system as with the first was that it failed to provide a display that could easily be understood. Both systems used number values for the RMS vibration instead which would be meaningless to the operators using the system. As well, both systems did not have the two types of vibration indicators that were desired for the project. As a result it was decided that in order to satisfy the specific criteria of the project, an in-house system had to be built.

5.2 System Design

To design the ideal feedback system with respect to the particulars of the project a few details had to be resolved in order to choose the system specifics such as software and hardware.

5.2.1 Visual Display

The first step was to determine what the cosmetics of visual display would be, and how to properly convey vibration information to the user so that it was easy to understand. For the instantaneous display it was decided that the simplest means of expressing vibration levels would be through a three color LED system similar to a traffic light. A green light would light up if the vibration levels were okay, a yellow light would indicate vibration levels in the cautionary range, and a red light would denote vibration levels in the dangerous zone. During operation the driver would try to maintain a green light. If the driver was receiving yellow and red lights during operation, it would indicate to him/her to change their driving pattern so that they would receiving a green light more consistently thus lowering vibration exposure. The second display showing the cumulative vibration for the duration of the shift would also have to be simple. The type of indicator that was decided to be the most suitable was a gauge type indicator similar to a speedometer. The gauge would have color coded graduated markers starting from a low cumulative vibration at the beginning of the scale indicated by green moving to higher cumulative vibration at the end of the scale indicated by red. This indicator would be directly related to the instantaneous green-yellow-red light system since it would use the cumulative vibration dose from each instantaneous dose. As a result the more consistent one is at receiving a green light the lower the cumulative vibration will be. Each dose of vibration received would cause the dial on the gauge to move towards the red zone with a threshold indicator line specifying when the operator is above the dangerous threshold level for a 12 hour shift based on ISO 2631-1 (1997) health caution guidelines. When the danger limit has been breached the operator should be removed from the machine.

Once the specifics of how the visual display would look and function were established the details of how to construct a system that would fulfill the system functionality was addressed. Careful consideration was given to choosing the type of software and hardware used for the project.

5.2.2 Software

The choice of software was based on its ability to allow for the calculation of vibration including necessary signal processing as well as its capability for a windows interface which could provide a simplistic display. After considering a number of software packages the one which best suited the needs for the project was Labview 6.0 by National Instruments. Labview 6.0 is programmable software used for data acquisition that provides customized displays using Windows. This software package provided an excellent platform for all the required needs including data acquisition, signal processing, calculation, and simplistic display. Labview 6.0 contains built-in functions that make data acquisition very easy and precise. As well, it contains built-in tool sets for signal processing that conform to International Electrotechnical Commission (IEC) and Automotive Electronics Council (AEC) standards. One of the predominant features of this programming language is that it is easy to use since it is visual based using diagrams and icons rather than text. The program created called *Vibration-Main.vi* consists of six basic steps: data acquisition, signal processing, equivalent vibration calculation (instantaneous), equivalent vibration calculation (cumulative), data recording, and results display (figure 5.1). The resulting steps are divided into sub-virtual instruments (sub VI) which are analogous to functions in other programming languages. In figure 5.1, the corresponding sub VI's for each step are listed in brackets where a sub VI exists.

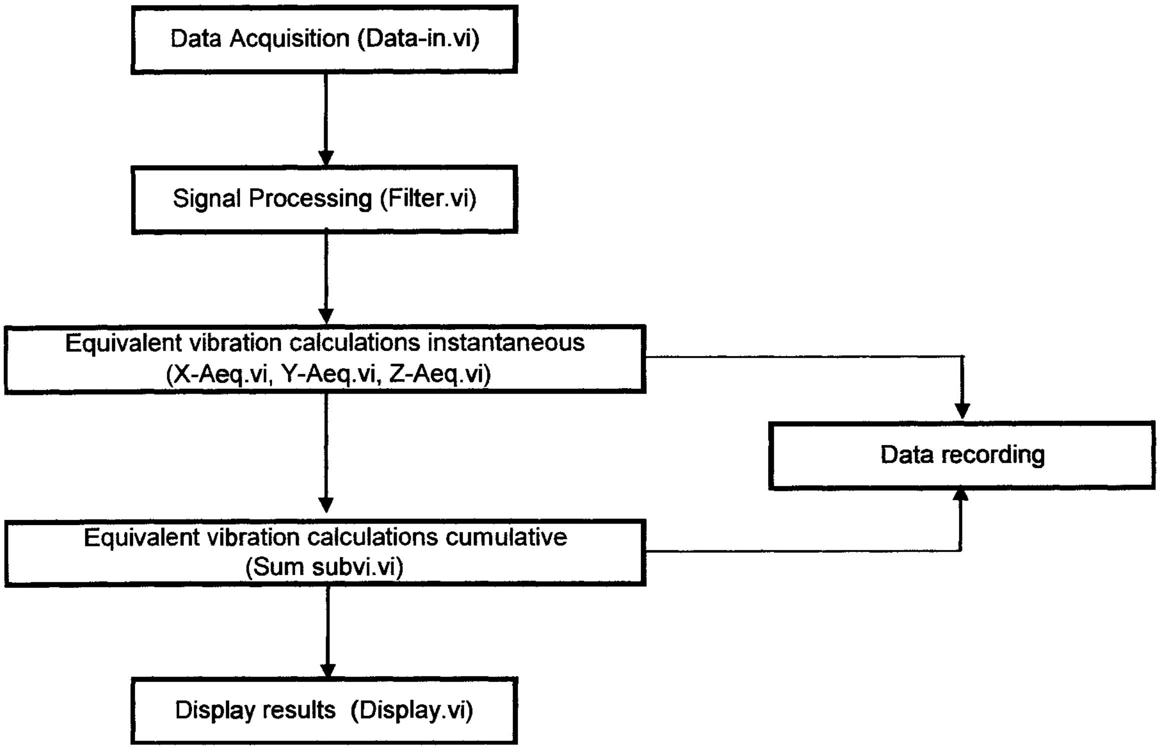


Figure 5.1 Vibration-main.vi Program Flow

The complete wiring diagrams for *Vibration-main, vi* used for programming are shown in Appendix A. The diagrams show how the program is compiled to produce the desired results.

5.2.3 Data-in.vi

Data-in.vi is a sub-vi making the first step of the program information flow. The general flow of information of the sub-routine is shown in figure 5.2. This sub-routine is responsible for acquiring data/signal from a selected device to send to the next routine. The option is given in *Data-in.vi* to use real data collected from accelerometers or use computer generated sine wave data. The computer generated sine wave was added to the program for debugging and calibration purposes. The sine wave generator is a Labview built-in function where the amplitude and frequency can be adjusted. The first process for the program is to select which type of data to use (real/fake). Once the data type is selected, (accelerometer data or sine wave data) the user is prompt to input the scan rate and the number of samples per channel. One thing to note is that for field testing, the program will be hard coded to use accelerometer data only so the operator will not be prompt for any input. The scan rate is the frequency with which the data sample will be taken, ie. a scan rate of 200 would indicate a sample rate of 200 samples per second or 200 Hz. The samples per channel are the amount of data points to be read for each data block. To satisfy ISO 2631-1 (1997) a scan rate of at least 200 Hz must be used to which is roughly the Nyquist frequency for the desired range of frequencies of interest. By using the Nyquist frequency, problems due to aliasing are reduced. Taking the block size and dividing by the sample rate, will give the duration of time the equivalent vibration is calculated for, or in other words averaging time. The averaging time for the equivalent vibration will also be the reporting time for the instantaneous display. For example, a scan rate of 200 and a block size of 400 will produce a reporting time of 2 seconds so equivalent vibration would be taken over 2 seconds therefore making the instantaneous display update every 2 seconds as well. Selection of a sampling rate of 200 Hz was used for the project but the number of samples per channel to attain a desirable reporting time, was to be determined through later testing.

Once the sampling rate and number of samples per channel were established, the next step consisted of establishing a few technical specifications for the complier so that data would read in from the measurement device. To satisfy the complier requirement in Labview 6.0 there are three built-in functions that are used. The first configures the input device so that it can be read by the program, the second starts the data reading by initiating the buffer, and the third reads the data from the buffer for all three directions X, Y, and Z. These functions and hard coded and will not prompt the user to input any values. After the data has been read in, a timestamp is created and assigned to each set of data to create a waveform which is a data type used by Labview. The waveform data type allows for the allocation of large amounts of data through its specialized compression technique and is required if the built-in Labview filtering functions are to be used. Once the waveforms for each direction are created for the block of data, the waveforms are sent to next process, *Filter.vi.*

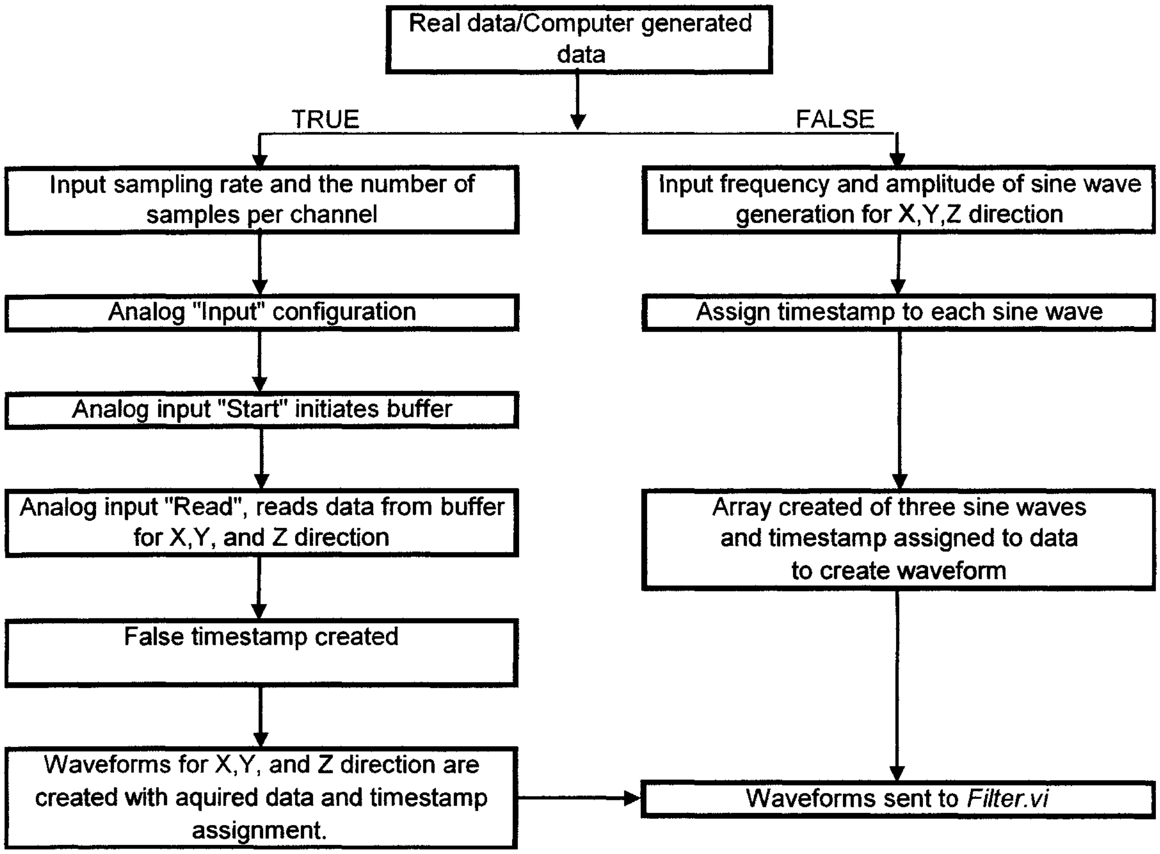


Figure 5.2 ***Data-in.vi*** **data flow**

5.2.4 Filter.vi

This portion of the program is a sub VI that is responsible for filtering data as per ISO 2631-1 (1997) requirements and separating the sets of data so that the necessary calculations can be performed. This sub program utilizes Labview's *IEC fractional filter.vi* built in function for performing the 1/3 octave band filtering. The filtering function conforms to the one-third octave filter specifications given in IEC 1260, as required by ISO 2631-1 (1997). There are a few different options that are offered within the built-in function. The filter band width, frequency range, and filter resetting are among the options that can be altered. For this project the filter options were set so that the ISO guidelines for whole-body vibration would be followed. The band width was set to 1/3 octave, the frequency range was set for 0.5 to 80 Hz, and filter resetting was selected to reset after each block of data went through so that there was no filter carry over from one block of data to the next. All of these settings are hard coded so the filter function will automatically be set for the ISO 2631-1 (1997) specifics making so that the user cannot change the settings, figure 5.3.

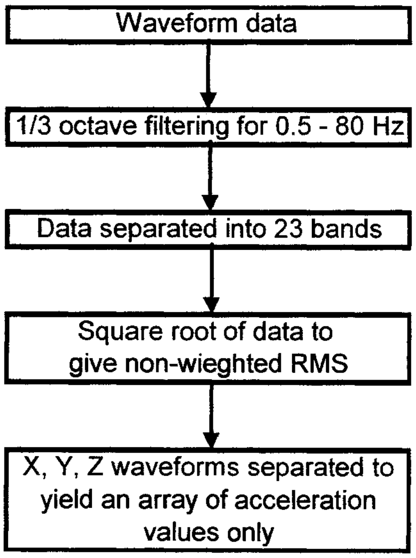


Figure 5.3 *Filter.vi* Information Flow

The general flow of the sub program starts with receiving waveform data, with three arrays within it (3d array), from *Data-in.vi* and performs filtering using the IEC filter function. Once the filtering has been completed and the data for each array is separated into the 23 octave bands (0.5 Hz to 80 Hz). The 3d waveform array is then converted into a single 2d array where the square root of the sum for each array is taken to give the root-mean-square. When this stage is completed the array is separated into three directions and sent to the calculating programs, *X-Aeq.vi, Y-Aeq.vi, Z-Aeq.vi.*

5.2.5 X-Aeq.vi, Y-Aeq.vi, Z-Aeq.vi

The *X-Aeq.vi, Y-Aeq.vi,* and *Z-Aeq.vi* programs are responsible for calculating the acceleration equivalent (Aeq) using the filtered data. In the *Vibration-Main.*vi program the acceleration equivalent calculations are separated into three identical (with exception of the frequency weightings) sub programs for each direction. Each sub program is named as to which direction it calculates for, *X-Aeq.vi* for the X direction, *Y-Aeq.vi* for the Y direction, and *Z-Aeq.vi* for the Z direction. The program accepts the 2d array from *Filter.vi* (figure 5.4) and applies the corresponding frequency weighting for the specific direction. Once the frequency weightings have been applied, the rest of the calculation is completed using the ISO 2631-1 (1997) basic method for calculating acceleration equivalent. The settings for this calculation are hard coded so it is done automatically with no user input. The results are sent to *Sum subvi.vi* for further calculations and are recorded to file.

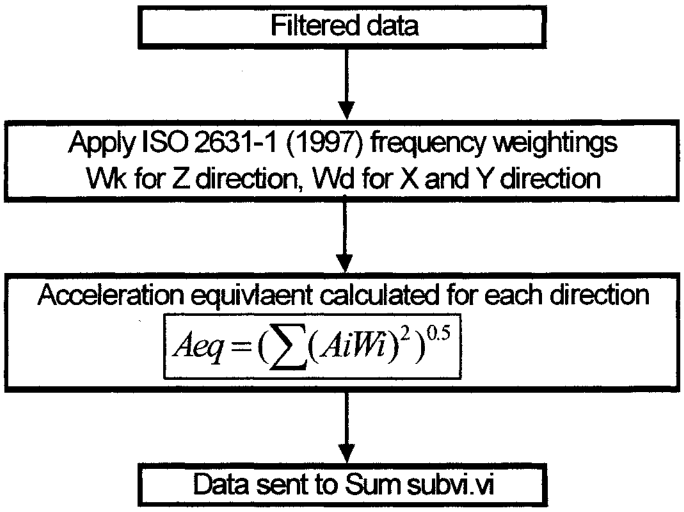


Figure 5.4 ***X-Aeq.vi, Y-Aeq.vi, Z-Aeq.vi*** **general data flow**

5.2.6 Sum subvi.vi

This sub program receives the acceleration equivalent from each direction and calculates the sum of acceleration equivalent of all three directions and the cumulative acceleration equivalent (figure 5.5). Once the sum of acceleration equivalent is calculated the resultant value is sent to Display.vi for the instantaneous display and is also used for the cumulative acceleration equivalent. The cumulative acceleration is calculated by summing the sum of the acceleration equivalent for each block of data until operation of the program is ceased giving the total vibration exposure for the time of operation. Once the value is calculated for the current block of data it is looped back into the program to be summed with the next block of data and is also sent to Display.vi for the vibration exposure display. All the calculated values are recorded to file once complete. This sub program serves as a calculator program only and has no user input.

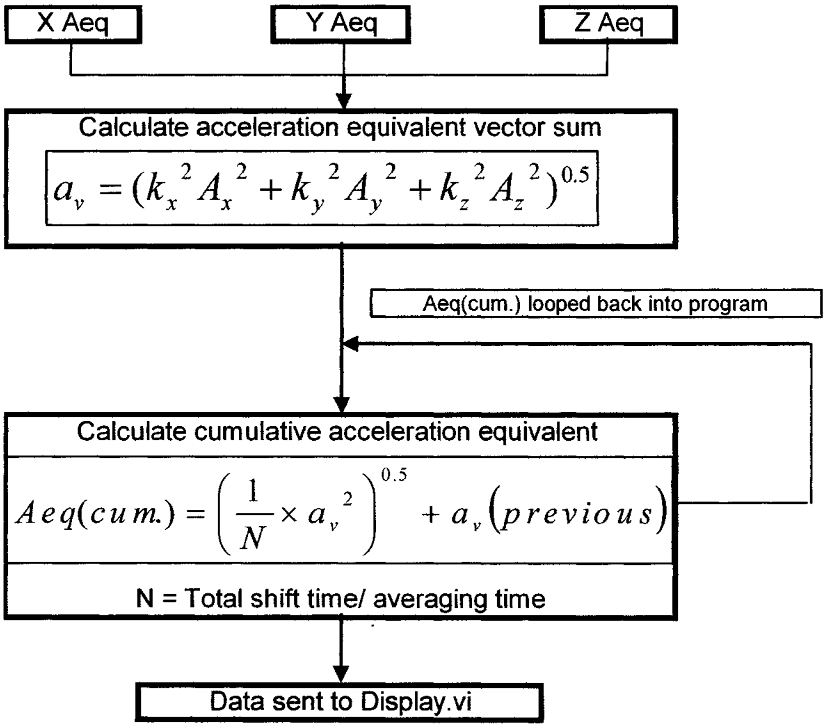


Figure 5.5 Sum subvi.vi

5.2.7 Display.vi

The Display.vi sub program is the final stage for the data flow for the entire program. It displays all of the results in the form of LED's for the instantaneous acceleration and a gauge for the cumulative vibration exposure. The display is in the form of a windows type interface (figure 5.6). The primary responsibility of this sub vi is to serve as the communicator to the user.

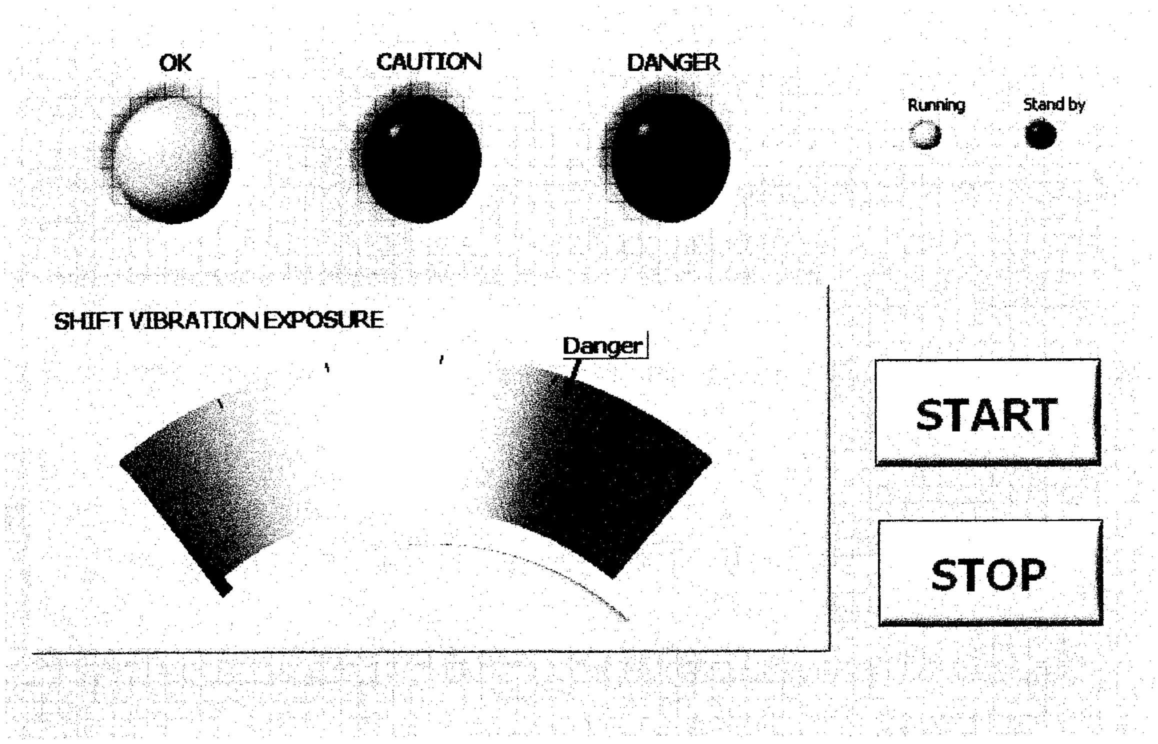


Figure 5.6 User display interface

The program begins with the data from Sum subvi.vi entering the program. The instantaneous acceleration values enter and are diverted to the instantaneous display component and the cumulative acceleration values are diverted to the cumulative display component (figure 5.7).

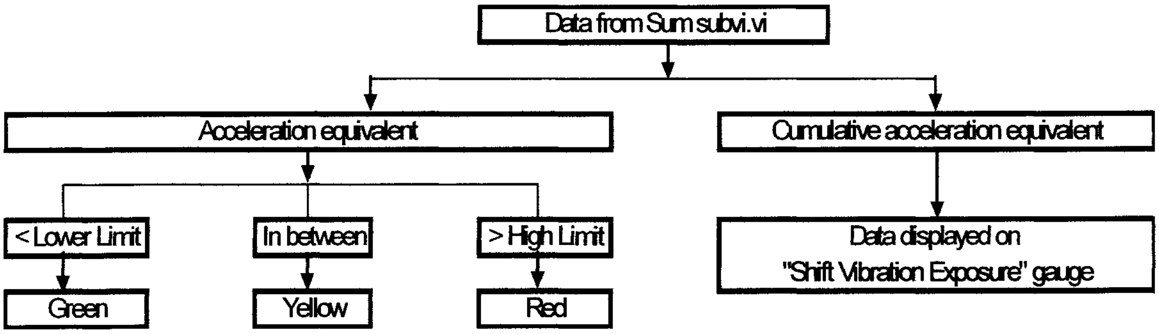


Figure 5.7 Display.vi progam flow

The values for the instantaneous acceleration equivalent are subject to Boolean logic where the value is compared three different cases that will determine what indicator will be stimulated. Each case is dependent on a threshold limit, which would have to be determined through testing since there are no definite health limits, suggested in ISO 2631-1 (1997), for minute durations of time. The selection of the threshold values are discussed in the proceeding section. During operation of the program, the acceleration equivalent values are tested to see if they are below the low threshold value, in between the low and high threshold values, or above the high threshold value. If the acceleration equivalent is below the low value a green "OK" light will light up indicating to the operator that they are receiving is acceptable (figure 5.8).

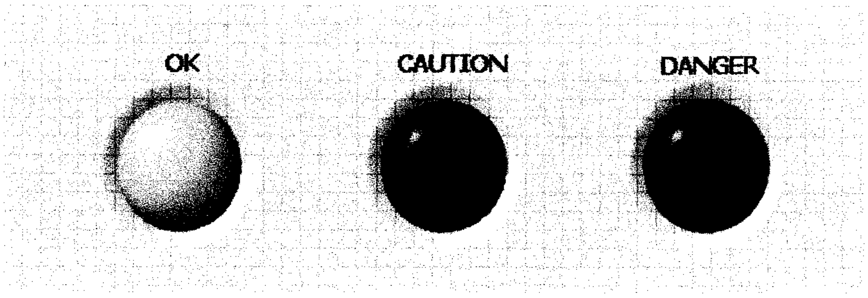


Figure 5.8 Instantaneous display "OK"

If the acceleration equivalent is between the low and high threshold values the yellow "CAUTION" light will light up signifying to the operator that the vibration they are receiving is undesirable so they should take caution (figure 5.9).

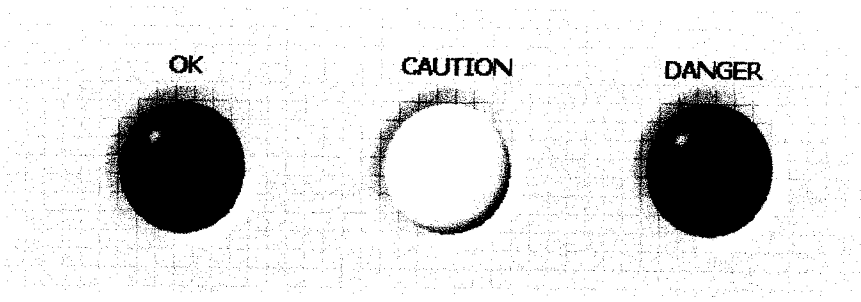


Figure 5.9 Instantaneous Display "CAUTION"

The final option is if the acceleration equivalent is above the high threshold value where a red "DANGER" light will display indicating to the operator that the vibration level could be dangerous to there health (figure 5.10).

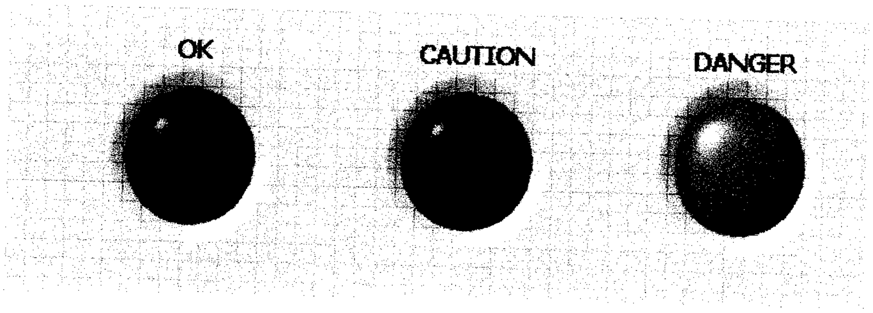


Figure 5.10 Instantaneous Display "DANGER"

The second gauge labelled "SHIFT VIBRATION EXPOSURE", keeps track of the cumulative vibration exposure for the duration of operation (figure 5.11).

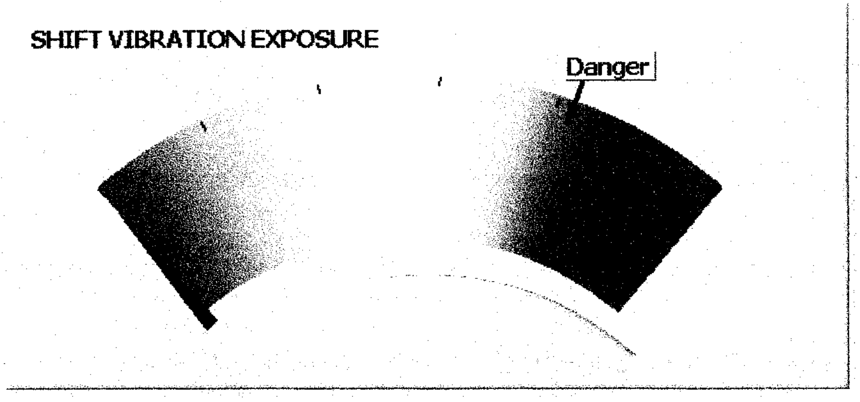


Figure 5.11 Cumulative Vibration Exposure Gauge

The cumulative acceleration equivalent values calculated in *Sum sbuvi.vi* are directly sent to this gauge. The dial begins at zero on the left most side of the gauge, as vibration is experienced the dial will move towards the red zone on the right side. The higher the instantaneous values the quicker the dial will move towards the right side (figure 5.12). On the gauge there is an arrow with the text "DANGER". This is the twelve hour exposure limit (0.68 m/s^2) obtained from ISO 2631-1 (1997) where there are adverse health effects due to vibration exposure. Once the dial has moved past the danger arrow the operator is in the danger zone of the health guidance caution zone.

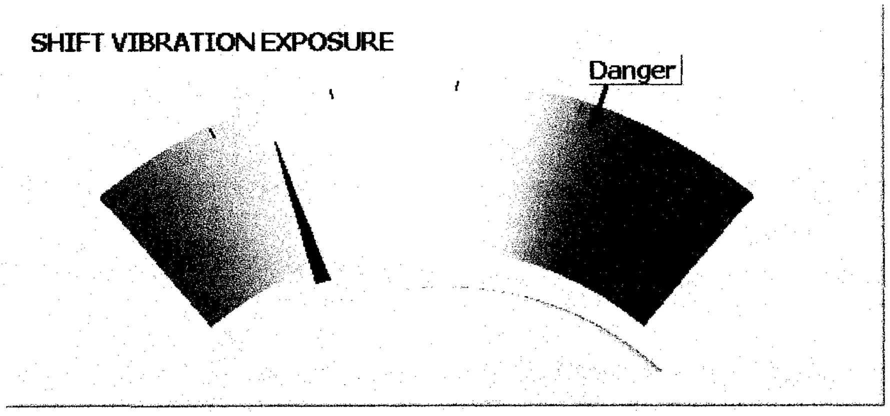


Figure 5.12 Cumulative Vibration Exposure Gauge Showing Dial Movement

The other features of the user panel are the START and STOP buttons (figure 5.13). The START button initiates the program to begin collecting data, performing calculations for the display and writing data to file. The STOP button ceases the system from collecting data, performing calculation, and writing data to file. When the STOP button is pressed, the system is reset so all the gauges return to the beginning at zero and the data file is stopped. A new data file will automatically be made when the system is initiated again with prompting from the START button.

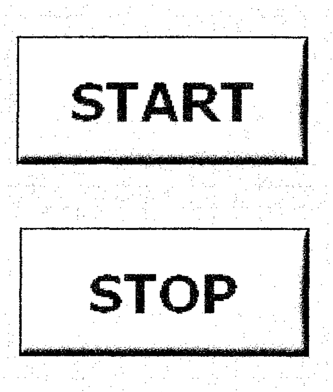


Figure 5.13 START/STOP Buttons on the User Interface

On the panel there are two lights with the titles "Running" and "Stand by". The lights indicate to the operator if the system is operating by a green light or if the system is waiting to begin by the yellow light (figure 5.14).

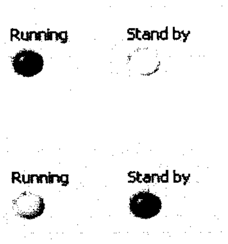


Figure 5.14 Running/Standby Indicators

5.2.8 Hardware

The hardware used by the system consisted of an accelerometer, data acquisition devices, a laptop and an 8" touch enabled screen. The process of information flow is shown in figure 5.15.

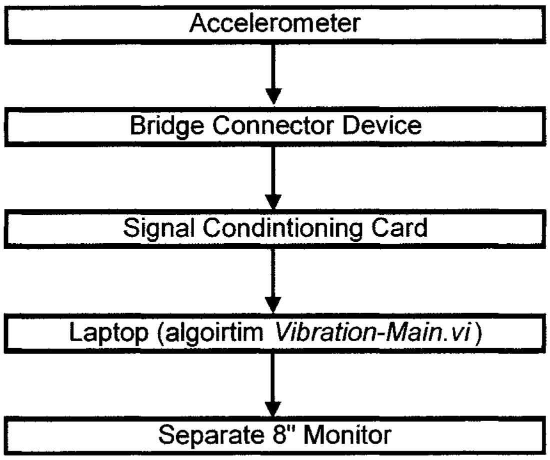


Figure 5.15 Information Flow Through Hardware

The first step of the process is collection of the vibration data by the accelerometer which is placed under the seat of the operator. The model chosen was the ENTRAN EGCS3-D triaxial accelerometer (figure 5.16).

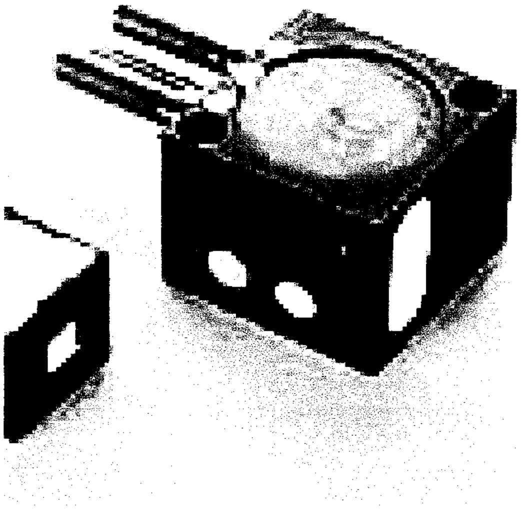


Figure 5.16 ENTRAN EGCS3-D Triaxial Accelerometer

The ENTRAN EGCS3-D accelerometer is fully shielded with a full bridge configuration and has a range of full scale of 5g's which is ample for this application. The specifications for the ENTRAN EGCS3-D are given in Appendix B. The next step of the process is for the separation of the wires (excitation in, excitation out) through a connector block. The instrument used for this was the SCB – 68 manufactured by National Instruments (figure 5.17) which is a 68 pin connector. This device provides extra shielding but its primary purpose is that is allows for the simplification of system set up. The SCB – 68 is connected to the accelerometer and the signal conditioning card through a shielded cable.

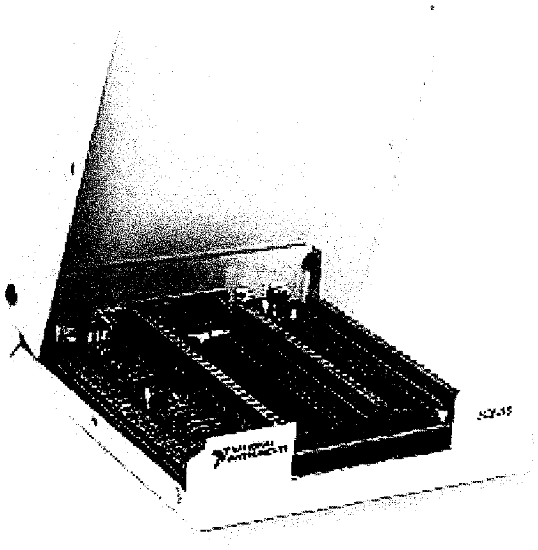


Figure 5.17 National Instruments SCB – 68

The signal conditioning card used was a NI DAQCard – 6036E (PCMCIA bus) manufactured by National instruments (figure 5.18). It has a 16-bit input/output resolution with a sampling rate of 200 kS/s. The signal processing card provides the necessary analog to digital conversion of vibration data so that the computer can use the data. The specifications can be seen in Appendix C.

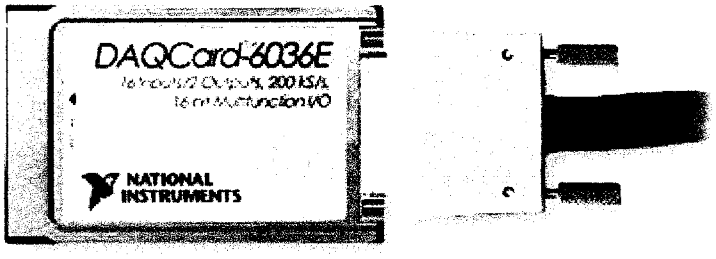


Figure 5.18 Signal Processing Card NI DAQCard – 6036E

The signal conditioning card is located inside the computer. The type of computer used for the project was a Panasonic Toughbook 28. This type of laptop was chosen based on its specifications and high durability. The laptop consists of a Intel Pentium III Processor – M at 1.0 GHz, 512 MB RAM, and Windows operating system. Labview 6.0 along with National Instruments Measurements and Automation Explorer were installed on the computer. The Measurements and Automation Explorer software is used to configure the accelerometer to the signal processing card and software.

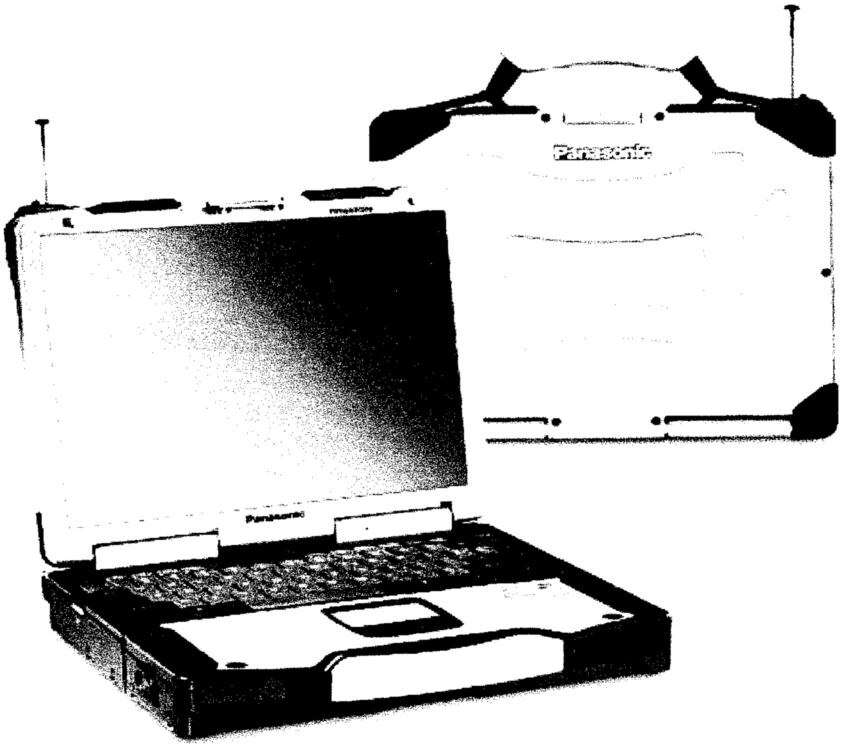


Figure 5.19 Panasonic Toughbook 28

The final component of hardware for the system is the 8" detachable screen (figure 5.20). This screen is touch enabled so that the user would only have to touch the screen to press the START and STOP buttons to use the system. All the components were placed in a case for storage purposes (figure 5.20) while on the truck with the exception of the accelerometer which would be placed under the seat and the detachable monitor that would be placed in a position where the operator could see it yet would not be in the way. The detachable monitor that would house the display would be located on top on the Wenco system and radio inside the cab (figure 21).

Figure 5.20 System Components with Storage Case

Figure 5.21 Location of Visual Display

5.3 Operation of the System

Before testing of the system is discussed, an overview of operator use of the system and how the system will potentially reduce vibration will be discussed.

To begin, in order for the system to be used properly the operator would have to be instructed on how to use the system. As a result, a set of laminated instructions on how to use the vibration feedback were placed inside the cab of the vehicle. The instructions given to the operators can be viewed in Appendix D. Within the instructions the procedure for system operation is discussed as well as the goals of what the operator should be trying to achieve using the system, ie. staying below the danger marker in the cumulative vibration display.

The operation of the system begins with the operator pressing the start button on the screen to initiate the system. Once the start button is pressed the system will be taking vibration measurements and calculating. The system will be running for the entire shift. It will be in function during breaks even when the vehicle is static. The system is not turned off during breaks or waiting periods where the vehicle is not moving since any length of time the operator is not receiving vibration during their shift is weighted against periods where they are receiving vibration. Only when the operator has completed their shift or is taken off the truck, the stop button will be pressed to terminate the vibration system operation.

During operation of the system a series of lights will be displayed depending on what magnitude of vibration is encountered. The objective is to consistently receive a green light during the shift so that the operator can remain below the danger marker of the shift vibration exposure gauge. When yellow or red lights are encountered it is the responsibility of the operator to change their driving patterns so that they are receiving green lights more consistently with intermittent yellow lights. This may be accomplished by slowing down, avoiding rough spots, etc... However, the operator will not be instructed on how to change their driving patterns; it will be up to them to determine the best methods. There were a number of reasons that the operators would not be advised on how to change their driving patterns, these reasons tended to be a result of the work culture at the mine site. Many of the operators have a great deal of experience and understand how to adjust driving to conditions. Since a large part of this project relied on the cooperation of the operators, it was decided that any orders on how to operate the equipment may jeopardize any cooperation. Another reason is that operators can be suspicious of any new devices placed in the equipment, out of fear of being spied on for vehicle misuse. For this reason operators were not told how to operate the truck, as an example, if it were said that operators should slow down to gain a green light, the wrong impression might be given due to the sensitivity of the subject. This may be interpreted that operators are driving too fast and this system is determining who is in violation when in reality the system is there to help operators. The final reason is that the mine conditions and terrain are complex, requiring different responses. To offer generalized statements referring to vehicle operation could be incorrect in many instances.

If the vibration feedback system is proven effective, eventually it would be used to determine if an operator has to be removed from the equipment when they have surpassed the danger limit on the shift vibration exposure gauge. The feedback system would also be used as an indicator when the operator is encountering situations where changing driving patterns are not able counter problems on roads and in the pit, or while being loaded by the shovel. In these cases the operator would inform their supervisor to correct the problem that is causing high vibration, ie. grading rough areas roads to make them more drivable.

6.0 Experimental Testing and Evaluation

For this project, testing was separated into three phases: laboratory testing, preliminary field testing, and final field testing. Each phase of testing was responsible for specific objectives described in the following sections. Testing was conducted in the same chronological order as presented in this chapter.

6.1 Laboratory Testing of the Vibration Feedback System

The first step in the course to developing a functional feedback system was to test the system in the laboratory to determine if the system was working correctly and to determine the optimal block size that would be reported (instantaneous reporting time). To determine if the *Vibration-Main.vi* program was correctly calculating acceleration equivalent values, computer generated sine wave data was selected in the *Data-in.vi* sub routine to be sent through the program. In this way, the exact amplitude and frequency were known so that theoretical calculations could be performed using the formulas from ISO 2631-1 (1997). The theoretical calculations were made using Microsoft Excel. During this testing the magnitude was held constant and the frequency was adjusted to match each band of the 1/3 octave. The results from *Vibration-Main.vi* and calculated values were compared and revealed that the program calculated values were the same as the theoretical calculated values (Appendix E). This confirmed that the calculation procedures in the Vibration-Main.vi program were correct. The system was ready for the second portion of laboratory testing where the hardware-program interaction was tested. To assess the vibration feedback system, two comparisons were made. The comparisons were between a commercially available system as well as theoretical calculated values. The commercially available system used was the Larson Davis HVM 100. For the comparison both units were connected to the same sine wave generator and the z-axis was tested. The amplitude was kept constant for both units and the frequency was adjusted to each one-third octave band and held for one minute at each frequency increment to allow for filter settling. Once the values produced by each unit were consistent for the one minute increment the value was recorded. This was carried out for both one and two second data blocks to determine what the optimal reporting time would be. The one and two second reporting times were only tested since a balance between operator reaction time and proper event representation was required. Times needed to be chosen that were small enough so that when an event was registered the proper light would show. If the reporting time was too long, the operator might be receiving a misrepresentative indication for the current vibration. However, within this problem, the indicator would have to remain stimulated long enough so that the operator would recognize it. Having the instantaneous indicator lights flashing sporadically would not serve any purpose since the operator would not have time to react. The accuracy of the vibration measurements also depends on the reporting time since laptops can only calculate so fast. The smaller the reporting time the less accurate the calculations will be. The results for the one second reporting time (Appendix F) showed that ***Vibration-*** *Main.vi* was more consistent with the theoretical calculated values then the HVM 100 for low frequencies, where as the HVM 100 was more consistent with the theoretical values in the higher frequency ranges. The results from the one second trials proved to be positive since the *Vibration-Main.vi* program was generally very consistent with both comparisons.

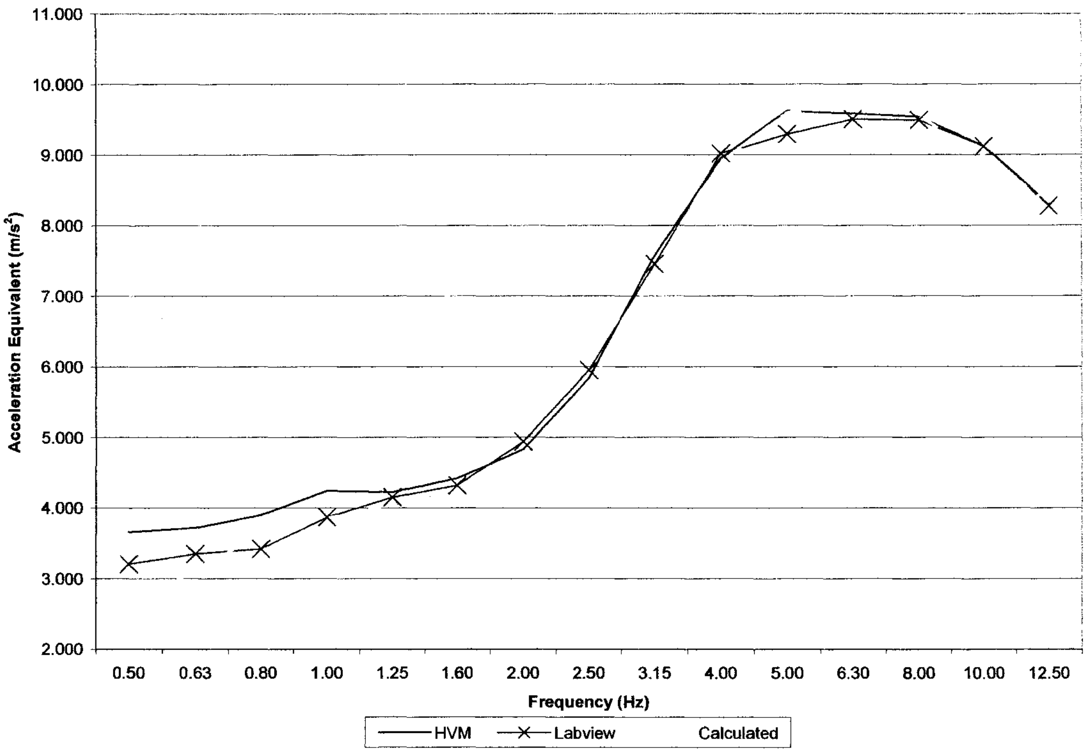


Figure 6.1 Example comparisons for 1 second reporting

The two second reporting time trials (Appendix F) produced results that were more in line with the theoretical calculations and the HVM 100 compared to the one second trials. Since the selection of a reporting time could not be solely be based on quantitative analysis, due to another consideration. This consideration was the fact that the reporting time would have to be adequate enough to give a proper indication of the current vibration. As a result, a reporting time of two seconds was selected for the project since the acceleration equivalent results were in line with the comparisons and it was concentrated enough that it would accurately portray current vibration events yet long enough for the user to be able to react.

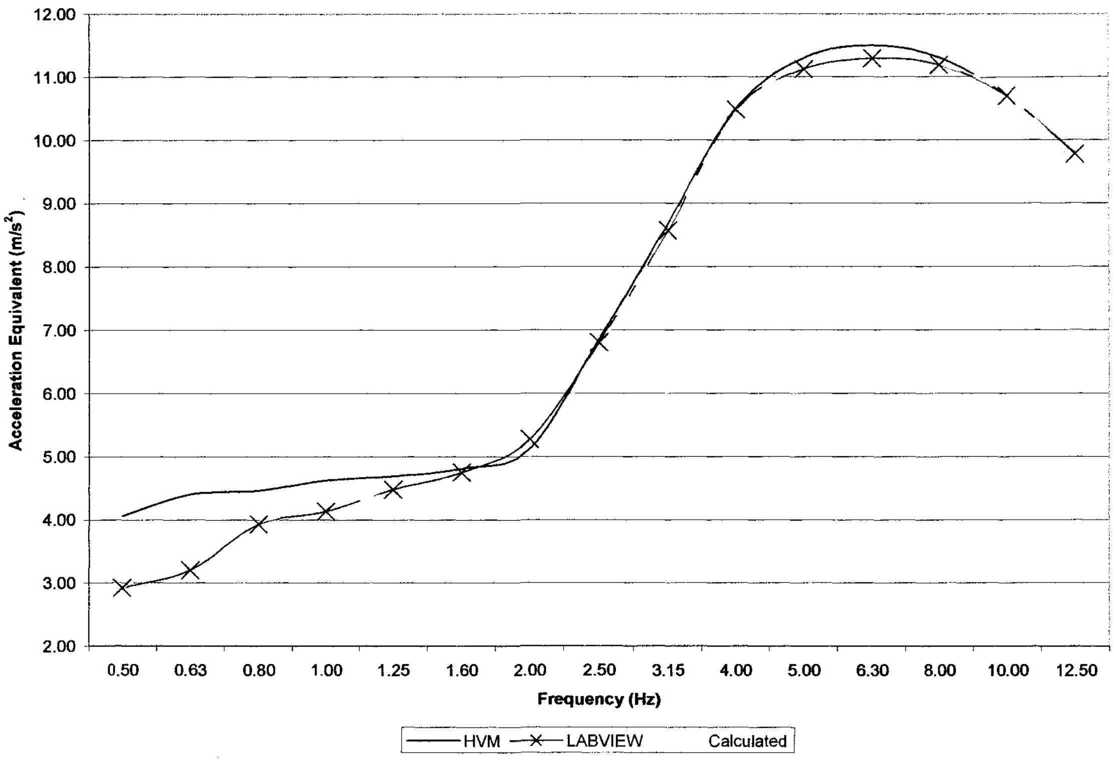


Figure 6.2 Example comparisons for 2 second reporting

6.2 Preliminary Testing and Validation

The second phase of testing consisted of preliminary field testing. There were three main objectives of this phase that had to be achieved before the system was ready for final testing. The first was the installation and operation of the system. The installation of the system in the laboratory setting compared to the testing environment was drastically different. This was in large part due to the ruggedness of the operating environment as well the hardware support such as available onboard truck power. Since the equipment would undergo vibrations as well as equipment shifting, such as pulling of wires, a way of setting up the equipment that would reduce these effects had to be physically devised. This included placement of hardware, with the exception of the touch screen, so that it was out of the way of the operator. After careful consideration a plan was devised for location and setup of the equipment. The case with the hardware consisted of hard plastic with soft foam protection so the hardware was relatively protected. The case was snugly placed behind the passenger seat with the wires leading out towards the driver's side. All the wires were fastened together with zip ties and were secured against the center console of the truck. This made the wires less susceptible to being pulled causing detachment from the rest of the equipment. The electrical and serial plug-ins to the hardware such as the touch monitor and laptop were equipped with clasps that secured plugs so that they would not fall out.

One of the challenges for the equipment setup was the placement of the accelerometer. ISO 2631-1 (1997) suggests that the accelerometer be placed on the seat pan of the vehicle. Typically to do this, the accelerometer is placed inside a rubber flat disk that the operator would sit on. Having this type of setup may be acceptable for short measurement durations (< 1 hour), however for longer measurement durations (8+ hours) this would be uncomfortable and irritate the operator. As a result the accelerometer was placed just under the seat pan. The directions of the accelerometer were checked to make sure that the directions were correct and not pointing in between axes. This arrangement not only ensured the operators comfort but it improved the integrity of the data that would be collected. By securing the accelerometer, it could not shift or bounce around due to operator shifting around in the seat.

The second objective to be completed by the preliminary field testing was to determine the power supply. The power supplied by the truck was much different than the power supplied in a laboratory setting. All that was available was a 12 V cigarette lighter, so a power inverter had to be used to adjust the voltage to 120 V for the laptop. The cigarette lighter proved to work however it was susceptible to being pulled out which would cause the system to lose power. With the help of on site electricians, a power cable was constructed that was connected directly to the battery of the truck. This set up was beneficial in the event the truck was shut down, the system would be able to hold power for a number days as indicated by the electricians. During preliminary testing the power cable system worked very well.

Once the setup and power supply were resolved the vibration feedback system was ready to begin the third objective of the preliminary testing. This was to collect data to evaluate what threshold values should be used for the instantaneous display which reports the weighted RMS acceleration for a period of two seconds. Based on the health caution guidance chart of ISO 2631-1 (1997), the maximum recommended dose of vibration is between 3.0 m/s^2 and 6.0 m/s^2 for exposure times under ten minutes. These values seemed high especially to be utilized by the vibration system. The problem with using these values would be that since the values are high, danger or caution lights might not be stimulated enough to indicate to the operator that they receiving harmful levels of vibration. As a result, operators would assume vibration levels are acceptable when in reality they could be over the dangerous limit for cumulative exposure. This would cause confusion since the instantaneous indicators could show consistent green light, but the cumulative vibration meter over time would indicate the opposite, showing vibration exposure in the danger realm of the gauge.

Determining what limits to use, proved to be a challenging task. The problem was that the value limits needed to be low enough so that the indicator would light up sufficiently to warn operators of harmful vibration events yet not be too low causing the caution and danger indicators to light up excessively leading to complacency. Low threshold values could jeopardize the reputability of the vibration feedback system if the operator received frequent caution and danger signals while driving on a relatively smooth road. The approach that was taken to solving this problem was to collect data with the vibration system while being in the cab with the operator during the course of a shift. During testing the values for weighted acceleration equivalent were observed as vibration events were encountered. This would help to gain a sense of the physical feeling associated with the typical magnitudes of vibration experienced during a shift. Operator input was also given with respect to what they felt was an uncomfortable vibration event. As jolts, bumps or rough sections were encountered the operator would simply indicate to the researcher that the vibration was uncomfortable. This was then cross-referenced with the weighted equivalent acceleration at that moment of the event. These tests were conducted over three days, testing a different truck and operator each day. Based on the findings of testing, the ISO 2631-1 (1997) values of 3.0 m/s^2 and 6.0 m/s^2 were too high. Vibrations levels around 2.0 m/s^2 were indicated by operators to be uncomfortable which is less than the lower value of ISO 2631-1 (1997). The data (Appendix G) from this series of testing shows that during the course of the shift the ISO limits were rarely encountered. Consequently based on both of these factors it did not make sense to use the ISO values as the threshold for the instantaneous display. To accomplish this task both operator input as to what was a comfortable limit and numerical analysis were used to determine what values to use. Bin counting was used in the numerical analysis to find out the number of times during the shift the yellow and red lights would be stimulated during a shift for different incremental values. Based on the results from operator input and numerical results values of 1.5 m/s^2 for the caution threshold and 2.25 m/s^2 for the danger threshold would be used for final testing. The graphical results located in Appendix G show the acceleration equivalent for the two second reporting time for the three testing days.

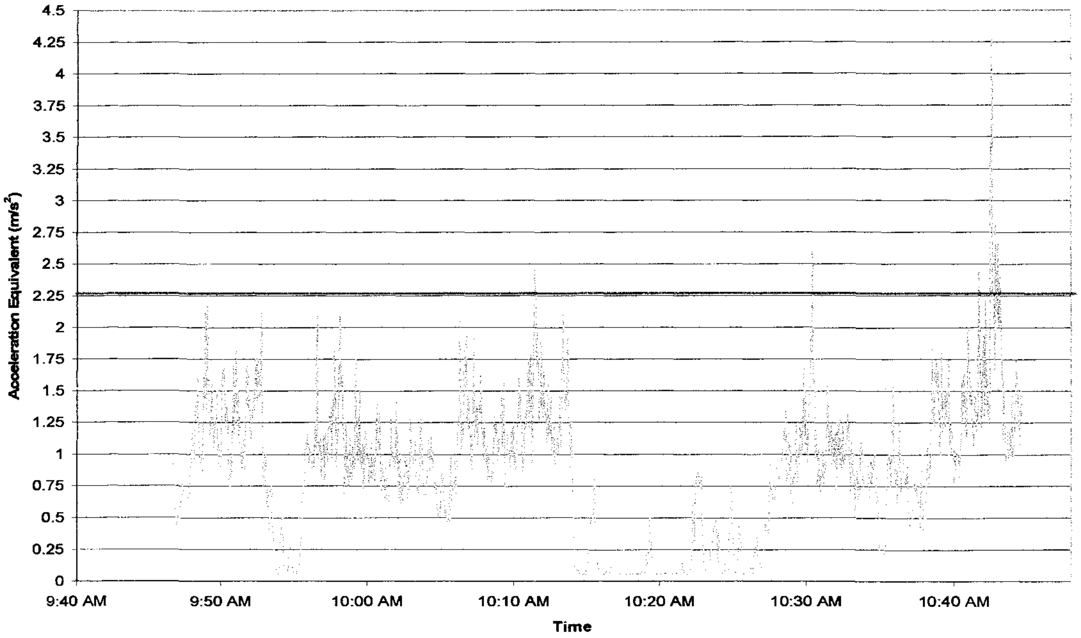


Figure 6.3 Example of threshold limit plot

Located on the graphs are lines showing caution and danger thresholds. These graphs illustrate the frequency that the caution and danger indicator lights would be stimulated.

Although the method of determining the limit values was somewhat arbitrary the premise of the system would still be accomplished. By trying to maintain a green light in the instantaneous display, the higher vibration events are reduced. As a result, the high values would not be present in the acceleration equivalent cumulative calculation. If vibration above the selected values is reduced then the overall vibration at the end of the shift can be reduced.

The final objective of preliminary testing was to get the operators opinion with regards to the cosmetics of the user screen and user friendliness. The general consensus was that the system user screen was clear and easy to comprehend. As far as the operation of the system, it was found to be easy to use. Permission to conduct an operator survey was obtained from the University of Alberta Research Ethics Committee. However, the survey was not conducted since consent had not been obtained soon enough before testing had been conducted.

6.3 Field Testing and Analysis

The final phase of testing was the field based data collection and analysis. The purpose of this phase was to collect the final data that would be used to determine if the vibration feedback monitoring system was effective or not. Testing consisted of three stages. The first was to collect baseline data with the researcher in the truck where the operator would not use system. This way data collected afterwards, where the operators used the system, could be compared with the baseline data to see if the system had any affect. The final stage was the data analysis.

6.3.1 Testing Without Using the System

For the collection of baseline data the setup that was used is described in previous sections. Data collection was conducted at oil sand mine during the month of June, 2003. During this phase of testing, each day the same truck (Caterpillar 797) with a different operator was used. It was fortunate for this series of testing that the same truck was available for use each day. In most cases it was not possible to use the same truck each day, as a result of the maintenance and production. At a mine operation, trucks are on strict schedules so that the required production is maintained. As a result, each day the same truck might not be obtained. The route of the truck was maintained the same for each day of testing. This was also by chance since any given day a truck will have a different travel route based on the mine's schedule. Having the same truck and same route is beneficial because a few variables are taken out of the equation. Different trucks may have different responses to vibration because of the strut settings. This will cause trucks to react to vibration differently. Different routes will also produce different vibration responses due to different ground conditions. For these reasons it is better to compare data when the same trucks and travel routes are used. During testing, the operator did not receive feedback from the system and the researcher remained in the vehicle during the shift. Feedback was not given so that the typical vibration exposure without using a system could be assessed and then compared to vibration exposure using the system. The researcher remained in the vehicle during testing to ensure the equipment was functioning correctly after a few minor power problems were encountered. In total, 19 hours of data was collected during baseline testing.

6.3.2 Testing With Operators Using the System

The final phase of testing consisted of collecting data with the operators using the system and with no researcher present. Testing was conducted at same oil sand mine during the month of November, 2004. It was desirable to use the same truck for the entire duration of testing so it was planned that the system would be connected and placed on the truck while it was down for maintenance. During testing the travel routes would be random based on hauling requirements. With the help of onsite electricians and welders, the system was installed on one of the Caterpillar 797 trucks. This way when the truck was up and running the system would be ready for an operator to use. The system would be running continuously until the truck was shut down for long periods of time or the system was removed from the truck. Installing the system on the truck with no researcher present proved to be troublesome. The first truck the system was installed on ran into a series on problems. The truck kept requiring maintenance as a result of on going problems. Consequently, each time the truck was taken down; power was lost to the system due to the duration of the shutdown. This required a trip to site so that the system could be reset. Once the system had been reset and was running for a period of time it came time to remove the system to retrieve the data, it was found that the system had been tampered with and disconnected. The data collected during this trial was found to be contaminated as a result of the equipment corruption. This series of tampering events occurred more than once. Consequently, to prevent any further problems a modified testing plan was created.

6.3.3 Modified Testing

To ensure that no more problems were encountered it was decided that the researcher would remain in the truck for the duration of testing. This way it would be assured that the equipment would not be tampered with and any other problems that might arise would be addressed on the spot rather than finding out upon a later return to site. Since the equipment would need to be installed each day, the choice of trucks was based on availability in the field. As a result each day a new truck was tested along with a new operator. During this phase of testing the travel routes each day were entirely based on haulage demand. For this phase of testing a total of over 17 hours of data was collected. The same procedure was used as in the original plan, only the researcher was present. The operator was instructed by the researcher on how to use the system then during the shift the researcher remained indifferent regarding the operation of the vehicle. Before the trial was begun, the operator was assured that the system or the researcher were not spying on them or reporting operation performance but this was strictly a research project using a device to help reduce vibration that they would experience.

6.4 Data Analysis

A total of 36 hours of data was collected during testing with a two second sampling rate for acceleration equivalent and a one second sampling rate for rack data. At these sampling rates, the total number of data points used for the data analysis was

64,800 for acceleration equivalent and 129,600 for rack. The data with operators using the system was compared to the data where operators did not use system to evaluate the effectiveness.

The method that was used to evaluate the system was to perform a regression between the acceleration equivalent and equivalent rack for the duration of each testing day with the operators not using the system. From the regression a correlation could be made that would provide an equation relating the acceleration equivalent to equivalent rack. Once the second part of testing was complete, the equivalent rack values from the data where the operators used the system could be plugged into the equation to determine the expected acceleration equivalent for each day. The expected acceleration equivalents could then be compared to the measured acceleration equivalents. If the measured acceleration equivalents were lower than the expected than the system would be considered successful at reducing vibration.

The first step for analyzing the data was to collect the acceleration equivalent values for each day, provided by the algorithm in the system. The next step was to collect the strut pressure data from the trucks for the period of measurement. The strut pressure data is collected by Caterpillar's Vital Information Management System (VIMS) which collects information through sensors placed throughout the truck. The VIMS data is stored in a system developed for the mine site from which the strut pressure data was retrieved. The data retrieved was one second strut pressure data from each cylinder. This data was used to calculate the rack (Joseph, 2002) for each data point. Once this was complete the rack data was plotted and compared to the two second acceleration data (Appendix H).

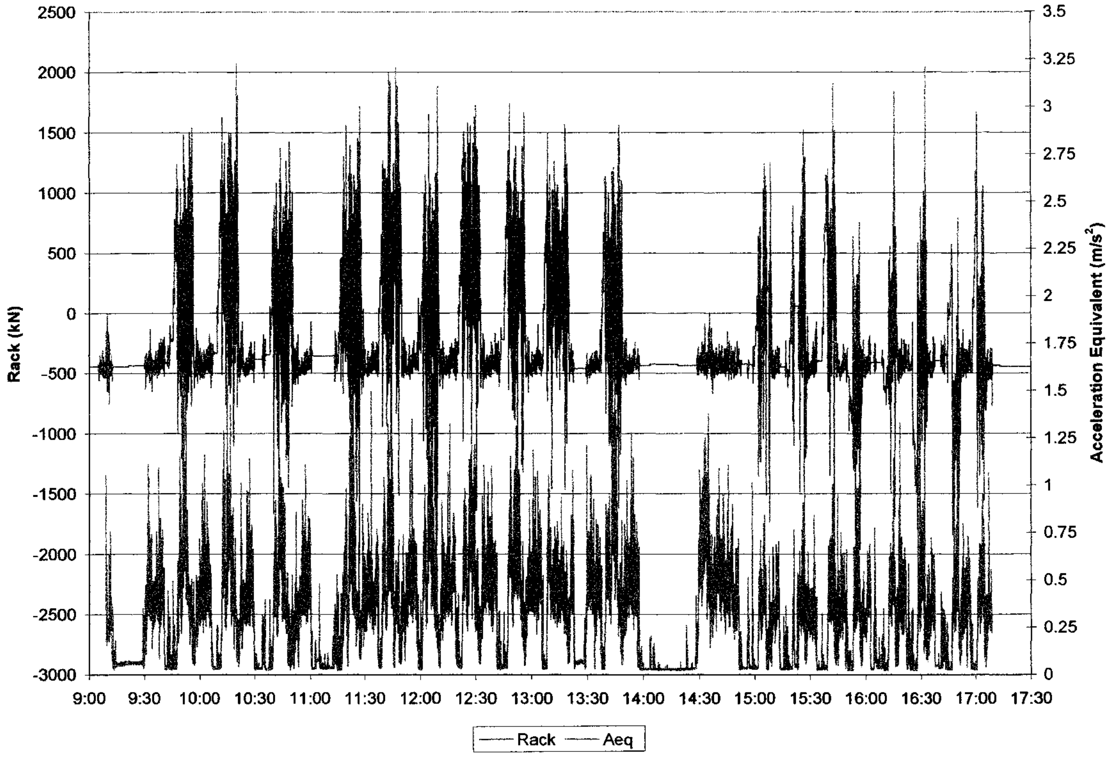


Figure 6.3 Example plot of rack and Aeq for a single test day

This would allow for the data to be aligned properly aligned since the timestamps were off as a result of clocks of the laptop and computer in VIMS being different from one another. To do the alignment distinctive points during the operating cycles were used such as shovel loading (figure 6.1). Once the timestamps were aligned the rack data for the corresponding testing period could be isolated and an equivalent rack value for the testing duration for each day could be calculated. The equivalent rack was calculated using a rain flow cycle counting method (ASTM E 1049, 1990) and then applying the equivalence equation (equation 6.0) to each bin. The equivalence equation given is a widely used as an accepted method for determining the equivalence for a data set (Joseph, 2004). When the equivalent rack values for each day were calculated the regression and comparison was performed.

$$R_{eq} = \sum \left[\frac{\left(Bin\_Value^{3} \times Counts\_per\_Bin\right)}{Total\_Counts} \right]^{1/3} \qquad (6.0)$$

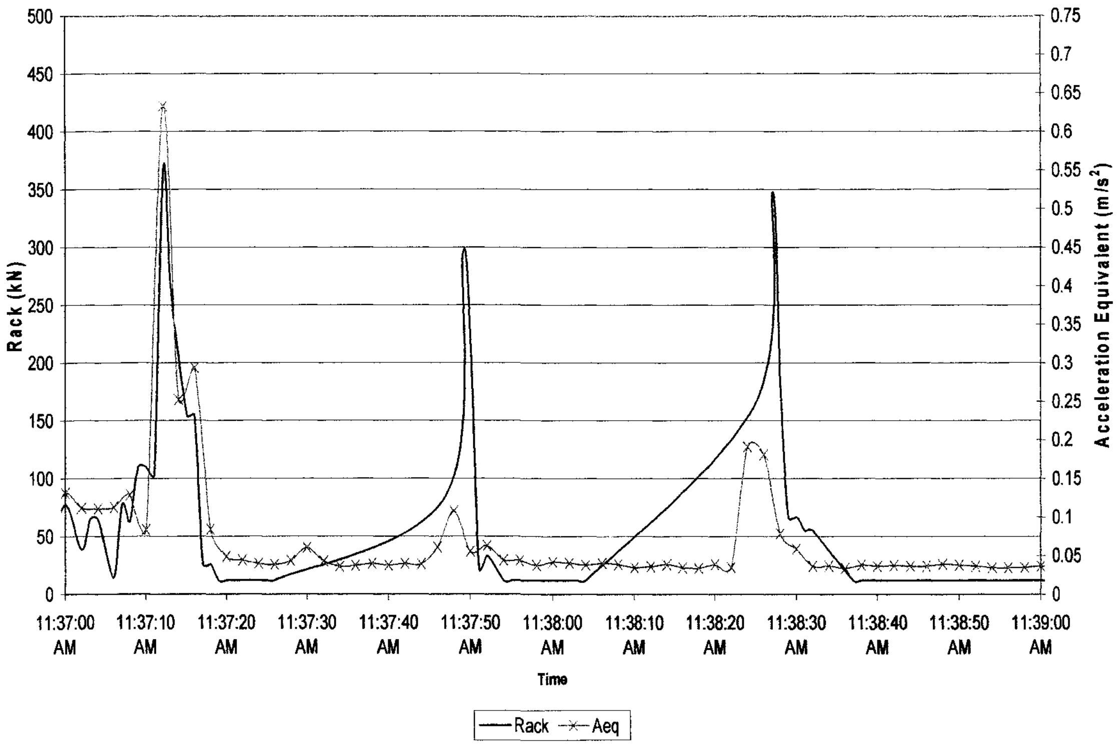


Figure 6.4 Alignment of data during shovel loading

7.0 Discussion

Using the method described in section 6.0 to analyze the data, results to evaluate the vibration feedback system's performance were obtained. The following section describes the results and attempts to answer the question as to whether the system was successful or not. Explanations are also given to account for any divergence that occurred in the results from what was expected.

The results for the duration of the entire testing period consisted of approximately 36 hours of data, with 1 second sampling of VIMS data and 2 second sampling for acceleration equivalent data. The summary plots for the entire data sets are provided in Appendix H. The entire data was reduced to the equivalence for each day shown in Table 7.1. The first three days (days 1-3) is the data summary for the testing that occurred where the operators did not use the system. The last three days (days 4-6) consists of the data that was collected where the operators used the system.

Day	Date	Equivalent Rack (kN)	Aeq (m/s^2)	Test Time
1	June 25/03	1097.52	0.5692	6:53:22
2	June 26/03	967.55	0.4024	7:59:58
3	June 27/03	1047.65	0.4967	3:58:37
4	October 19/04	875.09	0.6941	4:05:31
5	October 20/04	-	0.6761	7:56:00
6	October 21/04	882.97	0.6534	5:04:48

Table 7.1 Test Data Summary

The equivalent rack values located in table 7.1 were calculated for the duration of the test time located in the far right column. One thing to note is that the equivalent rack value for Day 5 is missing as a result of A data collection malfunction on the truck used for the test that day. As with equivalent rack the acceleration equivalent (Aeq) values were also calculated for the duration of the test. The data in the summary table provides the basis for the evaluation of the vibration feedback system. The results for the first three days show that with an increase in acceleration equivalent there is an increase in the equivalent rack. This confirms what was expected since the more vibration a vehicle is exposed to, the more twisting of the frame will occur. Using the summary data for the first three days, a regression was performed to correlate equivalent rack to equivalent acceleration. The results of the regression were plotted as shown in Figure 7.1.

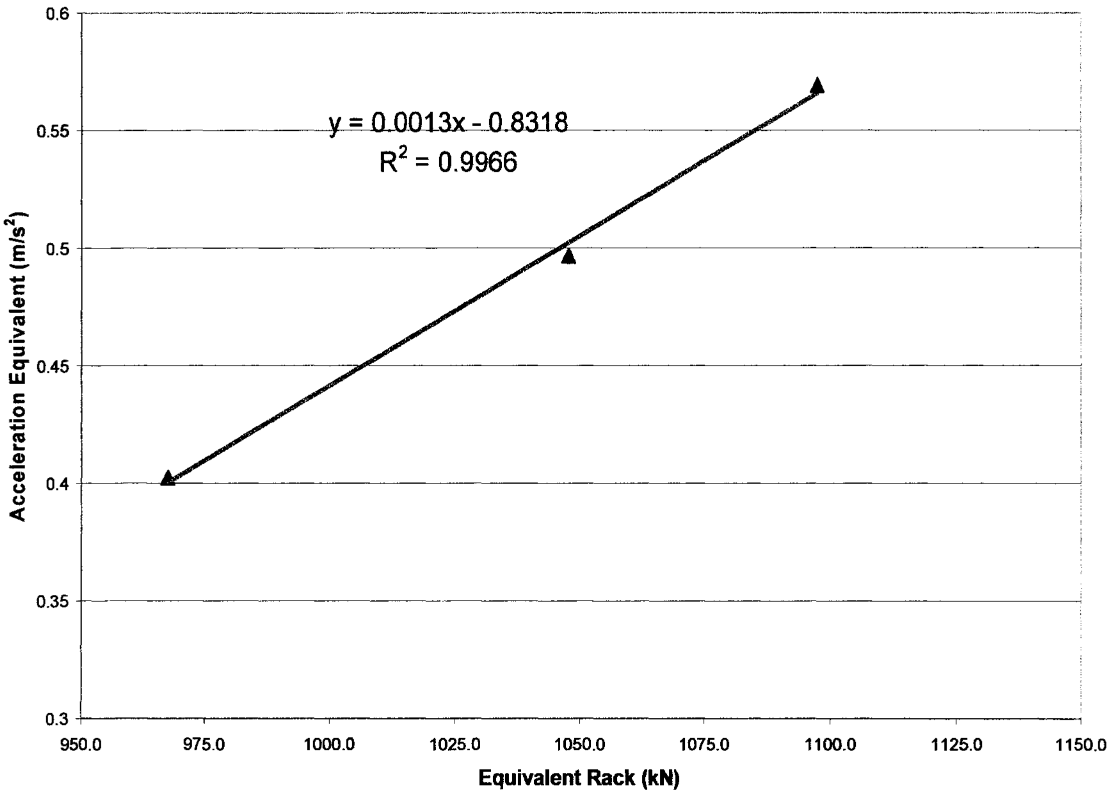


Figure 7.1 Equivalent Rack vs. Acceleration Equivalent Regression For Days 1-3

From the regression an equation with an r^2 value were obtained. The r^2 value for the regression of the data for first three days was 0.997. The regression provides adequate verification that equivalent rack and acceleration equivalent are correlated. The resulting equation (7.1) provides the mathematical relationship between the equivalent rack and equivalent acceleration.

$$A_{eq} = 0.0013R_{eq} - 0.8318 \qquad (7.1)$$

By using equation 7.1, the expected acceleration equivalent can be calculated using the equivalent rack for the test period. The expected acceleration equivalent for days 4-6 along with the corresponding equivalent rack and measured acceleration equivalent are shown in Table 7.2. The result for the expected acceleration equivalent was then compared to the measured acceleration equivalent to determine if the system was successful at reducing vibration.

Day	Req (kN)	Expected Aeq (m/s^2)	Measured Aeq (m/s^2)	% difference
4	875.09	0.369	0.694	88.24
5	-	-	0.676	-
6	882.97	0.320	0.653	103.91

Table 7.2 Expected and Measured Acceleration Equivalent Values for Days 4-6

The results show that the measured acceleration equivalent values were higher than the expected acceleration equivalent values. In both instances the percent difference between the expected and the measured were greater than 80 percent. This difference is very drastic to what was expected. As a result, the measured values from testing where the operators used the system indicate that the system may not have been effective at reducing vibration. However, there are a few factors that may account for the discrepancies between what was expected and what was measured

The problem of reducing vibration is a very complex one due to the variables involved. When considering the factors at hand, there are a number that can modify test results. The first one to consider is the mechanical factors which in this case relates to the trucks. Each truck has different strut pressure settings which will react to vibration differently. The second is the haul route. Each haul route at a mine will have different local conditions as a result of geology factors and operational factors. For example trucks driving in will be faced with stiffer road conditions than those driving on bitumen laden surfaces where the conditions are much softer. The third is the time of year. In the summer when the temperatures are warmer the ground is softer, so when trucks drive over bumps and ruts they, in most cases, are able to deform the ground and flatten any inconsistencies due to the shear size and weight of the machine. However, this changes once the weather begins to cool down and the ground starts to freeze. Inconsistencies in the ground cannot be flattened by the truck since it is too hard so these inconsistencies may produce higher vibrations. The final variable is the human factor involved in testing. Different operators will have different styles of driving that will contribute to higher vibrations.

There was success in correlating equivalent rack with the acceleration equivalent for days 1-3. This may be a result of being able to use the same truck for those three days as well the truck operated on the same routes for the most part during the three days. For the first three days it was seen that the acceleration equivalent values were generally lower than the values obtained from the last three days data when it was expected be lower with the use of the vibration feedback system. So why were the values actually higher when the system was used? This result may be attributed to the variables previously discussed including the mechanical, climate, and human factors.

During the final three days of testing it was not possible to setup the system on the same truck each day due to operational restriction so as a result the equipment was set up on a different truck each day. Each truck will have different responses to vibration because of the strut settings so the equivalent rack values may not correspond to what was expected. The second major factor was the difference in the time of year between the two sets of testing. The first set of testing occurred in the summer where the ground was soft where as the second set of testing occurred late October where the ground is beginning to firm up. During the summer the data showed higher rack values and lower vibration values than in the fall. This was expected since the soft ground would allow for more twisting of the truck frame but vibration would be relatively low since bumps would be smoothed by the truck. Consequently when the regression was done it was specific for the summer conditions so when it is applied to fall conditions it may be different. It was expected that the ground would not be as firm as it was at that time in the fall but according to the rack values it was. The last main factor might have been the human element. There is a misconception by the operators that there are being "spied" on by management. This is common at many mine sites. As a result, any new piece of equipment of the truck is thought of as a spying device and operators are very guarded against it. So initially when the equipment was installed the operators may have over compensated their driving so that low acceleration equivalent values were observed. However as the project was presented to the operators and they became familiar with it, the fear of the system was revoked and normal driving patterns were resumed.

With regard to the systems effectiveness at reducing vibration the decision is inconclusive due to the lack of solid evidence showing a reduction in vibration with operators using the system. However it did provide a basis to say that it is possible that the system could work if more data is acquired. Because a correlation was made between the equivalent rack and acceleration equivalent it is possible that these results may be used in further research for a vibration feedback system.

8.0 Summary

It has been demonstrated through previous research that whole-body vibration can have significant health effects. A majority of these health effects are related to back problems but effects on others parts of the body have been shown to occur. As a result, standards have been produced by various organizations to regulate what are acceptable levels of vibration for durations of time. Due to increasing concern regarding whole-body vibration, research into the vibration levels experienced by operators of heavy equipment in the mining industry has occurred to assess if there is a problem. The results have shown that the operators of heavy equipment are indeed exposed to levels of vibration in excess of the suggested level indicated by the standards. From these types of results, Syncrude Canada supported the initiative to develop a means of helping to reduce vibration. After consideration, a vibration feedback system was created to indicate to the operator when they were receiving vibrations in excess of the guidelines set by ISO 2631-1 (1997). The system would indicate to the operator through a series of lights on a screen when they were in excess, which would prompt the operator to change there driving pattern so that they were no longer being affected. In addition, another gauge was placed on the screen displaying the total accumulation of vibration for the duration of operation.

The system was developed and then tested to ensure it was functioning properly. Once completed the goal of the thesis project was to determine if a vibration feedback system could reduce vibration. To evaluate this, onsite testing would consist in two phases; one where the operators did not use the system and the other where they did use the system. The data used for comparison was the equivalent rack and acceleration equivalent for the duration of the shift. A regression analysis between equivalent rack and acceleration equivalent for the data set where operators did not use the system was conducted and it was found that they were correlated. Using the equation produced by the regression, the expected acceleration equivalent values were calculated from the equivalent rack values for the data collected from the testing where the operators used the system. These were compared to the actual measured values. If the measured values were lower than the system was considered successful. It was found in this set of testing that the values were actually higher when using the system, which was not expected. This would indicate that the system might not be effective at reducing vibration, however there were a few external factors that might have affected the outcome. These include: the difference in testing environmental and climatic conditions for one test set to the other, the difference in trucks between the test sets, and the human factors involved.

9.0 Conclusions and Recommendations

Overall the project was successful at shedding light into the use of such systems for reducing vibration, but more testing is required to gain an affirmative answer as to whether or not this type of system is effective. It is recommended that more data be collected in further research into the effectiveness of a vibration feedback system. More data should be collected with operators using and not using the system to provide further data points. It is important that the same truck be used in each set of testing, however this may be difficult since availability of trucks is dictated by operational requirements as was the case during this research. Therefore it is extremely important that cooperation with operations is met. In addition to this, testing should coincide with the change of seasons. Separate tests should be made for when the ground is soft versus when it is hard.

As far as data is concerned, it is recommended that direct downloading of VIMS data be used rather than the use of a database. Syncrude's MDSP is a very good system however problems were encountered when using the system. It was found that MDSP contained gaps and missing data which was the case in the fifth day of testing.

One further area to explore is this research topic would be to compare not only rack, but pitch, roll, and bounce of the vehicle for regression analysis. This may provide additional insight into the effectiveness of a vibration feedback system.

Bibliography

ASTM E 1049 – 45 (Reapproved 1990), *Standard Practices for Cycle Counting in Fatigue Analysis*. 1990.

Author Unknown, 2002. *Whole body vibration- trucks and tractors (WBV).* Noise and Vibration Worldwide, 33(1): 11-15.

Bonvenzi, M., 1999. *Disorders of the human spine caused by occupational exposure to whole-body vibration.* Noise and Vibration Worldwide, 30(7): 19-24.

British Standards Institution, 1987. *British Standard BS 6841: Measurement and evaluation of human response to whole-body mechanical vibration and repeated shock.* British Standards Institution, London.

Cann, A.P., Salmoni, A.W., Vi, P., Eger, T.R, 2003. *An exploratory study of whole-body vibration exposure and dose while operating heavy equipment in the construction industry.* Applied Occupational and Environmental Hygiene, 18(12): 999-1005.

Carroll, M. 1997. *Dragline #4 Boom Loading Condition Monitoring.* Syncrude Canada Research Department. Progress Report, 25(5), pg. 89-105.

Dias, B., Phillips, J., I., 2002. *To identify the need for and formulate further research on whole body vibration.* National Centre for Occupational Health, Health 703 part 2, 14 pg.

Donati, P., 2002. *Survey of technical preventative measures to reduce whole-body vibration effects when designing mobile machinery.* Journal of Sound and Vibration, 253(1): 169-183.

Dupuis, H. and Zerlett, G., 1986. *The effects of whole-body vibration.* Springer, Berlin Heidelberg, New York.

Dupuis, H., 1994. *Medical and occupational preconditions for vibration-induced spinal disorders: occupational disease no.2110 in Germany.* International Archives of Occupational and Environmental Health, 66(5): 303-308.

European Union- Committee on Employment and Social Affairs, 2001. 16th individual directive within the meaning of Article 16(1) of Directive 89/391/EEC. A5-0320/2001.

Griefahn, B., Brode, P., 1999. *The Significance of Lateral Whole-Body Vibration Related to Separately and Simultaneously Applied Vertical Motions. A Validation Study of ISO 2631.* Applied Ergonomics, 30(6): 505-513.

Griffin, M.J., 1990. *Handbook of Human Vibration,* London: Academic Press. 988 pg.

International Organization for Standardisation, 1985. *Mechanical Vibration and Shock Evaluation of Human Exposure to Whole-Body Vibration.* ISO 2631-1, Part 1: General requirements. International Organization for Standardisation, Geneva.

International Electrotechnical Commission, 1995. *Electroacoustics- Octave-band and fractional-octave-band filters, first edition.* IEC 1260 1995-07. International Electrotechnical Commission, Geneva.

International Organization for Standardisation, 1997. *Mechanical Vibration and Shock Evaluation of Human Exposure to Whole-Body Vibration.* ISO 2631-1, Part 1: General requirements. International Organization for Standardisation, Geneva.

Joseph, T.G., 2002. *OsEIP: the oil sands-equipment interactions program.* Canadian Institute of Mining and Metallurgy Bulletin, 95(1064): 58-61.

Joseph, T.G, 2003. *Large Mobile Mining Equipment Operating On Soft Ground.* 18th International Mining Congress and Exhibition of Turkey-IMCET 2003: 143-147.

Joseph, T.G, 2004. Conversations with T.G Joseph.

Lewis, C., Griffin, M.J., 1998. *Measurment, evaluation and assessment of whole-body vibration-A comparison of standardized methods for predicting the hazards of whole-body vibration.* Journal of Sound and Vibration. 215(4): 883-914.
Society of Automotive Engineers, 1992. *Measurement of whole body vibration of the seated operator of off-highway work machines- SAE J1013.* Society of Automotive Engineers.

Mabbott, N.A., Newman, S.L., 2001. *Safety improvements in prescriptive driving hours.* AUSTROADS Report AP-R182, Sydney, New South Wales.

Miyashita, K., Morioka, I., Tanabe, T., Iwata, H., Takeda, S., 1992. *Symptoms of construction workers exposed to whole body vibration and local vibration.* International Archive of Occupational and Environmental Health, 64: 347-351.

Ozkaya, N., Willems, B., Goldsheyder, D., 1994. *Whole-body vibration exposure: A comprehensive field study.* American Industrial Hygiene Association Journal, 55(12): 1164-1171.

Radke C.L., del Valle V.R., 2002. *Heavy Hauler Operator Vibration Study.* Syncrude Canada Research Department. Progress Report, 31 (8) 742 - 759.

Seidel, H., Heide, R., 1986. *Long-term effects of whole-body vibration: a critical survey of the literature.* International Archive of Occupational and Environmental Health, 58(1): 1-26.

Teschke, K., Nicol, A., Davies, H., Ju, S., 1999. *Whole Body Vibration and Back Disorders Among Motor Vehicle Drivers and Heavy Equipment Operators: A Review of the Scientific Evidence.* Report for Workers' Compensation Board of British Columbia. 21 pgs.

Thalheimer, E., 1996. *Practical approach to measurement and evaluation of exposure to whole-body vibration in the workplace.* Semin Perinatol, 20(1): 77-89.

van Niekerk, J.L., Heyns, P.S., Heyns, M., Hassall, J.R., 1999. *The Measurement of Vibration Characteristics of Mining Equipment and Impact Percussive Machines and Tools.* Project number GEN 503, Safety in Mines Research Advisory Committee, Laboratory for Advanced Engineering University of Pretoria. 50 pgs.

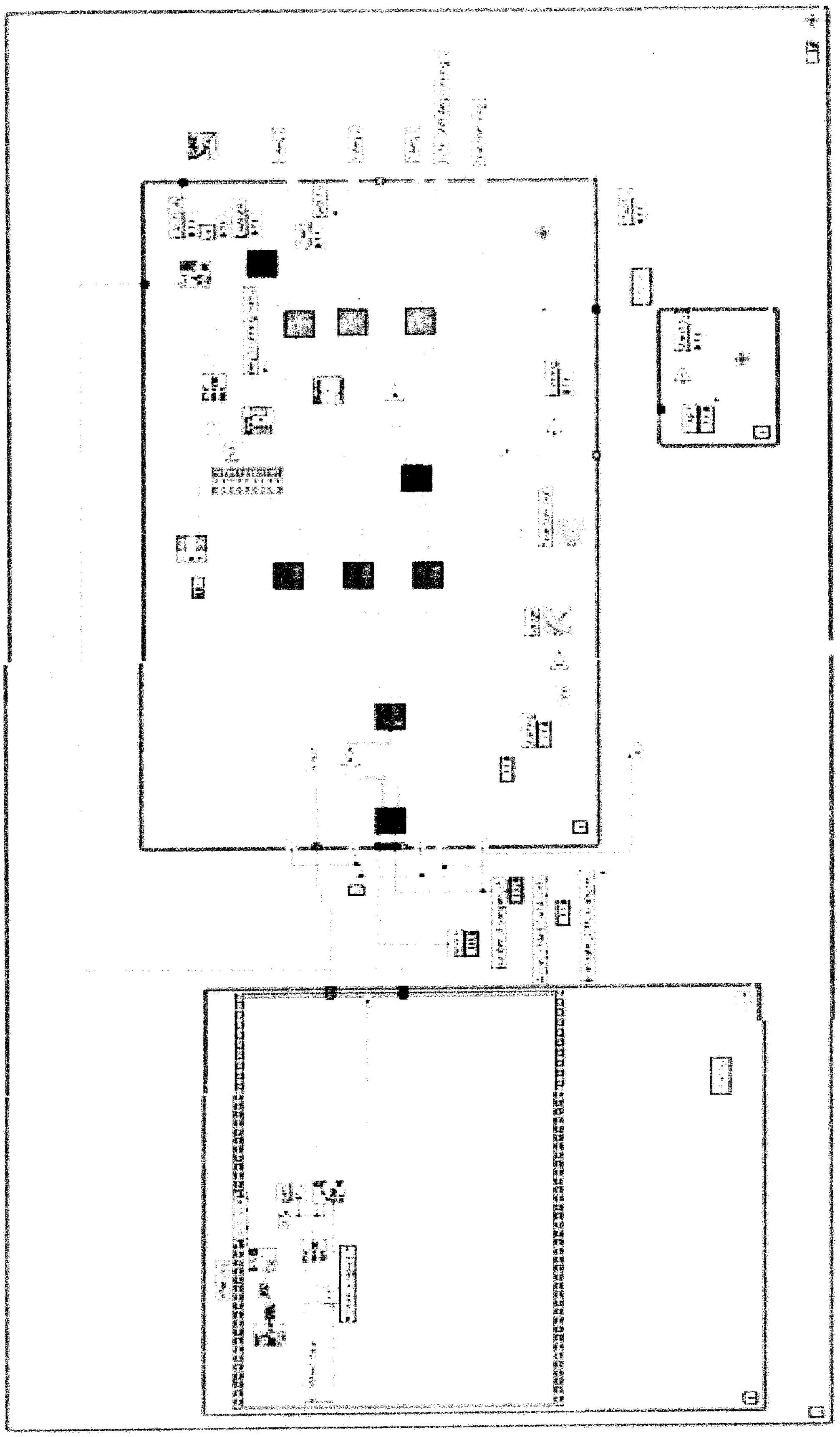
Wikström, B.O., Kjellberg, A. and Landström, U., 1994. *Health effects of long-term occupational exposure to whole-body vibration*: A review, International Journal of Industrial Ergonomics, 14: 273-292.

Workers Compensation Board Alberta, report generated November, 2004. Edmonton, Alberta.

APPENDICES

APPENDIX A

Algorithm Wiring Diagram



APPENDIX B
Accelerometer Specifications

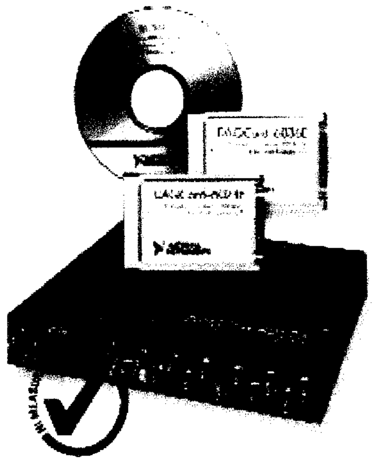
Model	S/N	Sensitivity (mV/g)	Input ohm	Output ohm	FS (g)	FO	Excitation (V)	Wiring Code
EGCS3-D-5-/Z1/X	Q00235 (10V)	32.05/35.66/34.28 21.37/23.8/22.85	1880/1937/1928	1004/1061/1053	5	22791 (37792)	15	+In= Red +Out= Green -In= black -Out= white

Extension Cable Colour Code	S+	S-	P+	P-	G
Channel X	Green	White	red	black	silver
Channel Y	Green	White	red	black	silver
Channel Z	Green	White	red	black	silver

APPENDIX C

Hardware Specifications

Portable E Series Multifunction DAQ
12 or 16-Bit, up to 1.25 MS/s, 16 Analog Inputs



E Series – Portable

- 16 analog inputs at up to 1.25 MS/s. 12 or 16-bit resolution
- Up to 2 analog outputs at up to 1 MS/s. 12 or 16-bit resolution
- 8 digital I/O lines (TTL/CMOS): two 24-bit counter/timers
- Analog and digital triggering
- 4 analog input signal ranges
- NI-DAQ driver simplifies configuration and measurements

Models

- NI DAQCard-6036E for PCMCIA[1]
- NI DAQCard-6062E for PCMCIA
- NI DAQCard-6024E for PCMCIA[1]
- NI DAQPad-6052E for FireWire
- NI DAQPad-6070E for FireWire
- NI DAQPad-6020E for USB[1]

Operating Systems

- Windows 2000/NT/XP
- Others such as Linux and Mac OS X (page 187)

Recommended Software

- LabVIEW
- LabWindows/CVI
- Measurement Studio
- VI Logger

Other Compatible Software

- Visual Basic, C/C++, and C#

Driver Software (included)

- NI-DAQ 7

[1] Digital triggering only

Calibration Certificate Included
See page 21.

Family	Bus	Analog Inputs	Input Resolution	Max Sampling Rate	Input Range	Analog Outputs	Output Resolution	Output Rate	Output Range	Digital I/O	Counter/Timers	Triggers
DAQCard-6036E	PCMCIA	16 SE/8 DI	16 bits	200 kS/s	±0.05 to ±10 V	2	16 bits	1 kS/s	± 10 V	8	2	Digital
DAQCard-6062E	PCMCIA	16 SE/8 DI	12 bits	500 kS/s	±0.05 to ±10 V	2	12 bits	850 kS/s	± 10 V	8	2	Analog, digital
DAQCard-6024E	PCMCIA	16 SE/8 DI	12 bits	200 kS/s	±0.05 to ±10 V	2	12 bits	1 kS/s	± 10 V	8	2	Digital
DAQPad-6052E	IEEE 1394	16 SE/8 DI	16 bits	333 kS/s	±0.05 to ±10 V	2	16 bits	333 kS/s	± 10 V	8	2	Analog, digital
DAQPad-6070E	IEEE 1394	16 SE/8 DI	12 bits	1.25 MS/s	±0.05 to ±10 V	2	12 bits	1 MS/s	± 10 V	8	2	Analog, digital
DAQPad-6020E	USB	16 SE/8 DI	12 bits	100 kS/s	±0.05 to ±10 V	2	12 bits	100 kS/s	± 10 V	8	2	Digital

Table 1. NI Portable E Series Model Guide (See page 228 for detailed specifications.)

Overview and Applications

National Instruments portable E Series DAQ products deliver the same functionality available in PCI and PXI E Series DAQ devices – in a portable format. The DAQPad devices are hot swappable and available in up to three different configurations. The 15 cm enclosure is ideal for desktop or portable applications and features a 68-pin shielded connector. The 30 cm enclosure with mass termination offers a low-profile package that fits under your laptop computer. It features a 68-pin shielded connector to connect signals from our SCC modular signal conditioning products or from our CA-1000 custom connectivity enclosure. The 30 cm enclosure with BNC connectivity is ideal for applications where portability and quick connectivity are needed, such as in-vehicle automotive or aircraft testing and portable data logging.

NI DAQCards are Type II, PC Card compliant and provide performance equivalent to their PCI or PXI counterparts. However, due to their compact design, they can be used in applications where space constraints are an important concern, such as field service and research.

Highly Accurate Hardware Design

NI portable E Series DAQ devices provide the functionality of E Series data acquisition devices in a portable format:

Temperature Drift Protection Circuitry – Designed with components that minimize the effect of temperature changes on measurements to less than 0.0010% of reading per °C.

Resolution Improvement Technologies – Carefully designed noise floor maximizes the resolution.

Onboard Self-Calibration – Precise voltage reference included for calibration and measurement accuracy. Self-calibration is completely software controlled, with no potentiometers to adjust.

NI DAQ-STC – Timing and control ASIC designed to provide more flexibility, lower power consumption, and a higher immunity to noise and jitter than off-the-shelf counter/timer chips.

NI MITE – ASIC designed to optimize data transfer for multiple simultaneous operations using bus mastering with DMA channels, interrupts, or programmed I/O.

Portable E Series Multifunction DAQ
12 or 16-Bit, up to 1.25 MS/s, 16 Analog Inputs

Models		NI 6052E	NI 6070E	DAQCard-6062E	DAQPad-6020E	DAQCard-6036E,	DAQCard-6024E
Measurement Sensitivity* (mV)		0.0025	0.009	0.010	0.006	0.004	0.009
Nominal Range (V)							
Positive FS	Negative FS	Absolute Accuracy (mV)					
10	-10	4.747	14.369	17.945	14.836	8.653	19.012
5	-5	0.676	5.193	6.969	4.671	2.357	6.517
2.5	-2.5	1.190	3.605	4.502	3.719	–	–
1	-1	0.479	1.452	1.813	1.496	–	–
0.5	-0.5	0.243	0.735	0.917	0.757	0.454	0.0972
0.25	-0.25	0.137	0.379	0.474	0.367	–	–
0.1	-0.1	0.064	0.163	0.203	0.165	–	–
0.05	-0.05	0.035	0.091	0.113	0.091	0.067	0.119
10	0	1.232	6.765	8.56	5.721	–	–
5	0	2.119	5.391	6.266	5.619	–	–
2	0	0.890	2.167	2.528	2.258	–	–
1	0	0.436	1.092	1.274	1.137	–	–
0.5	0	0.242	0.558	0.653	0.577	–	–
0.2	0	0.111	0.235	0.274	0.241	–	–
0.1	0	0.059	0.127	0.149	0.129	–	–

Note: Accuracies are valid for measurements following an internal Calibration. Measurement accuracies are listed for operational temperatures within ±1 °C of internal calibration temperature and ±10 °C of external or factory calibration temperature. One-year calibration interval recommended. The Absolute Accuracy at Full Scale calculations were performed for a maximum range input voltage (for example, 10 V for the ±10 V range) after one year, assuming 100 pt averaging of data. *Smallest detectable voltage change in the input signal at the smallest input range.

Table 2. NI Portable E Series Analog Input Absolute Accuracy Specifications

Models		NI 6052E	NI 6070E	DAQCard-6062E	DAQPad-6020E	DAQCard-6036E,	DAQCard-6024E
Nominal Range (V)							
Positive FS	Negative FS	Absolute Accuracy (mV)					
10	-10	1.405	8.127	10.566	6.193	2.547	10.566
10	0	1.176	5.695	–	5.691	–	–

Table 3. NI Portable E Series Analog Output Absolute Accuracy Specifications

NI PGIA – Measurement and instrument class amplifier that guarantees settling times at all gains. Typical commercial off-the-shelf amplifier components do not meet the settling time requirements for high-gain measurement applications.

PFI Lines – Eight programmable function input (PFI) lines that can be used for software-controlled routing of intraboard digital and timing signals.

RSE Mode – In addition to differential and nonreferenced single-ended modes, NI portable E Series devices offer referenced single-ended (RSE) mode for use with floating signal sources in applications with channel counts higher than eight.

Onboard Temperature Sensor – Included for monitoring the operating temperature of the device to ensure that it is operating within the specified range.

Analog and Digital Triggering – Some portable E Series devices provide the ability to set a trigger based on the level of an analog signal, in addition to the ability to trigger off an edge of a digital signal.

High-Performance, Easy-to-Use Driver Software

NI-DAQ is the robust driver software that makes it easy to access the functionality of your data acquisition hardware, whether you are a beginning or advanced user. Helpful features include:

Automatic Code Generation – The DAQ Assistant is an interactive guide that steps you through configuring, testing, and programming measurement tasks and generates the necessary code automatically for LabVIEW, LabWindows/CVI, or Measurement Studio.

Cleaner Code Development – Basic and advanced software functions have been combined into one easy-to-use yet powerful set to help you build cleaner code and move from basic to advanced applications without replacing functions.

High-Performance Driver Engine – Software-timed single point input (typically used in control loops) with NI-DAQ achieves rates of up to 50 kHz. NI-DAQ also delivers maximum system throughput I/O with a multithreaded driver.

Test Panels – With NI-DAQ, you can test all of your device functionality before you begin development.

Scaled Channels – Easily scale your voltage data into the proper engineering units using the NI-DAQ measurement-ready virtual channels by choosing from a list of common sensors and signals or creating your own custom scale.

LabVIEW Integration – All NI-DAQ functions use the waveform data type, which carries acquired data and timing information directly into more than 400 LabVIEW built-in analysis routines for display of results in engineering units on a graph.

Multifunction DAQ
Absolute Accuracy Specifications

Specifications (continued)

	Absolute Accuracy						Relative Accuracy	
	% of Reading			Noise + Quantization (mV)			Resolution (mV)	
Nominal Range (V)	24 Hours	1 Year	Offset (mV)	Single Point	Averaged	Temp Drift (%/°C)	Single Point	Averaged
NI 607xE Analog Input Accuracy – 12-bit, 1.25 MS/s, Up to 64 Analog Inputs								
±10	0.0672	0.0714	6.38	6.10	0.846	0.0010	7.37	1.11
±5.0	0.0272	0.0314	3.20	3.05	0.423	0.0005	3.68	0.557
±2.5	0.0672	0.0714	1.61	1.53	0.211	0.0010	1.84	0.278
±1.0	0.0672	0.0714	0.653	0.610	0.085	0.0010	0.737	0.111
±0.5	0.0672	0.0714	0.335	0.305	0.042	0.0010	0.368	0.056
±0.25	0.0672	0.0714	0.176	0.208	0.024	0.0010	0.236	0.032
±0.1	0.0672	0.0714	0.061	0.098	0.011	0.0010	0.111	0.015
±0.05	0.0672	0.0714	0.049	0.071	0.007	0.0010	0.082	0.009
10 to 0	0.0272	0.0314	3.20	3.05	0.423	0.0005	3.68	0.557
5 to 0	0.0672	0.0714	1.61	1.53	0.211	0.0010	1.84	0.278
2 to 0	0.0672	0.0714	0.653	0.610	0.085	0.0010	0.737	0.111
1 to 0	0.0672	0.0714	0.335	0.305	0.042	0.0010	0.368	0.056
0.5 to 0	0.0672	0.0714	0.176	0.208	0.024	0.0010	0.236	0.032
0.2 to 0	0.0672	0.0714	0.061	0.098	0.011	0.0010	0.111	0.015
0.1 to 0	0.0672	0.0714	0.049	0.071	0.007	0.0010	0.082	0.009
NI 6040 E Analog Input Accuracy – 12-bit, 500 kS/s, 16 Analog Inputs								
±10.0	0.0672	0.0714	7.380	4.640	0.846	0.0010	6.270	1.110
±5.0	0.0272	0.0314	3.700	2.320	0.423	0.0005	3.140	0.557
±2.5	0.0672	0.0714	1.860	1.160	0.211	0.0010	1.570	0.278
±1.0	0.0672	0.0714	0.757	0.464	0.085	0.0010	0.627	0.111
±0.5	0.0672	0.0714	0.389	0.269	0.042	0.0010	0.339	0.056
±0.25	0.0672	0.0714	0.205	0.134	0.021	0.0010	0.169	0.028
±0.1	0.0672	0.0714	0.095	0.076	0.010	0.0010	0.086	0.013
±0.05	0.0672	0.0714	0.066	0.056	0.006	0.0010	0.064	0.008
10 to 0	0.0272	0.0314	3.700	2.320	0.423	0.0005	3.140	0.557
5 to 0	0.0672	0.0714	1.860	1.160	0.211	0.0010	1.570	0.278
2 to 0	0.0672	0.0714	0.757	0.464	0.085	0.0010	0.627	0.111
1 to 0	0.0672	0.0714	0.389	0.269	0.042	0.0010	0.339	0.056
0.5 to 0	0.0672	0.0714	0.205	0.134	0.021	0.0010	0.169	0.028
0.2 to 0	0.0672	0.0714	0.095	0.076	0.010	0.0010	0.086	0.013
0.1 to 0	0.0672	0.0714	0.066	0.056	0.006	0.0010	0.064	0.008
NI PCI-6034, NI PCI-6036 Analog Input Accuracy – 16-bit, 200 kS/s, 16 Analog Inputs								
±10.0	0.0546	0.0586	±1.601	±0.933	±0.082	0.0010	1.0350	0.1065
±5.0	0.0146	0.0186	±0.811	±0.467	±0.041	0.0005	0.5420	0.0522
±0.5	0.0546	0.0586	±0.100	±0.056	±0.005	0.0010	0.0663	0.0066
±0.05	0.0546	0.0586	±0.026	±0.026	±0.002	0.0010	0.0362	0.0006
NI DAQCard-6036E Analog Input Accuracy – 16-bit, 200 kS/s, 16 Analog Inputs								
±10	0.0549	0.0591	2.602	1.500	0.137	0.0010	1.806	0.180
±5	0.0149	0.0191	1.311	0.750	0.068	0.0005	0.904	0.090
±0.5	0.0549	0.0591	0.150	0.064	0.007	0.0010	0.102	0.010
±0.05	0.0549	0.0591	0.031	0.032	0.003	0.0010	0.042	0.004
NI 6023E, PCI-6024E, and NI 6025E Analog Input Accuracy – 12-bit, 200 kS/s, 16 Analog Inputs								
±10.0	0.0672	0.0914	6.380	3.910	0.975	0.0010	5.690	1.380
±5.0	0.0272	0.0314	3.200	1.950	0.486	0.0005	2.950	0.642
±0.5	0.0672	0.0914	0.340	0.196	0.049	0.0010	0.295	0.064
±0.05	0.0672	0.0914	0.054	0.063	0.006	0.0010	0.073	0.006
DAQCard-6024E Analog Input Accuracy – 12-bit, 200 kS/s, 16 Analog Inputs								
±10.0	0.0672	0.0914	8.630	3.910	1.042	0.0010	5.690	1.370
±5.0	0.0272	0.0314	4.420	1.950	0.521	0.0005	2.950	0.686
±0.5	0.0672	0.0914	0.462	0.452	0.052	0.0010	0.516	0.069
±0.05	0.0672	0.0914	0.066	0.063	0.007	0.0010	0.073	0.009
DAQCard-6062E Analog Input Accuracy – 12-bit, 500 kS/s, 16 Analog Inputs								
±10.0	0.0672	0.0714	9.83	6.100	0.975	0.0010	7.370	1.280
±5.0	0.0272	0.0314	4.92	3.050	0.488	0.0005	3.680	0.642
±2.5	0.0672	0.0714	2.47	1.530	0.244	0.0010	1.840	0.321
±1.0	0.0672	0.0714	1.001	0.610	0.098	0.0010	0.737	0.128
±0.5	0.0672	0.0714	0.511	0.306	0.049	0.0010	0.368	0.064
±0.25	0.0672	0.0714	0.266	0.206	0.029	0.0010	0.238	0.039
±0.1	0.0672	0.0714	0.119	0.096	0.012	0.0010	0.111	0.016
±0.05	0.0672	0.0714	0.070	0.071	0.006	0.0010	0.082	0.010
10 to 0	0.0272	0.0314	4.920	3.050	0.488	0.0005	3.66	0.642
5 to 0	0.0672	0.0714	2.470	1.530	0.244	0.0010	1.84	0.321
2 to 0	0.0672	0.0714	1.001	0.610	0.098	0.0010	0.737	0.128
1 to 0	0.0672	0.0714	0.511	0.306	0.049	0.0010	0.368	0.064
0.5 to 0	0.0672	0.0714	0.266	0.206	0.029	0.0010	0.238	0.039

16-Bit E Series Multifunction DAQ Specifications

Specifications – NI 6052E and NI 603xE

These specifications are typical for 25 °C unless otherwise noted.

Analog Input

Accuracy specifications .... See page 228

Input Characteristics

	Number of Channels
6052E	16 single-ended or 8 differential (software selectable per channel)
6030E	
6032E	
6034E	
6036E	
6031E	64 single-ended or 32 differential (software-selectable per channel)
6033E	

Resolution.. 16 bits, 1 in 65,536

	Maximum Sampling Rate
6052E	333 kS/s
6034E	200 kS/s
6036E	
6030E	100 kS/s
6031E	
6032E	
6033E	

Input signal ranges

Device	Range Software Selectable	Bipolar Input Range	Unipolar Input Range
6052E	20 V	±10 V	–
	10 V	±5 V	0 to 10 V
	5 V	±2.5 V	0 to 5 V
	2 V	±1 V	0 to 2 V
	1 V	±500 mV	0 to 1 V
	500 mV	±250 mV	0 to 500 mV
	200 mV	±100 mV	0 to 200 mV
	100 mV	±50 mV	0 to 100 mV
6030E	20 V	±10 V	–
6031E	10 V	±5 V	0 to 10 V
6032E	5 V	–	0 to 5 V
6033E	4 V	±2 V	–
	2 V	±1 V	0 to 2 V
	1 V	±500 mV	0 to 1 V
	500 mV	–	0 to 500 mV
	400 mV	±200 mV	–
	200 mV	±100 mV	0 to 200 mV
	100 mV	–	0 to 100 mV
6034E	20 V	±10 V	–
6036E	10 V	±5 V	–
	1 V	±500 mV	–
	100 mV	±50 mV	–

Input coupling.. DC

Maximum working voltage

(signal + common mode) .... Each input should remain within ±11 V of ground

Overvoltage protection

Powered on.................................... ±25 V

Powered off .... ±15 V

	Inputs Protected
6052E	AI<0..15>, AI SENSE
6030E	
6032E	
6034E	
6036E	
6031E	AI<0..63>, AI SENSE, AI SENSE2
6033E	

FIFO buffer size .... 512 samples (1024 samples for DAQCard)

Data transfers

PCI, PXI .... DMA, interrupts, programmed I/O

DAQCard .... Interrupts, programmed I/O

DMA modes

PCI, PXI .... Scatter-gather (single transfer, demand transfer)

Configuration memory size .... 512 words

Transfer Characteristics

Relative accuracy (dithered)

Device	Typical	Maximum
6052E	±1.5 LSB	±3 LSB
6034E		
PCI-6036E		
6030E	±0.75 LSB	±1 LSB
6031E		
6032E		
6033E		
DAQCard-6036E	±3.0 LSB	±6 LSB

DNL

Device	Typical	Maximum
6052E 603xE (except DAQCard-6036E)	±0.5 LSB	±1 LSB
DAQCard-6036E	±1.0 LSB	+4, -2 LSB

No missing codes

DAQCard 6036E.................................. 15 bits, guaranteed

Others .... 16 bits, guaranteed

Amplifier Characteristics

Input impedance

Device	Normal Powered On	Powered Off	Overload
6052E 603xE	100 GΩ in parallel with 100 pF	820 Ω	820 Ω

Input bias and offset current

Device	Bias Current	Offset Current
6052E	±200 pA	±100 pA
6034E		
PCI-6036E		
6030E	±1 nA	±2 nA
6031E		
6032E		
6033E		
DAQCard-6036E	±500 pA	±100 pA

16-Bit E Series Multifunction DAQ Specifications

Specifications – NI 6052E and NI 603xE (continued)

External reference input (6052E only)

Range	±11 V
Overvoltage protection	±25 V powered on, ±15 V powered off
Input impedance	10 kΩ
Bandwidth (-3 dB)	3 kHz
Slew rate	0.3 V/μs

Dynamic Characteristics

Settling time and slew rate

Device	Settling Time For Full-Scale Step	Slew Rate
6052E	3.5 μs to ±1 LSB accuracy	15 V/μs
6030E	10 μs to ±1 LSB accuracy	5 V/μs
6031E		
PCI-6036E	5 μs to ±1 LSB accuracy	15 V/μs
DAQCard-6036E	5 μs to ±4.5 LSB accuracy	5 V/μs

	Noise
6052E	60 μV_{rms}, DC to 1 MHz
6030E	
6031E	
PCI-6036E	110 μV_{rms}, DC to 400 kHz
DAQCard-6036E	160 μV_{rms}, DC to 400 kHz

Glitch energy (at mid-scale transition)

Device	Magnitude	Duration
6052E	±10 mV	1 μs
PCI-6036E	±10 mV	1 μs

Digital I/O

Number of channels	8 input/output
Compatibility	5 V/TTL/CMOS
Power-on state	Input (high impedance)
Data transfers	Programmed I/O

Digital logic levels

Level	Minimum	Maximum
Input low voltage	0.0 V	0.8 V
Input high voltage	2.0 V	5.0 V
Output low voltage (I_{OL} = 5 mA)	–	0.4 V
Output high voltage (I_{OH} = -3.5 mA)	4.35 V	–

Timing I/O

General-Purpose Up/Down Counter/Timers

Number of channels	
Up/down counter/timers	2
Frequency Scaler	1
Resolution	
Up/down counter/timers	24 bits
Frequency Scaler	4 bits
Compatibility	5 V TTL/CMOS
Digital logic levels	
Base clocks available	
Up/down counter/timers	20 MHz and 100 kHz
Frequency Scaler	10 MHz and 100 kHz
Base clock accuracy	±0.01%
Maximum external source frequency	
Up/down counter/timers	20 MHz
External source selections	PFI <0..9>, RTSI <0..6>, analog trigger; software selectable
External gate selections	PFI <0..9>, RTSI <0..6>, analog trigger; software selectable
Minimum source pulse duration	10 ns, edge-detect mode
Minimum gate pulse duration	10 ns, edge-detect mode
Data transfers	
PCI/PXI Up/down counter/timer	DMA (scatter-gather), interrupts, programmed I/O
DAQCard Up/down counter/timer	Interrupts, programmed I/O
Frequency Scaler	Programmed I/O

Triggers

Analog Triggers

	Number of Triggers
6052E	1
6030E	
6031E	
6032E	
6033E	
6034E	None
6036E	

Purpose	
Analog input	Start and stop trigger, gate, clock
Analog output	Start trigger, gate, clock
General-purpose counter/timers	Source, gate

	Source
6052E	AI <0..15>, PFI 0/AI START TRIG
6030E	
6032E	
6031E	AI <0..63>, PFI 0/AI START TRIG
6033E	

Level	
Internal source, AI <0..15/63>	±full-scale
External source, PFI 0/AI START TRIG	±10 V
Slope	Positive or negative; software-selectable
Resolution	12 bits, 1 in 4,096
Hysteresis	Programmable
Bandwidth (-3 dB)	

Device	Internal Source AI <0..15/63>	External Source PFI 0/AI START TRIG
6052E	700 kHz	700 kHz
PCI-6030E, PCI-6031E, 6032E, 6033E	255 kHz	4 MHz
PXI-6030E, PXI-6031E	255 kHz	255 kHz

Accuracy .... ±1% of full-scale range maximum

Digital Triggers (all devices)

Purpose	
Analog input	Start and stop trigger, gate, clock
Analog output	Start trigger, gate, clock
General-purpose counter/timers	Source, gate
Source	PFI <0..9>, RTSI <0..6>
Compatibility	5 V TTL
Response	Rising or falling edge
Pulse width	10 ns minimum

16-Bit E Series Multifunction DAQ Specifications

Specifications – NI 6052E and NI 603xE (continued)

External Input for Digital or Analog Trigger (PFI 0/AI START TRIG)

(6052E, 6033E, 6032E, 6031E, 6030E only)

Impedance .... 10 kΩ

Coupling .... DC

Protection

  Digital trigger .... -0.5 to Vcc + 0.5 V

  Analog trigger

    On/off/disabled .... ±35 V

Calibration

Recommended warm-up time .... 15 minutes; 30 minutes for DAQCard

Calibration Interval .... 1 year

Onboard calibration reference

	DC Level	
6052E, 6030E 6031E, 6032E, 6033E	5.000 V (±1.0 mV)	Over full operating temperature, actual value stored in EEPROM
6034E, 6036E	5.000 V (±3.5 mV)	

	Temperature Coefficient
6052E, 6030E, 6031E, 6032E, 6033E	±0.6 ppm/°C max
6034E, 6036E	±5.0 ppm/°C max

	Long-Term Stability
6052E, 6030E 6031E, 6032E, 6033E	±6.0 ppm/$\sqrt{1000\ h}$
6034E, 6036E	±15.0 ppm/$\sqrt{1000\ h}$

RTSI

Trigger lines

  PCI 7

  DAQPad 4

PXI Trigger Bus (PXI only)

Trigger lines 6

Star trigger 1

Bus Interface

PCI, PXI .... Master, slave

DAQCard .... Slave

DAQPad .... Master, slave, asynchronous, 400 Mb/s

Power Requirements[1]

Device	+5 VDC (±5%)	Power Available at I/O Connector
PCI-6052E, PXI-6052E	1.3 A	+4.65 to +5.25 VDC, 1 A
6030E, 6031E, 6032E, 6033E	1.5 A	+4.65 to +5.25 VDC, 1 A
6034E PCI-6036E	0.9 A	+4.65 to +5.25 VDC, 1 A
DAQCard-6036E	300 mA	+4.65 to +5.25 VDC, 0.75 A

DAQPad-6052E .... 20W @ 9-24 VDC

Physical[1]

Dimensions (not including connectors)[1]

PCI .... 17.5 by 10.6 cm (6.9 by 4.2 in.)

PXI .... 16.0 by 10.0 cm (6.3 by 3.9 in.)

DAQCard .... Type II PC Card

DAQPad .... 20.7 by 25.4 by 4.3 cm (8.1 by 10 by 1.7 in.)

	I/O Connectors
PCI-6052E 6030E 6032E 6034E PCI-6036E	68-pin male SCSI-II type
6031E 6033E	100-pin female 0.050 D-type
DAQCard-6036E	68-position VHDCI female
DAQPad-6052E	68-pin male SCSI-II type, or 15 BNCs and 30 removable screw terminals

Environment

Operating temperature

6052E, 6036E, 6034E .... 0 to 55 °C

6030E, 6031E, 6032E, 6033E .... 0 to 50 °C

Storage temperature .... -20 to 70 °C

Relative humidity .... 10 to 90%, noncondensing

Certifications and Compliances

CE Mark Compliance CE

See page 134 for RT Series device power requirements and physical parameters.

TOUGHBOOK

Computers for the Outside World

toughbook 28

Powerful, Rugged and Wireless

DURABILITY FEATURES
- Designed using MIL-STD-810F test procedures
- Full Magnesium Alloy case with carry handle
- Moisture- and Dust-resistant LCD, keyboard and touchpad
- Sealed port and connector covers
- Shock-mounted, removable HDD in stainless steel case
- Vibration and drop-shock resistant design
- Rugged hinges

CPU
- Low Voltage Mobile Intel® Pentium® III Processor-M 1GHz or 800MHz featuring Enhanced Intel® SpeedStep™ technology
- 512KB on-die L2 cache

STORAGE & MEMORY
- 256MB SDRAM standard, expandable to 512MB (PC133 memory is required)
- 30GB HDD
- 1.44MB FDD [also accepts Combo Drive (DVD-ROM*/CD-RW**)]

DISPLAY
- 13.3" 1024 x 768 (XGA) transmissive, anti-reflective, outdoor-readable TFT Active Matrix Color LCD with or without Touchscreen or 12.1" 800 x 600 (SVGA) transflective, sunlight-readable TFT Active Matrix Color LCD with Touchscreen
- External video support up to 1024 x 768 at 16 million colors (24 bit color depth)
- Intel 830MG graphic controller, UMA (Unified Memory Access) up to 32MB

AUDIO
- SigmaTel® 9767 audio controller
- Integrated speaker
- Convenient keyboard volume controls (Fn+F5/F6 keys)

PC CARD SLOTS
- Type II x 2 or Type III x 1

MULTIMEDIA POCKET
- Holds 3.5" FDD (standard)
- Accepts optional Combo Drive (DVD-ROM*/CD-RW**) (CF-VDR283U)
- Combo Drive and FDD can be used simultaneously (w/FDD cable CF-VCF271)
- Accepts optional 2nd battery pack (CF-VZSU1428)
- Accepts Telephone Line Tester Modules

KEYBOARD & INPUT
- 87-key with dedicated Windows® key
- Enhanced pressure sensitive touchpad
- Touchscreen LCD

INTERFACE

• Infrared	4Mbps IrDA
• Serial	D-sub 9 pin
• Parallel	D-sub 25 pin
• External Keyboard/Mouse	Mini-DIN 6 pin
• USB	4 pin
• Port Replicator	80 pin (Reinforced)
• Headphones/Speaker	Mini-jack Stereo
• Microphone/Line In	Mini-jack
• Modem	Integrated 56Kbps
• External Video	Mini D-sub 15 pin

POWER SUPPLY
- Lithium Ion battery pack (11.1V, 5.4Ah)
- Battery operation: up to 4 hours (with first battery), up to 10 hours (with second battery)***
- Battery charging time: approximately 3 hours/OFF, 5.5 hours/ON***
- AC Adapter: AC 100V-240V 50/60Hz, Auto Sensing/Switching worldwide power supply
- Quick access battery/HDD cover for easy battery replacement
- Pop-up on-screen battery status reporting

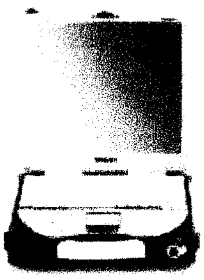
POWER MANAGEMENT
- Suspend/Resume Function, Hibernation, ACPI BIOS

SOFTWARE
- Microsoft® Windows® XP Professional (Microsoft® Windows® 2000 Professional also available)
- Setup, Diagnostics, DMI Viewer, On-line Reference Manual, Adobe® Acrobat® Reader, Panasonic® Battery Monitor

SECURITY FEATURES
- Password Security: Supervisor, User
- Integrated Kensington Lock Slot

WARRANTY
- 3 year limited warranty, parts & labor

DIMENSIONS & WEIGHT
- 2.3"(H) x 9.5"(D) x 11.8"(W)
- 9 lbs., including battery, FDD and handle



- *Full Magnesium Alloy Case with Carry Handle*
- *Moisture- and Dust-resistant Design*
- *Shock-mounted, Removable HDD*
- *Wireless-ready Design*

INTEGRATED OPTIONS****
- Wired LAN (10/100 ethernet)*****
- 802.11b Wireless LAN*****
  - Cisco Aironet
- Wide Area Wireless Solutions
  - CDPD
  - Mobitex (Cingular™ Wireless) (availability may vary)
  - GSM/GPRS with external SIM slot (availability may vary)
  - 1xRTT/CDMA 2000 (availability may vary)
- Global Positioning System (GPS) Receiver
- Full Travel EL Backlit Keyboard
- Sealed Rubber LED Backlit Keyboard

ACCESSORIES****

• Combo Drive (DVD-ROM*/CD-RW**)	CF-VDR282U
• Telephone Line Tester Modules******	
• Desktop Port Replicator	CF-VEB272AW
• Vehicle Mount Port Replicator	CF-WEB273
• Vehicle Mount Port Replicator with Integrated High-gain Antenna Pass-thru Cable	CF-WEB2703BL
• External FDD Cable	CF-VCF271
• Battery Charger	CF-VCBTB1U
• Lithium Ion Battery Pack	CF-VZSU18AU
• 2nd Battery Pack	CF-VZSU1428W
• AC Adapter (3 pin)	CF-AA1653M
• Memory Cards	
– 128MB	CF-WMBA91128
– 256MB	CF-WMBA91256
• 13.3" LCD Protector	CF-VPF03U
• 12.1" LCD Protector	CF-VPF02U
• ToughMate Sling Carrying Case	CF-TM28
• ComFolio Universal Carrying Case	CF-COMUNIV
• Stylus Pen with Tether Hold	CF-VNP004U

*Decoder software is required for DVD movie play (included).

**CD authoring software is required to write CD-RW (included).

***Battery performance features such as charge time and life span can vary according to the conditions under which the computer and battery are used. Battery operation and recharge times will vary based on many factors including screen brightness, applications, features, power management, battery conditioning and other customer preferences.

****Accessories and Integrated Options may vary depending on your notebook configuration.

*****Choosing both the Integrated Wired LAN and Integrated 802.11b Wireless LAN options together means that the 56Kbps Modem cannot be added as an option due to hardware space limitations.

******Special order item

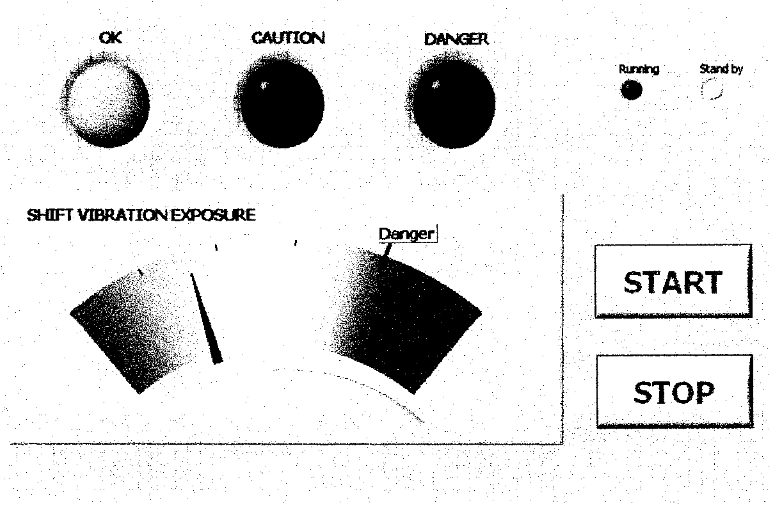
Please consult your reseller or Panasonic representative before purchasing.

APPENDIX D

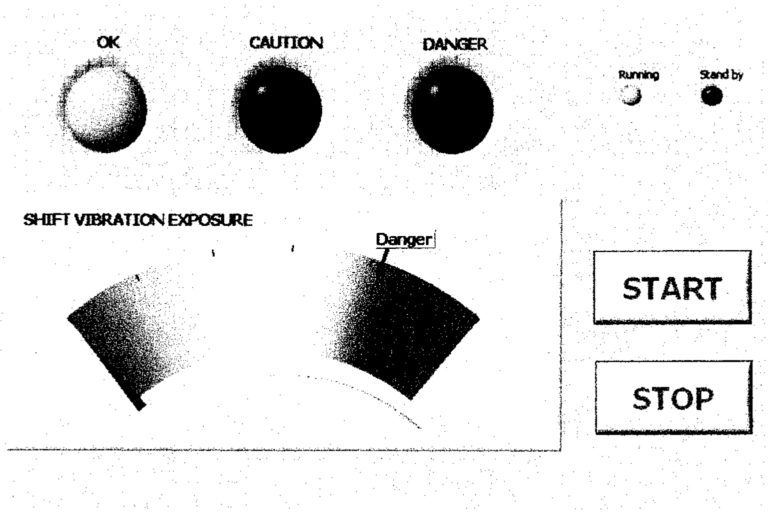
Vibration Feedback System Instructions

Vibration Feedback Warning System Instructions

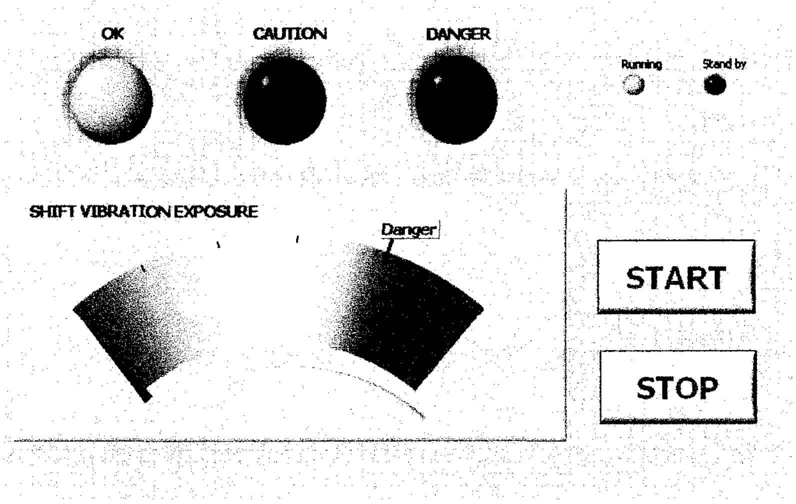
1. At beginning of shift, the far right of the screen should show a yellow light indicating "STAND BY", as shown below. If the green "RUNNING" light is on, press "STOP", the yellow "STANDBY" light will come on shortly.

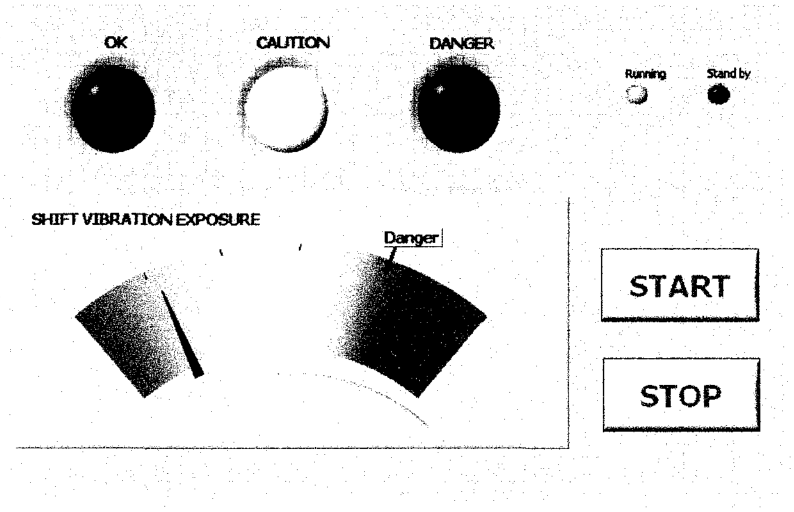


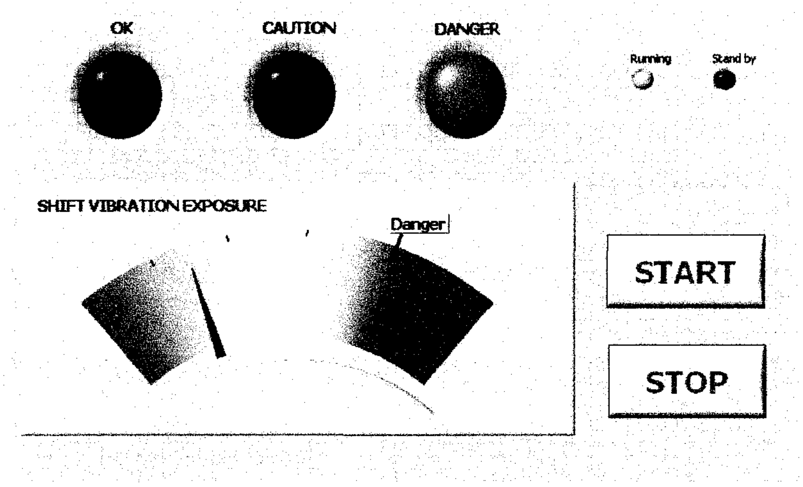
2. Press the "START" button in the bottom right of the screen at the beginning of the shift to put the system into operation. A green light on the right of the screen will indicate, "RUNNING" to show the system is operational as shown below.



3. While the system is running during operation three lights, green “OK”, yellow “CAUTION, and red “DANGER” will light up. The goal is to maintain a steady green light with periodic yellow lights during the course of the shift. The other indicator labeled “SHIFT VIBRATION EXPOSURE” shows the vibration exposure accumulated during the shift with the maximum recommended vibration exposure indicated by the “DANGER MARKER”. The goal of this display is remain below the marker by the end of the shift.







4. At the end of the shift press the "STOP" button to end operation of the system. The yellow "STAND BY" light will come on shortly. If the yellow "STANDBY" light does not come on press, "STOP" again. <u>DO NOT PRESS THE "STOP" BUTTON UNTIL THE END OF THE SHIFT WHEN YOU ARE FINISHED</u>.

APPENDIX E

Laboratory Testing and Verification of System Part 1

Test #1

5/9/2003 13:53

TIME	X	Y	Z	SUM	RUNNINGSUM	XAeqSum	YAeqSum	ZAeqSum	AeqSum
1:53:47 PM	0.241173	0.241173	0.225787	0.528189	0.114951	0.241173	0.241173	0.225787	0.528189
1:53:49 PM	1.621687	1.621687	0.79848	3.308573	4.625362	1.159317	1.159317	0.58675	2.369139
1:53:51 PM	4.490208	4.490208	2.145675	9.145427	39.087522	2.759831	2.759831	1.328216	5.623299
1:53:53 PM	6.865835	6.865835	3.27554	13.98273	119.647335	4.182992	4.182992	2.001362	8.520288
1:53:55 PM	7.845164	7.845164	3.741364	15.976872	224.823673	5.12906	5.12906	2.450283	10.446451
1:53:57 PM	7.160967	7.160967	3.414676	14.583396	312.453465	5.519899	5.519899	2.635636	11.242161
1:53:59 PM	7.084099	7.084099	3.377817	14.426805	398.211524	5.76938	5.76938	2.753985	11.750075
1:54:01 PM	6.878942	6.878942	3.279929	14.008987	479.074182	5.91946	5.91946	2.825045	12.055608
1:54:03 PM	7.160757	7.160757	3.414171	14.582873	566.697704	6.06993	6.06993	2.896427	12.361957
1:54:05 PM	6.921772	6.921772	3.300254	14.096189	648.570182	6.160417	6.160417	2.939307	12.546172
1:54:07 PM	7.146678	7.146678	3.407465	14.554203	735.849505	6.256605	6.256605	2.984903	12.741803
1:54:09 PM	6.929237	6.929237	3.303813	14.111391	817.898668	6.315304	6.315304	3.012768	12.861507
1:54:11 PM	7.162264	7.162264	3.414878	14.585939	905.559042	6.384445	6.384445	3.045585	13.002278
1:54:13 PM	6.92412	6.92412	3.301371	14.100968	987.487046	6.424497	6.424497	3.064564	13.083816
1:54:15 PM	7.15043	7.15043	3.409238	14.561842	1074.858011	6.475424	6.475424	3.088739	13.187506
1:54:17 PM	6.923201	6.923201	3.30093	14.099096	1156.764263	6.504314	6.504314	3.102426	13.246318
1:54:19 PM	7.15521	7.15521	3.411514	14.571574	1244.252054	6.544394	6.544394	3.121455	13.327923
1:54:21 PM	6.924926	6.924926	3.301754	14.102609	1326.19913	6.566113	6.566113	3.131744	13.372138
1:54:23 PM	7.154031	7.154031	3.410954	14.569175	1413.658114	6.598362	6.598362	3.147057	13.437799
1:54:25 PM	6.92395	6.92395	3.301287	14.100621	1495.58209	6.615022	6.615022	3.154947	13.471715
1:54:27 PM	7.154087	7.154087	3.410978	14.569287	1583.04242	6.641684	6.641684	3.167609	13.526
1:54:29 PM	6.92433	6.92433	3.301469	14.101395	1664.975391	6.654792	6.654792	3.173816	13.552684

Hand Calculated for Vibration Main

Time	$(AeqX)^2$	$(AeqY)^2$	$(AeqZ)^2$				
2	0.058164416	0.058164416	0.050979769				
4	2.629868726	2.629868726	0.63757031				
6	20.16195788	20.16195788	4.603921206				
8	47.13969025	47.13969025	10.72916229				
10	61.54659819	61.54659819	13.99780458				
12	51.27944838	51.27944838	11.66001218				
14	50.18445864	50.18445864	11.40964769				
16	47.31984304	47.31984304	10.75793425				
18	51.27644081	51.27644081	11.65666362				
20	47.91092762	47.91092762	10.89167646				
22	51.07500644	51.07500644	11.61081773				
24	48.0143254	48.0143254	10.91518034				
26	51.29802561	51.29802561	11.66139175				
28	47.94343777	47.94343777	10.89905048				
30	51.12864918	51.12864918	11.62290374				
32	47.93071209	47.93071209	10.89613886				
34	51.19703014	51.19703014	11.63842777				
36	47.95460011	47.95460011	10.90157948				
38	51.18015955	51.18015955	11.63460719				
40	47.9410836	47.9410836	10.88849586				
42	51.1809608	51.1809608	11.63477092				
44	47.94634595	47.94634595	10.89969756				
	974.2977446	974.2977446	221.608334	6.654792342	6.654792342	3.173816	13.55268

Test #2

5/9/2003 14:33

TIME	X	Y	Z	SUM	RUNNINGSUM	XAeqSum	YAeqSum	ZAeqSum	AeqSum
2:33:31 PM	0.241173	0.241173	0.225787	0.528189	0.114951	0.241173	0.241173	0.225787	0.528189
2:33:33 PM	1.621687	1.621687	0.79848	3.308573	4.625362	1.159317	1.159317	0.58675	2.369139
2:33:35 PM	4.490208	4.490208	2.145675	9.145427	39.087522	2.759831	2.759831	1.328216	5.623299
2:33:37 PM	6.865835	6.865835	3.27554	13.98273	119.647335	4.182992	4.182992	2.001352	8.520288
2:33:39 PM	7.845164	7.845164	3.741364	15.976872	224.823673	5.12906	5.12906	2.450283	10.446451
2:33:41 PM	7.160967	7.160967	3.414676	14.583386	312.453465	5.519899	5.519899	2.635636	11.242161
2:33:43 PM	7.084099	7.084099	3.377817	14.426805	398.211524	5.76938	5.76938	2.753935	11.750075

Hand Cal. Vibration
Main

Time	$(AeqX)^2$	$(AeqY)^2$	$(AeqZ)^2$
2	0.058164416	0.058164416	0.050979769
4	2.629866726	2.629866726	0.63757031
6	20.16195788	20.16195788	4.603921206
8	47.1396025	47.1396025	10.72916229
10	61.54659819	61.54659819	13.99780468
12	51.27944838	51.27944838	11.66001218
14	50.18446864	50.18446864	11.40964769
	233.0001965	233.0001965	53.08909808

| 5.76937972 | 5.76937972 | 2.753934796 | 11.75007519 |

APPENDIX F

Laboratory Testing and Verification of System Part 2

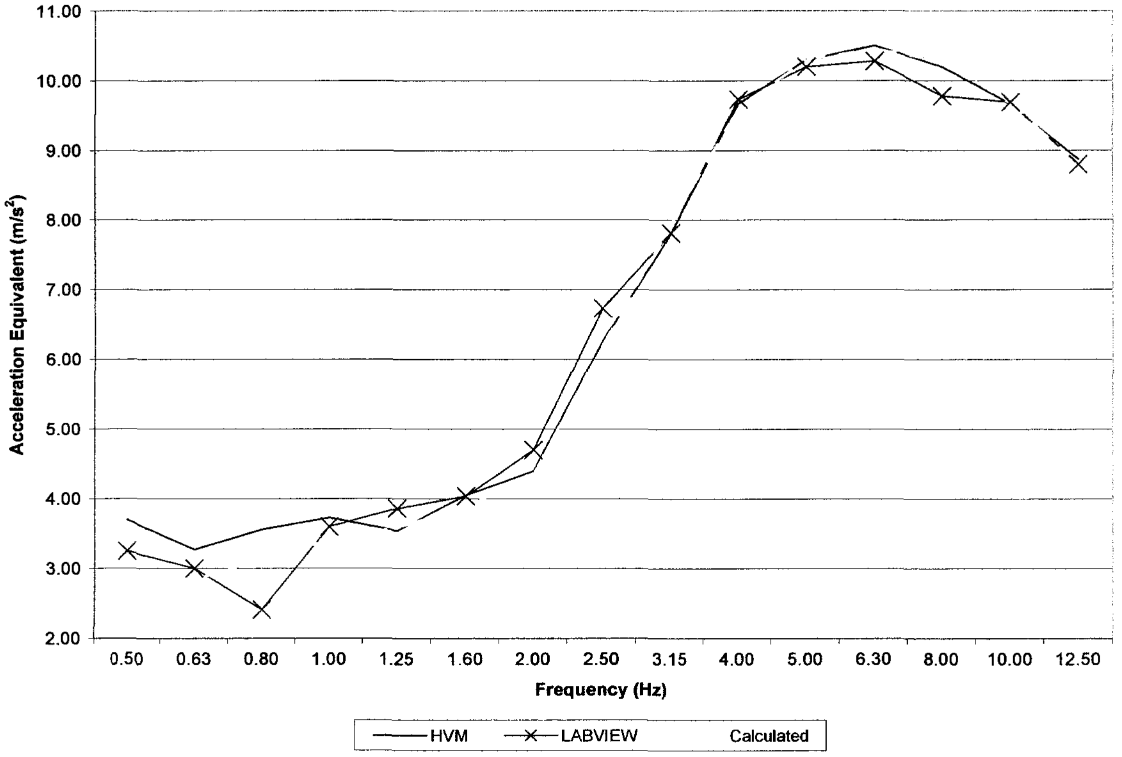
1 second sampling trials:

Vibration Acceleration Comparison (1s sample time) Trial #1

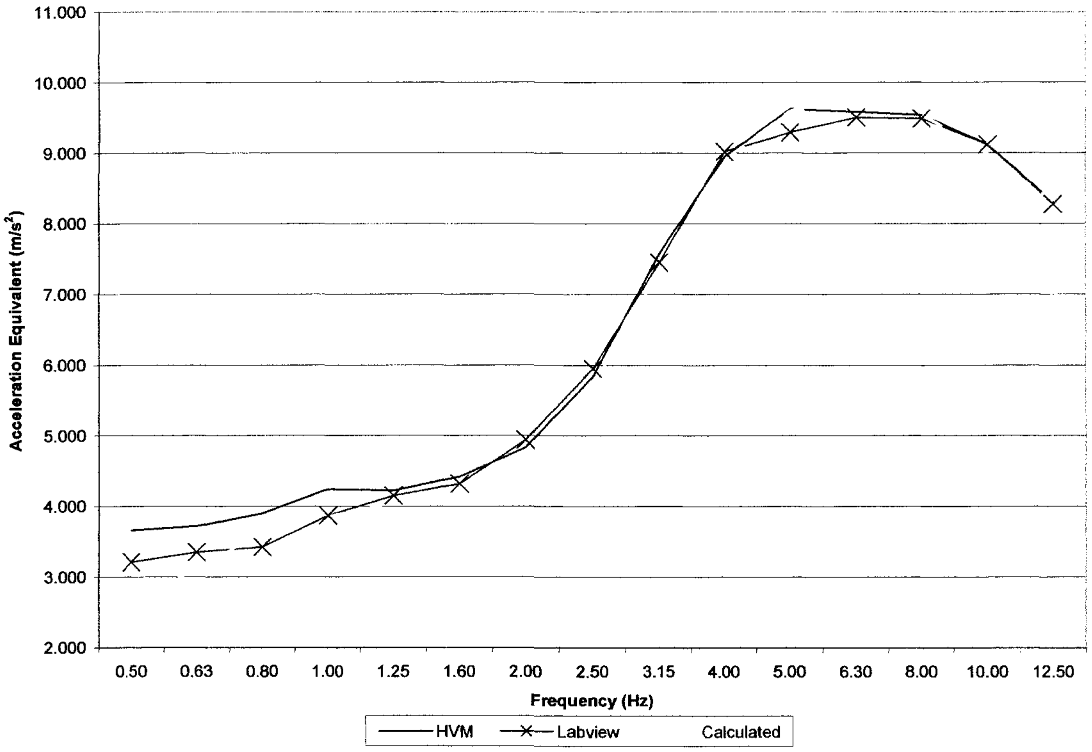
frequency	HVM(m/s^2)	LABVIEW(m/s2)	AMP	RMS	Wk	Calculated (m/s2)
0.50	3.70	3.25	16.96	5.996265604	0.418	2.506438981
0.63	3.27	3.00	17.48	6.180113268	0.459	2.83657199
0.80	3.56	2.41	18.60	6.576093065	0.477	3.136796392
1.00	3.73	3.60	19.95	7.053390142	0.482	3.399734049
1.25	3.54	3.86	20.96	7.410479067	0.484	3.586671868
1.60	4.05	4.04	22.23	7.859491873	0.494	3.882588965
2.00	4.40	4.70	23.13	8.177689924	0.531	4.34236335
2.50	6.26	6.73	27.78	9.821713191	0.631	6.197501023
3.15	7.80	7.81	27.96	9.885352801	0.804	7.947823652
4.00	9.67	9.73	28.06	9.92070814	0.957	9.593324771
5.00	10.30	10.20	28.05	9.917172606	1.039	10.30394234
6.30	10.50	10.28	28.05	9.917172606	1.054	10.45269993
8.00	10.20	9.78	28.06	9.92070814	1.036	10.27785363
10.00	9.66	9.69	27.70	9.793428919	0.988	9.675807772
12.50	8.87	8.80	27.58	9.751002513	0.902	8.795404266

Vibration Acceleration Comparison (1s sample time) Trial #2

frequency	HVM(m/s^2)	LABVIEW(m/s2)	AMP	RMS	Wk	Calculated (m/s2)
0.50	3.660	3.210	18.010	6.367496565	0.418	2.661613564
0.63	3.720	3.350	19.080	6.749334226	0.459	3.09794441
0.80	3.900	3.420	21.600	7.636753237	0.477	3.642731294
1.00	4.240	3.870	22.610	7.993842161	0.482	3.853031922
1.25	4.220	4.150	23.670	8.368608755	0.484	4.050406638
1.60	4.420	4.320	24.250	8.573669722	0.494	4.235392843
2.00	4.830	4.940	25.100	8.874190104	0.531	4.712194945
2.50	5.840	5.950	25.540	9.029753696	0.631	5.697774519
3.15	7.580	7.450	25.840	9.135819613	0.804	7.345198969
4.00	8.950	9.020	26.010	9.195923689	0.957	8.892458208
5.00	9.630	9.300	26.150	9.245421164	1.039	9.605992589
6.30	9.590	9.510	26.110	9.231279028	1.054	9.729768096
8.00	9.540	9.490	26.070	9.217136893	1.036	9.548953821
10.00	9.120	9.120	25.730	9.09692874	0.988	8.987765595
12.50	8.310	8.280	26.060	9.213601359	0.902	8.310668426



Trial #1 Comparison between HVM, Labview, and Theoretical Calculation



Trial #2 Comparison between HVM, Labview, and Theoretical Calculation

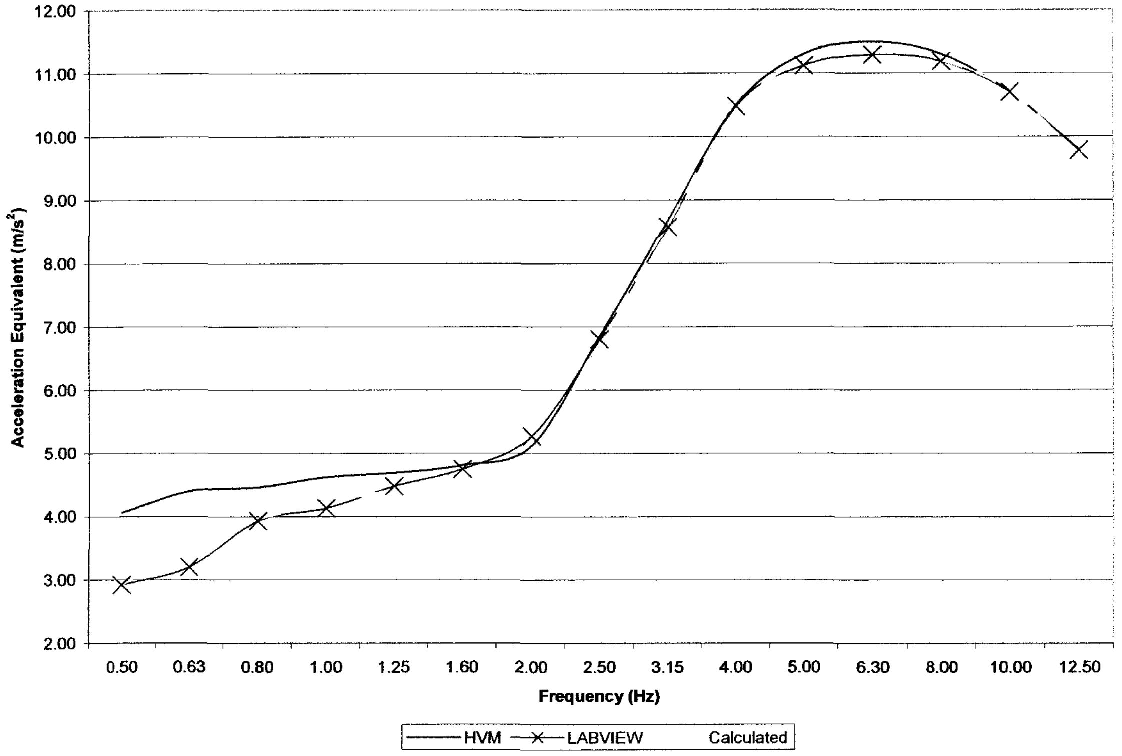
2 second sampling trials:

Vibration Acceleration Comparison (2s sample time) Trial #1

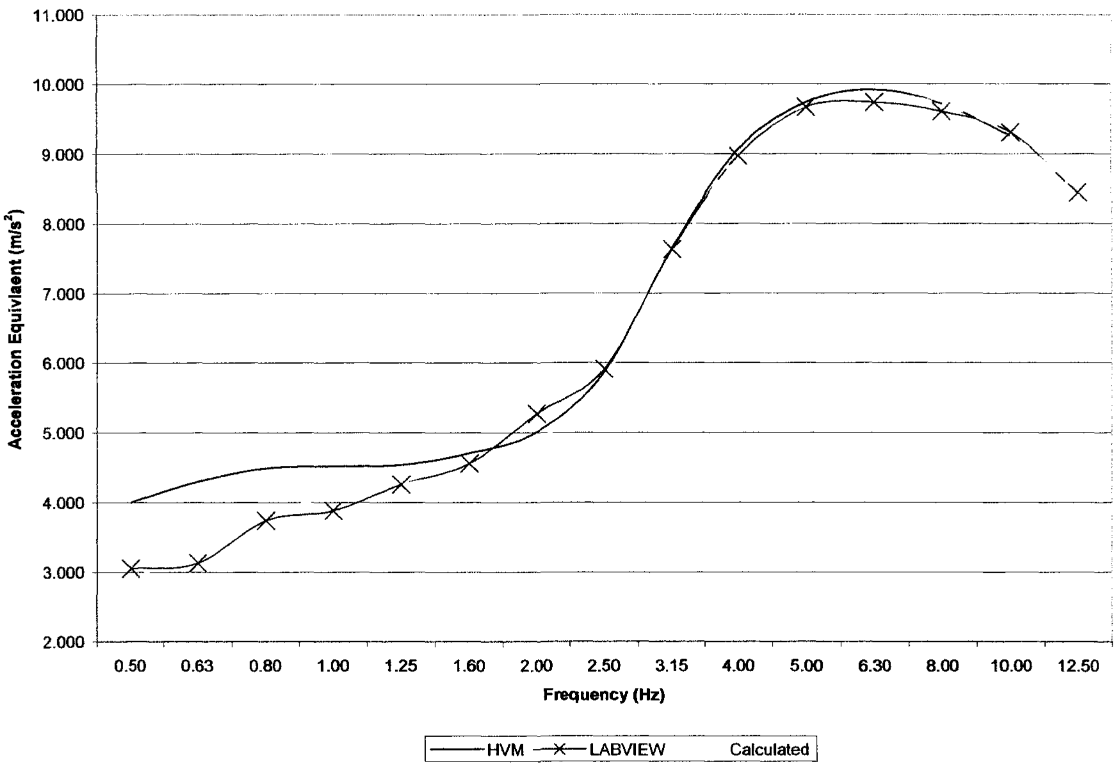
frequency	HVM (m/s^2)	LABVIEW (m/s2)	AMP	RMS	Wk	Calculated (m/s2)
0.50	4.06	2.92	19.81	7.003892668	0.418	2.927627135
0.63	4.40	3.20	21.88	7.735748186	0.459	3.550708417
0.80	4.46	3.93	23.50	8.308504679	0.477	3.963156732
1.00	4.62	4.13	24.60	8.697413409	0.482	4.192153263
1.25	4.69	4.48	25.86	9.142890681	0.484	4.425159089
1.60	4.81	4.75	26.32	9.30552524	0.494	4.596929469
2.00	5.12	5.27	26.68	9.432804461	0.531	5.008819169
2.50	6.85	6.80	30.16	10.66317026	0.631	6.728460434
3.15	8.68	8.57	30.34	10.72680987	0.804	8.624355136
4.00	10.50	10.48	30.45	10.76570074	0.967	10.41043262
5.00	11.30	11.12	30.51	10.78691395	1.039	11.20760359
6.30	11.50	11.29	30.61	10.82226929	1.054	11.40667183
8.00	11.30	11.19	30.60	10.81873375	1.036	11.20820817
10.00	10.70	10.70	30.70	10.85408909	0.988	10.72384002
12.50	9.79	9.78	30.32	10.7197388	0.902	9.6692044

Vibration Acceleration Comparison (2s sample time) Trial #2

frequency	HVM (m/s^2)	LABVIEW (m/s2)	AMP	RMS	Wk	Calculated (m/s2)
0.50	4.000	3.050	19.280	6.816509371	0.418	2.849300917
0.63	4.300	3.130	21.250	7.51300955	0.459	3.448471383
0.80	4.490	3.740	22.840	8.075159441	0.477	3.851851053
1.00	4.520	3.880	24.020	8.492352442	0.482	4.093313877
1.25	4.540	4.260	24.880	8.796408358	0.484	4.257461645
1.60	4.710	4.560	25.480	9.008540392	0.494	4.450218954
2.00	5.010	5.270	25.860	9.142890681	0.531	4.854874951
2.50	5.870	5.910	26.080	9.220672427	0.631	5.818244301
3.15	7.650	7.630	26.250	9.280776503	0.804	7.461744308
4.00	9.070	8.970	26.340	9.312596308	0.967	9.00528063
5.00	9.740	9.670	26.400	9.333809512	1.039	9.697828083
6.30	9.920	9.740	26.470	9.358558249	1.054	9.863920394
8.00	9.720	9.610	26.510	9.372700385	1.036	9.710117598
10.00	9.260	9.310	26.550	9.38684252	0.988	9.27420041
12.50	8.470	8.450	26.510	9.372700385	0.902	8.454175747



Trial #1 Comparison between HVM, Labview, and Theoretical Calculation



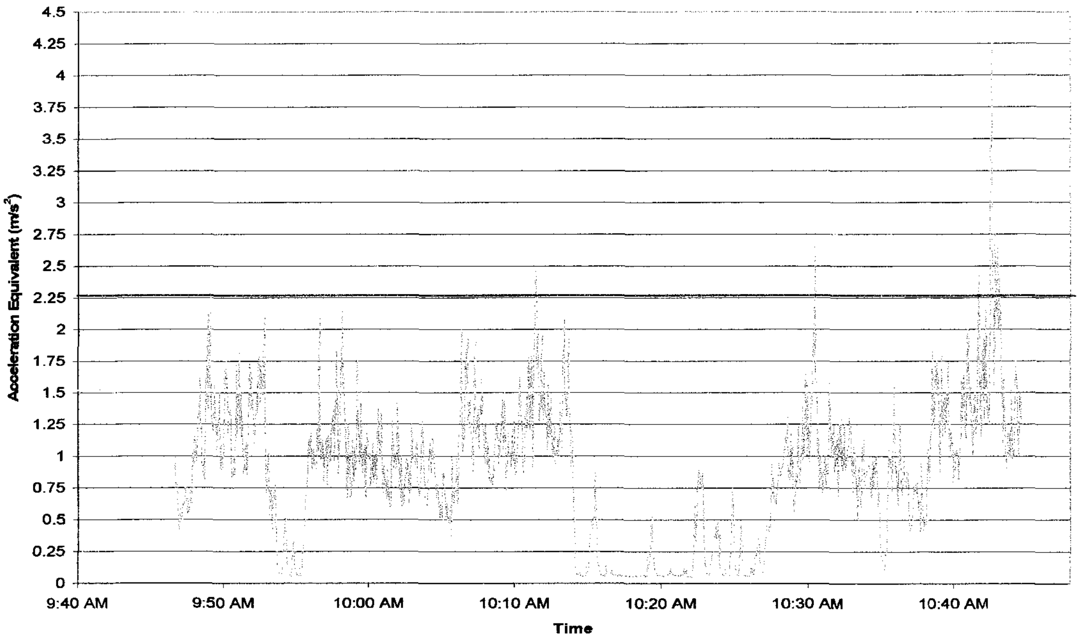
Trial #2 Comparison between HVM, Labview, and Theoretical Calculation

APPENDIX G

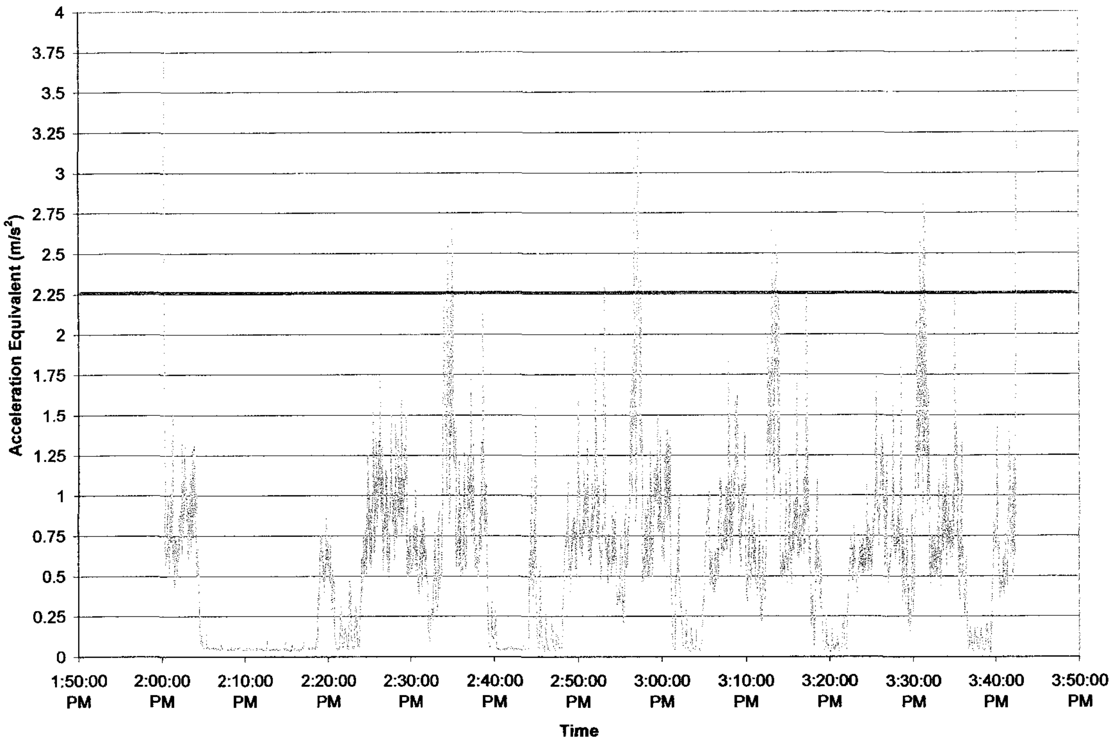
Determining Indicator Threshold Values

Red Lines Indicate Danger Threshold
Orange Lines Indicate Danger Threshold

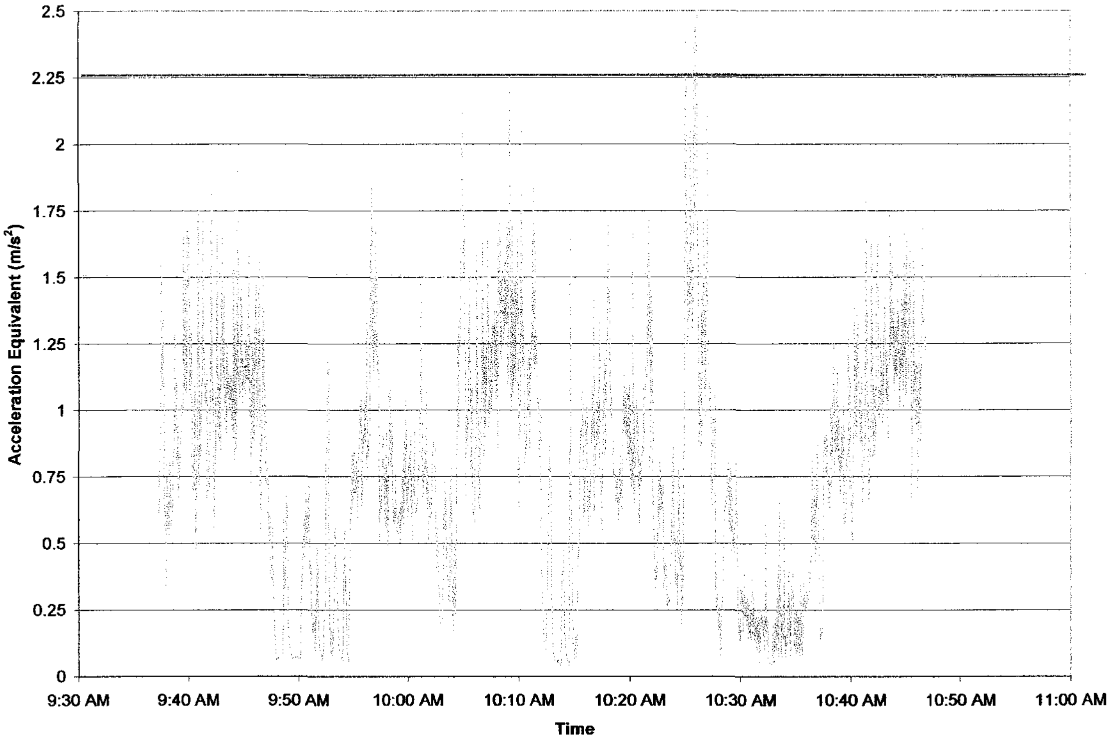
Threshold Selection Field Test #1



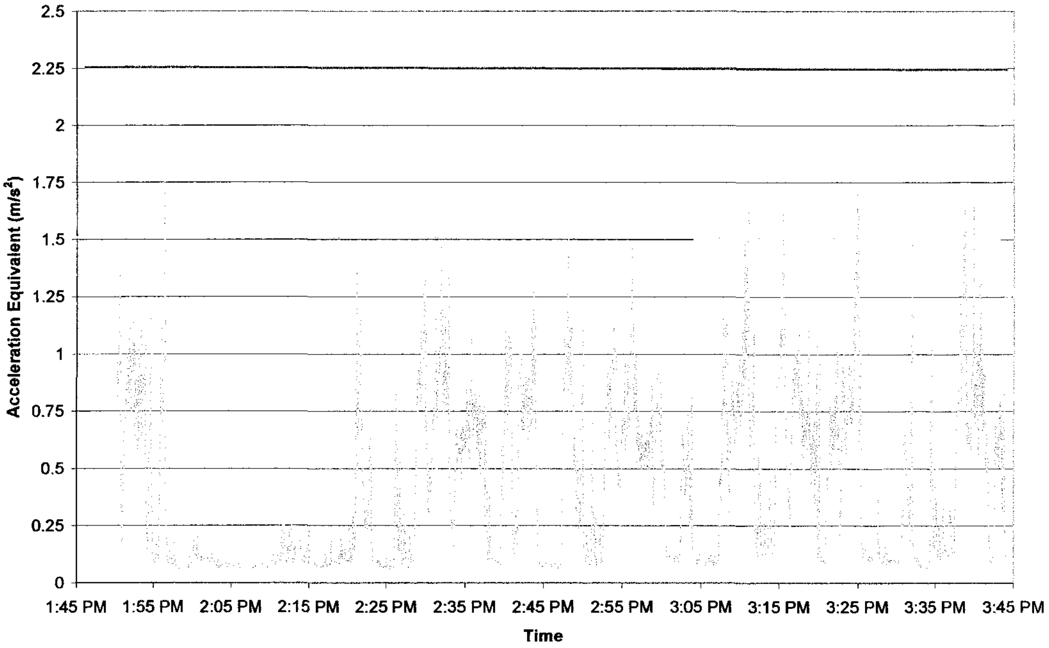
Threshold Selection Field Test #2



Threshold Selection Field Test #3

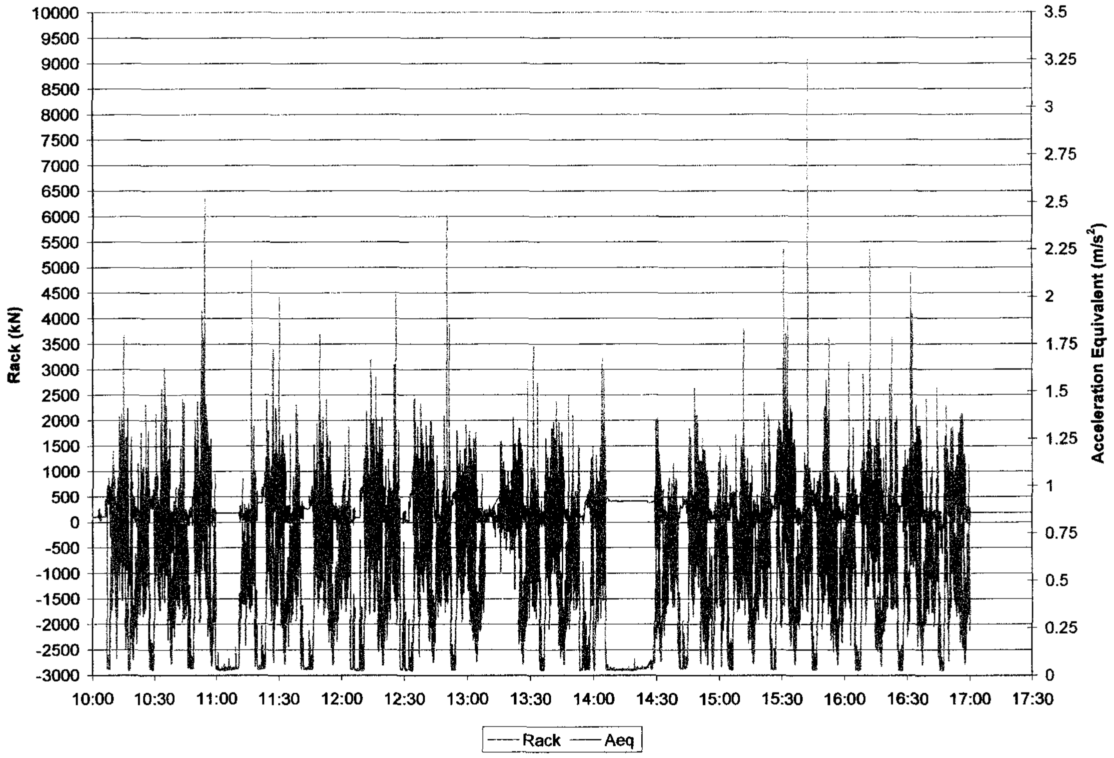


Threshold Selection Field Test #4

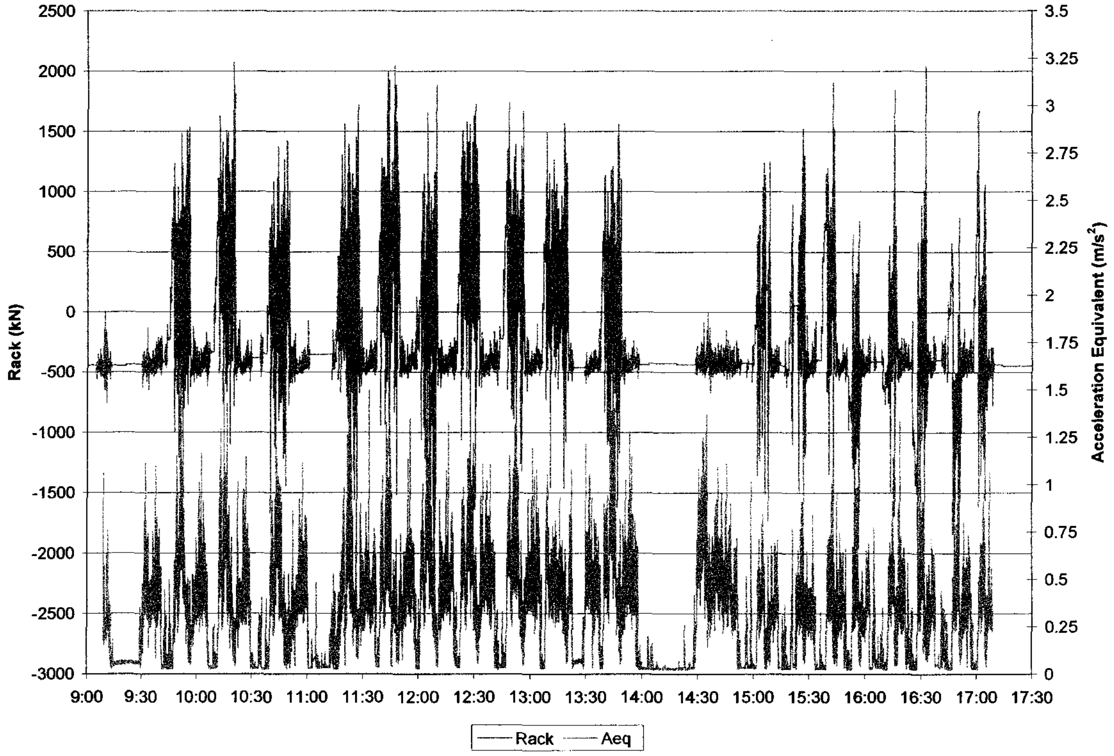


APPENDIX H

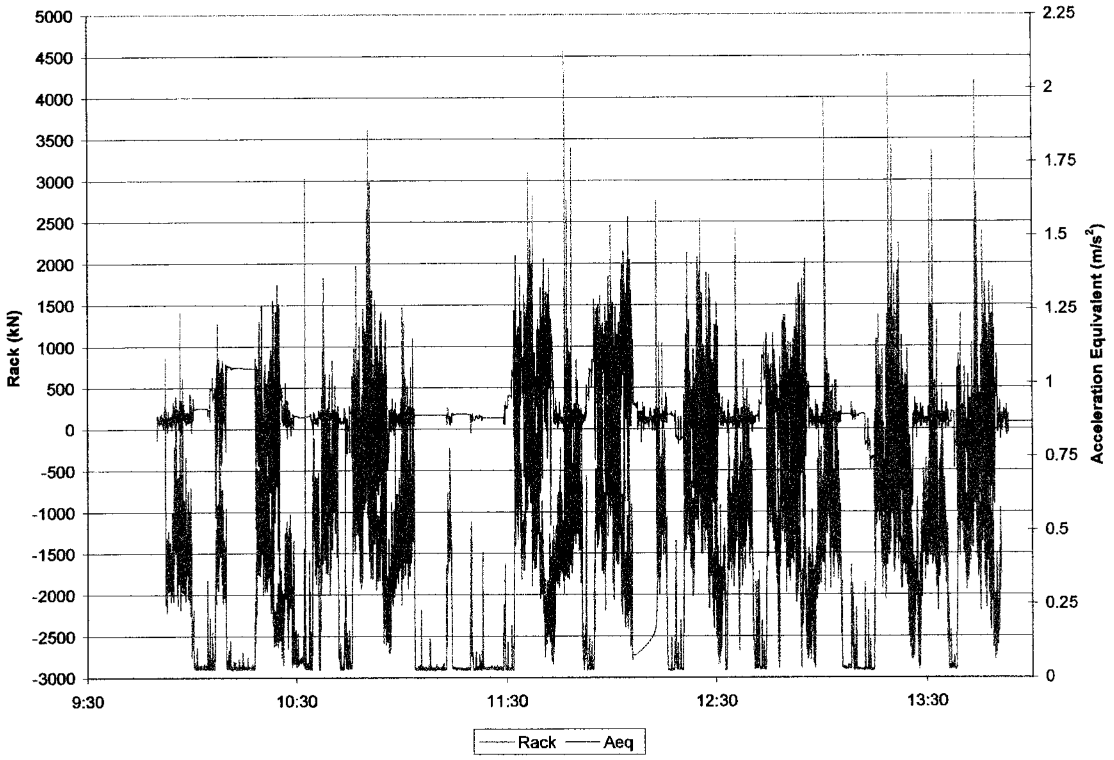
Plots of Instantaneous Rack and Acceleration Equivalent Values for Each Day



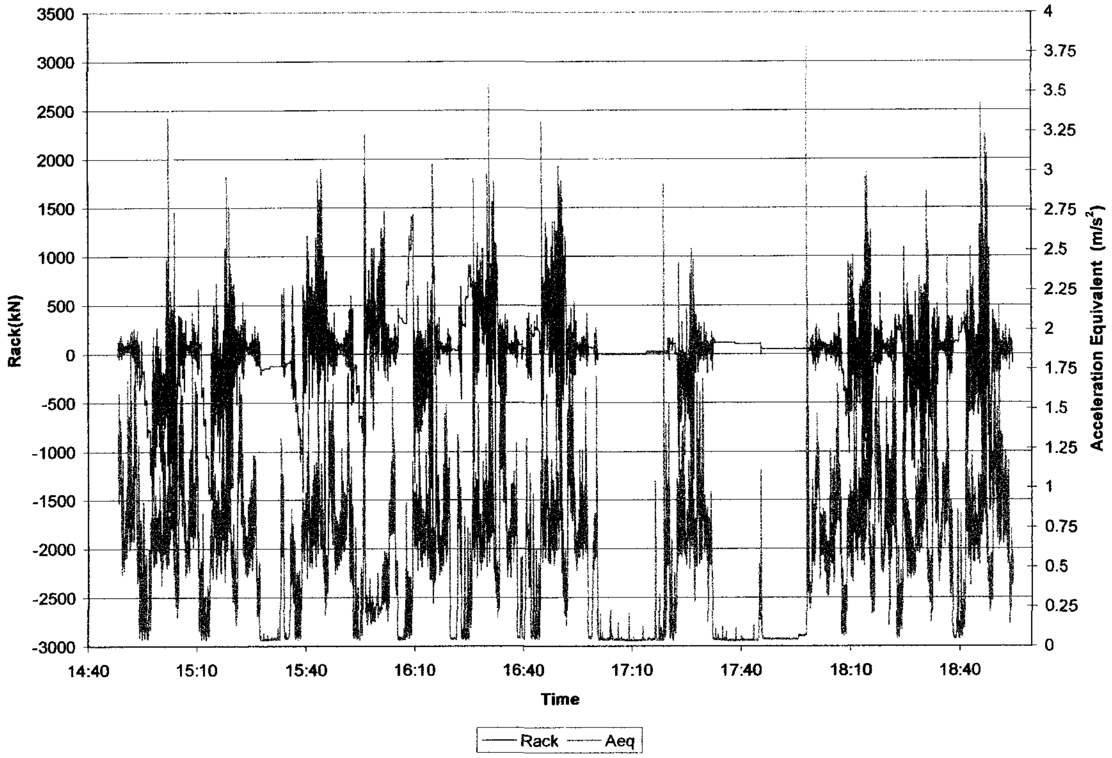
June 25/03 Test Data



June 26/03 Test Data

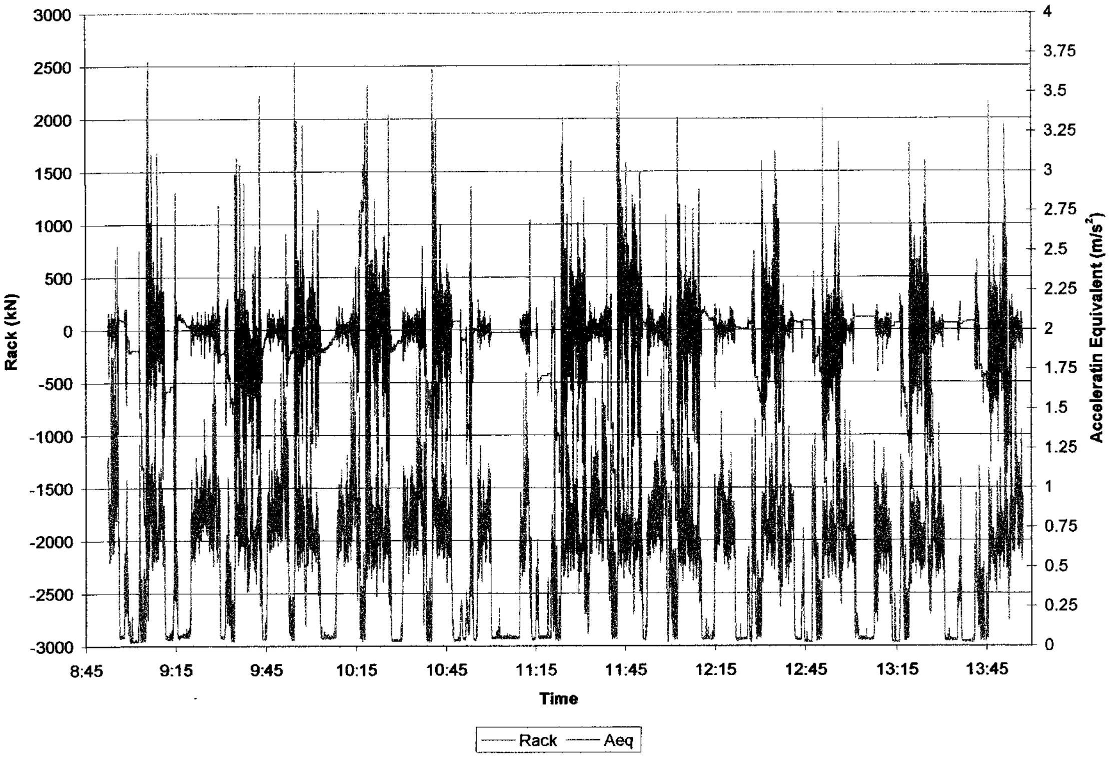


June 27/03 Test Data



October 19/04 Test Data

Rack data missing for October 20/04 due to truck sensor malfunction



October 21/04 Test Data