Evaluation of Whole Body Vibrations from Mine Haul Trucks

by

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ABSTRACT

Research related to Whole Body Vibrations (WBV) within the mining industry has identified adverse effects for human interactions using handheld or operator-mounted instruments. For instances where measurements were taken, haul trucks have indicated major concerns when measured against standards. Currently the regulations for WBV exposure and measurement of WBV are limited due to the requirement of additional measurement equipment, human resources and obstruction to routine mine operations. This research here, focuses on analyzing truck motion parameters derived from suspension strut pressures/forces, against accelerometer measured individual axes of vibration, towards possible development of a WBV measurement system integrated to onboard data monitoring systems. Variations in roll, pitch and Left Front (LF) strut vertical motions, relative to the operator location from an onboard dataset, were analyzed against x, y and z axis vibrations simultaneously recorded using a tri-axial accelerometer. The datasets were analyzed at varying time lengths using a Root Mean Square (RMS) method and a Vibration Dosage Value (VDV), in accordance with ISO2631-1(1997), to calculate equivalent overall acceleration and truck motion parameters. Statistical analysis was carried out to validate data correlations, while data collected from a two secondary field studies were used to verify the initial correlations. A phase analysis of each of the six key parameters further indicated roll, pitch and Left Front (LF) all have a strong correlation during the haul cycle, where the truck is stationary or moving at constant velocity and a negative correlation when the truck is in acceleration or deceleration. When considered for the entire haul cycle, 87% of the time, the Z-axis vibration indicates a strong correlation with the LF strut motion equivalent. The fact that the Z-axis had the dominant vibration for mine haul trucks, based on studies in the literature as well as field studies carried out during this research, the use of LF strut motions for WBV evaluation is solely indicated.

Results from this study indicate the possible development of a proactive system applicable for mine haul trucks to continuously measure WBV levels, without disrupting operations. Development of such a WBV measurement system will increase the opportunity for continuous measurements, which will lead to the guidelines regarding WBV to be strictly regulated, to prevent exposures having adverse effects on operator health and safety.

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LIST OF ABBREVIATIONS

ANN	Artificial Neural Network
CF	Crest Factor
EAV	Exposure Action Value
ELV	Exposure Limit Value
EU	European Union
FEL	Front End Loader
GPS	Global Positioning System
HGCZ	Health Guidance Caution Zone
HT	Haul Truck
HVM	Human Vibration Meter
ISO	International Standard Organization
LBP	Lower Back Pain
LF	Left Front
LHD	Load Haul Dump
LR	Left Rear
MTTV	Maximum Transient Vibration Value
RF	Right Front
RMS	Root Mean Square

RR	Right Rear
SABS	South African Bureau of Standards
VDV	Vibration Dosage Value
VIMS	Vehicle Information Management System
VR	Virtual Reality
WBV	Whole Body Vibration

CHAPTER 01

Introduction

1.1 Issue Identification

Whole Body Vibrations in mine haul trucks as a severe underlying health issue has not been addressed due to a lack of development in evaluation procedure and immediate identifiable impact; instances when measured WBV exposure has exceeded limits set by current ISO standards and EU guidelines. Even though regulations exist with regard to WBV exposure, they remain at a state of "best practice" or "recommended" within major mining economies, but not meaningfully enforced due to lack of continuous measurement.

When considering the reasons behind lack of WBV measurement, the following were identified.

Need for additional resources: In order to measure WBV using ISO 2631-1(1997) the minimal requirement would be the use of a tri-axial accelerometer and a data logger on each piece of equipment. In addition to the capital cost of the equipment, human resources are required for equipment setup, measurement and analysis.

Obstruction to operations: The mining industry is a profit oriented industry, with principal focus on the productivity of operations. Haul truck fleet scheduling is carried out to optimize utilization towards maximizing profits. When WBV instrument setup and measurement is added to shift tasks, it will consume time, counter to the daily production goals of a mine.

Possibility to tamper with the instrument setup: When considering WBV measurement within a haul truck without the presence of a researcher/data collector, there have been instances where operators have meddled with the instruments and tampered with the results with intentional action. Being seated on the rubber pad enclosed accelerometer setup for the duration of the shift has been identified to cause discomfort to the operator, leading to destructive actions.

1.2 Research Objectives

- To understand truck motion parameters as vibration level indicators in the development of a real-time, continuous WBV monitoring system without causing obstruction to routine operations.
- To evaluate the critical nature of WBV exposure in mine haul trucks, to emphasize the need for a more regulated approach to reduce whole body vibrations for mine haul truck operators.

1.3 Limitations

Since this research is in line with operator health and safety regulations that are currently at a state a best practice in major mining economies, the data acquiring process for the study proved to be a difficult task. As a result the effect of different road conditions, driving patterns, climate conditions or size of haul truck towards WBV evaluation could not be comparatively analyzed. However the overall impact caused by these parameters towards the operator’s WBV exposure can be representatively measured using the evaluation procedure stated in the study.

1.4 Background study

Vibrations are defined as wave form motions resulting from energy passing through material bodies. These exist naturally, but are mostly generated at higher magnitudes and varied frequencies due to operation of mechanical devices and vehicles in industrial environments. Even though occupational safety and health related issues are becoming a greater subject of concern , whole body vibrations and related adverse health effects still effectively pass under the radar, due to lack of immediate visible impact to a worker’s health. In the simplest definition, vibrations caused due to the displacement of particles transfer energy through a material. With respect to the human body, the exposure of two or more limbs of the body to such vibrations, defines Whole Body Vibration manifest as resonance in body tissues, leading to spinal damage and other major long-term health issues.

This thesis provides background to vibration mechanics and adverse health and safety issues in general. The literature analysis evaluates methodologies and standards currently in practice for measurement and evaluation of WBV with special reference to ISO2631-1. Analysis is then focused on case studies and research around WBV measurement and identification of causes in general, related to the mining industry with a special focus on mine haul trucks, where vibrations cause operator health issues as well as damage to the truck structure. An objective of this thesis is to provide an overview understanding of whole body vibrations and their significance to haul truck operator’s health and safety; while highlighting the areas for improvement within existing standards and legislation to move towards a WBV risk reduced working environment. The analysis of research work and related case studies focused on this issue indicates a need for an accurate, low cost and convenient real time WBV measurement solution.

1.5 Mechanics of Vibration

Vibration refers to oscillating motions which cause propagation of wave energy. These can be mainly categorized as deterministic and stochastic where a random exposure causing vibrations is a stochastic scenario while a continuous source will lead to deterministic vibrations. Generally this phenomenon of energy transfer through a material cause particle displacement, but returning to an original position.

Magnitude and frequency, as a parallel to structural fatigue evaluation, highlights the most important characteristic in defining a vibration motion. Magnitude is an indicator of the energy carried by the wave form, quantified by amplitude via velocity or acceleration of the wave. Wavelength (λ), amplitude (A) and period (T) indicted in Figure 1.1 describe a vibration motion. With regard to vibration measurements, general practice is the use of acceleration (measured in m/s^2) as the magnitude in a known measured direction. (Berezan, 2006).

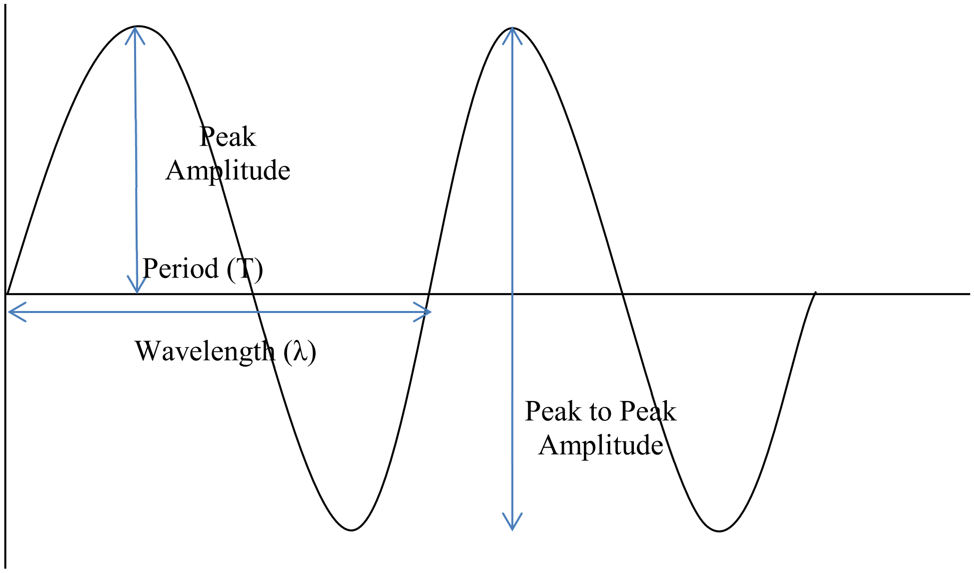


Figure 1.1: Characteristics of a vibration wave form

When an object is under free vibration it will continue to oscillate with the same amplitude and wave length since there is no external force to alter the energy of motion. In the case of dampening, the energy of the free vibration wave form is dissipated with time which can be observed by a drop in amplitude until it ceases; Figure 1.2.

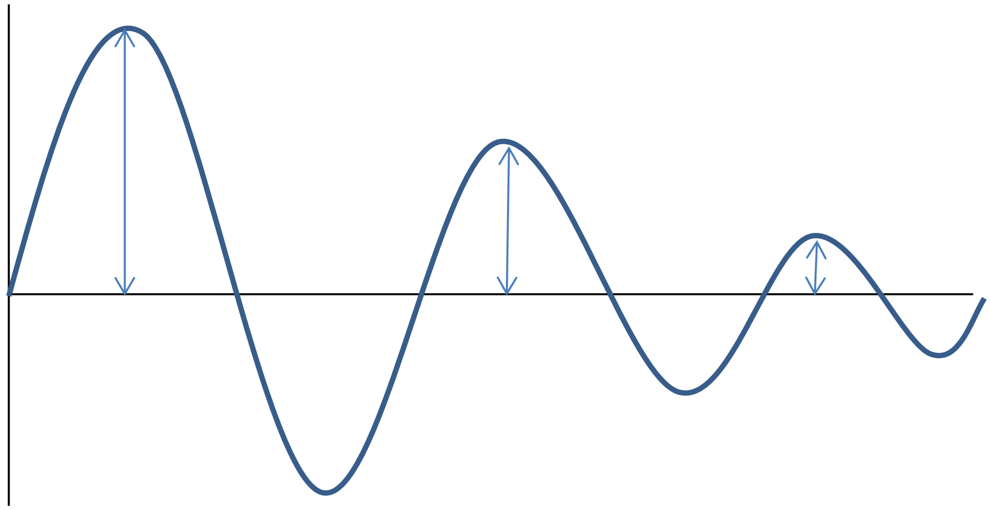


Figure 1.2: Energy dissipation from a damped wave form

Even though velocity and acceleration are basic terms used to discuss motion in the case of vibration, it is sometimes significant to look into higher derivatives like a “Jerk” motion which is a 3rd derivative of motion. “Jerk” or “change in acceleration” can be felt as an instantaneous increasing or decreasing force. If a static load is in operation a constant acceleration will take place. When considering scenarios such as moving in an elevator or travelling in a vehicle, vibrations felt on the body are often a result of such jerk motions or changes in acceleration. (Eager et al, 2016)

1.6 Effects on the human body

Mechanical vibrations are predominantly identifiable to have an adverse effect on equipment and people when being propagated through them. Harmful human vibrations can be primarily in the form of either Hand-Arm Vibration or Whole Body Vibration (WBV). This study will focus only on Whole Body Vibration (WBV), defined as the exposure of two or more limbs to vibration. Whole Body Vibration is effected as a transfer of mechanical energy to the musculoskeletal system, which causes body tissues to vibrate, causing discomfort and injury.

A comprehensive literature study by Wikström et al. (1994) stated that long-term exposure to WBV results in injuries or disorders to lower back regions; severely enhanced due to unsuitable postures and prolonged sitting, mainly in the case of drivers. In addition to lower back injuries, the study covered injuries to neck/ shoulder, gastrointestinal system, urogenital, cardiovascular and nervous systems when exposed to WBV.

Magnusson et al. (1998) showed that exposure to WBV can result in mostly lower back pain as well as major musculoskeletal disorders within the spinal region. The study resulted in the development of a protocol accounting for vibration exposure, as well as contributing factors to a relationship between level of exposure and health effects, since existing standards are not clear on exposure – response relationships.

When considering health effects of WBV, Marjanen (2010) stated that it is not limited to lower back or neck pain but may severely affect internal organs. Severity of an event increases with internal organs exposed to resonance vibration with similar natural frequency. Changes in heart rate, respiration and gastric motility were amongst some of the identified health effects due to WBV.

According to Griffin (1998), damage caused by vibration may vary based on multiple factors as a function of characteristics of vibration or shock waves, versus characteristics of the exposed person or the environment. When it comes to the evaluation of immediate effects, according to Zhao et al. (2013), a definition does not discern between operator comfort and discomfort, where comfort is simply stated as an absence of discomfort associated with pain, soreness or feeling of numbness.

Further literature indicates that at frequencies below 20 kHz, accelerations of around $0.315 m/s^2$ cause motion sickness and discomfort while at the value exceeding $2 m/s^2$, severe discomfort leading to injuries and unsafe conditions due to loss of control over mobile equipment may occur. (Phillips et al., 2003).

More recent work by Burström (2015) concluded that exposure to WBV leads to lower back pain and/or sciatica, caused by compression of spinal nerve roots in lower back.

CHAPTER 02

Human Exposure to Vibration

Even though mechanical vibration exists with countless activities around us, the major focus should be on immediate instances of human interaction with such energy from mechanical vibrations.

In order to identify the existence of the issue, measurement and evaluation of Whole Body Vibration is necessary. In this chapter, equipment used for measurement of WBV and standards set by organizations for evaluation of the harmful nature of human exposure to vibration is introduced.

Scenarios of harmful exposure of human body to WBV are then discussed for different industries with focus on the mining industry. In this study, the literature focuses on previous studies of WBV in mine haul trucks. Regulations and standards in use globally, with regard to WBV are analyzed. Research works that are reviews focuses on ergonomic and other solutions to WBV. The results of this literature study were used to identify underlying root causes of WBV and to formulate objectives of this thesis.

2.1 Measurement of WBV

Vibration transducers are used to measure WBV where accelerometers are commonly used. These transducers convert vibration energy into a voltage output. It is important to have an understanding of the range within which expected vibration measurements may fall, to select a transducer that is proportionally more sensitive to that range of vibration frequencies.

A tri-axial accelerometer is the principle transducer used to measure WBV, in combination with a data logger to filter, process and store the vibration signal captured by the transducer.

2.2 Standards for Evaluation of Vibrations

Before assessing WBV, it is necessary to refer to the standards currently in use to understand the exposure impact of WBV. The International Standards Organization (ISO) defined ISO 2631-1(1997) and IS0 2631-5(2004) as the principle standards used for such evaluations, while European Union Directives (EUD) regulates the limitations of exposure for humans to vibration.

2.2.1 ISO 2631-1 (1997)

The ISO 2631-1(1997) standard entitled “Evaluation of Human Exposure to Whole Body Vibrations”, replaced the previous ISO 2631-1 (1985) and ISO 2631-3(1985). Even though ISO 2631-1 (1985) considered the effect of vibration exposure to be the same for health, comfort and working proficiency, ISO 2631-1(1997) provided a new framework to evaluate the effect of each type of exposure differently (health, comfort and vibration perception, and the onset of motion sickness).

It evaluated vibration exposure using a tri-axial measuring system with the human body in standing, recumbent or seated positions. Figure 2.1 is a tri-axial measurement guide for placing transducers at contact planes supporting a human body, as the major points of vibration transmission. Analysis of studies indicated that vibrations have historically been measured at the seat pan position for evaluation (Chaudhary et al. (2015), Aye & Heyns (2011)).

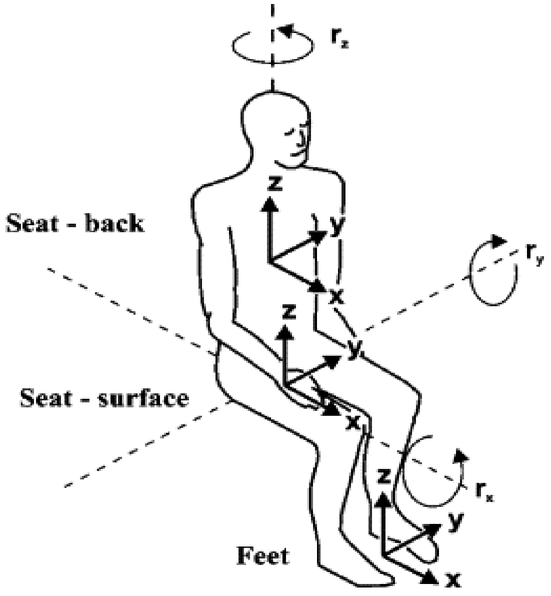


Figure 2.1: Basicentric Axes of Human Body in Seated Position
Source: ISO 2631-1 (1997)

Monitoring frequencies from 0.5 to 80 Hz are targeted for health, comfort and vibration perception; while frequencies from 0.1 to 0.5 Hz are targeted for motion sickness. Even though ISO 2631-1(1997) states that measurements must be taken at the body contact, in this case, the seat, back support and feet; it allows measurements taken from adjacent locations like a seat frame, beneath the seat etc. with the necessity to calculate relevant damping or transmissibility corrections for the measurements. An accelerometer mount specified as in ISO 2631-1(1997) is generally used to prevent any significant alteration of vibration when transmitted towards the human body from a non-rigid seat surface. Even though duration is not specified for measurement, it is indicated to be recorded and be long enough to be representative of the vibration exposure.

This standard provides two methods; via a Root Mean Square (RMS) and Vibration Dose Value (VDV) for vibration exposure assessment. RMS is a basic method of evaluation in which a frequency weighted acceleration value is calculated using equation (2.1). If the weighting factors given in the standard are used then the RMS equivalent acceleration can be obtained using equation (2.2), where integration or summation is used for dealing with discrete time intervals. (ISO 2631-1, 1997)

$$a_w = \left[\sum_i (W_i a_i)^2\right]^{\frac{1}{2}} \tag{2.1}$$

$$a_w = \left[\frac{1}{T}\int_0^T a_w^2\,(t)dt\right]^{\frac{1}{2}} = \left[\frac{1}{T}\sum_{i=0}^{T} a_w^2 . t\right]^{\frac{1}{2}} \tag{2.2}$$

Where, a_w(t) = weighted acceleration as a function of time (in m/s^2)

and T = duration of measurement

An alternative is to evaluate each individual axis separately and identify the one with the highest weighted frequency acceleration to assess the health effects of vibration exposure. Even though a use of a vector sum is not required, the work of Paddan & Griffin (2002) suggested the use of a vector sum, equation (2.3) to provide an improved evaluation of whole body vibration.

$$a_v = \left[k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2\right]^{\frac{1}{2}} \tag{2.3}$$

When obtaining the vector sum at a seat pan for a seated position, $k_x = k_y = 1.4$ and $k_z = 1$ was used to account for the more significant effect of vibrations in x and y directions to an operator's health. Certain studies have indicated the need for a vector sum of WBV measurement variables instead of using only a dominant axis of evaluation. (Smets et al., 2010)

Crest Factor (CF) is a parameter considered before evaluating a Vibration Dose Value (VDV) method, where:

$$\text{Crest Factor} = \frac{\text{Maximum Instantaneous Peak Value of frequency weighted acceleration}}{RMS\ value\ of\ \text{frequency weighted acceleration}}$$

(2.4)

Based on Crest Factor value, a judgment can be made whether a RMS value provides a representative evaluation of a vibration exposure or whether it does not appropriately represent the peak values within the measurement. The standard states that when a CF is greater than 9, a basic method of evaluation using RMS value is insufficient and the VDV method is required.

VDV method is very similar to the RMS method, the only difference being the use of a 4th power for evaluation as indicated in equation (2.5). (ISO 2631-1, 1997)

$$VDV = \left[\int_0^T [a_w(t)]^4\,dt\right]^{\frac{1}{4}} = \left[\sum_{i=0}^{T} a_w^4.\,t\right]^{\frac{1}{4}} \qquad (2.5)$$

Where,

a_w(t) = instantaneous frequency weighted acceleration as a function of time (m/s^2)

a_w = instantaneous frequency weighted acceleration (m/s^2)

t = time (s)

T = duration of measurement (s)

VDV = Vibration Dose Value (m/s$^{1.75}$)

The standard also states that in a situation when there are two or more periods with different magnitudes, the total vibration exposure must be calculated using the fourth root of the sum of fourth power of each individual VDV value. The total VDV for an (i) number of such periods can be found using equation (2.5).

$$VDV_{Total} = \left[\sum_i VDV_i^4\right]^{\frac{1}{4}} \tag{2.6}$$

A vector sum for VDV may also be calculated using the same scaling factors as per the RMS vector sum calculation. After calculation of RMS or VDV values, the standard provides a Health Guidance Caution Zone (HGCZ) chart as indicated in Figure 2, which is used to decide whether a vibration exposure is of any concern to operator's health. (ISO 2631-1, 1997)

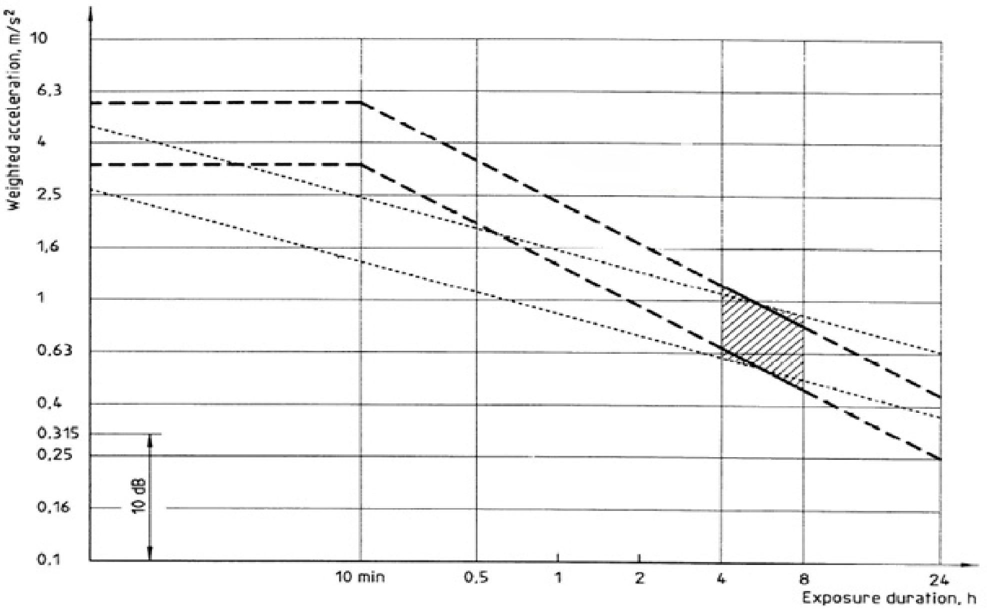


Figure 2.2: Health Guidance Caution Zone for Whole Body Vibration Exposure

Source: After ISO 2631-1 (1997)

Even though the standard does not specify a measurement duration for WBV exposure evaluation and 8 hour exposure value or A(8) value for can be evaluated and analyzed with reference to the HGCZ in the chart.

2.2.2 ISO 2631-5 (2004)

In 2004, ISO 2631-1 (1997) was modified with the introduction of a method using a 6th power calculation for accelerations, plus the use of spine models to calculate acceleration doses in each x, y, and z directions before an equivalent (S_e) was calculated. Based on the S_e value and estimated daily exposure (T), upper and lower boundaries for an allowable exposure region was created. The S_e value calculated in the 2004 ISO standard proved to be more sensitive to peak shocks amplitude than VDV measurements. (Zhao & Schindler, 2014)

This standard focused on measurement of spinal acceleration in order to account for more peak values or shocks within a measurement period. Initially lumbar spine accelerations along x, y, z directions were measured and the acceleration dose (D) was calculated for each axis using equation (2.7).

$$D_k = \left[\sum_i A_{ik}^6\right]^{\frac{1}{6}} \qquad (2.7)$$

Where A_{ik} was the i^{th} peak of the response acceleration in the respective direction. (k = x, y or z.) Then the daily average dose for each axis was calculated as in equation (2.8).

$$D_{kd} = D_k \left[\frac{t_d}{t_m}\right]^{\frac{1}{6}} \qquad (2.8)$$

Where t_d = duration of daily exposure and t_m = measurement period of D_k

Then a Daily Static Compressive Stress Value (S_{ed}) was calculated as equation (2.9),

$$S_{ed} = \left[(0.015D_{kx})^6 + (0.035D_{ky})^6 + (0.032D_{kz})^6\right]^{\frac{1}{6}} \qquad (2.9)$$

Further analysis could then be carried out based on the number years of exposure and the age of the operator from which exposure began. Lower and upper limit S_{ed} of the HGCZ has been defined as 0.5 and 0.8MPa respectively. (ISO 2631-5, 2005)

2.2.3 EU Directives (2002)

Directive 2002/44/EC of the European Parliament Council regulated exposure to reduce human exposure to mechanical vibrations. Amongst the limitations set for WBV, an Exposure Limit Value (ELV) and an Exposure Action Value (EAV) were defined. The Exposure Action Value regulates the employer to take immediate organizational or technical measures to reduce the exposure of workers below daily exposure limits of 0.5 m/s^2 and $9.1 m/s^{1.75}$ for 8 hour RMS and VDV values respectively. (European Parliament, 2002/44/EC)

2.2.4 BS 6841

This standard is very similar in application to ISO 2631-1 (1997), but with the use of a 4th measurement as an x-axis value at the back-support point with weighting factors used in each direction. These weighting factors are not biased towards x, y directions as in ISO 2631-1 (1997). Furthermore this only uses a vibration dosage value and has defined limits, (Berezan, 2006). This method is however rarely used in practice for WBV evaluation.

A comparative analysis carried out by Griffin (1998) on existing standards indicated that in BS 6841(1987) the use of a Vibration Dose Value (VDV), for defining an action level, enables simpler and more convenient evaluation of harmful dosages of WBV. Although a novel methodology, ISO 2631-1 (1997) was highlighted as relatively confusing, due to its method with multiple interpretations, as well as to a lack of clarity in procedure.

In using VDV or RMS values; the body positions, a 1.4 weighting factor for x and y axes, a crest factor value to decide between RMS or VDV evaluation and by exposure dependence are very confusing in ISO 2631-1(1997).

Paddan & Griffin (2002) confirmed that for the same data set evaluation using RMS or VDV method, a significantly different outcome occurs, primarily due to poor use of weighting factors as suggested in the standard.

A recent study by Johnson et al. (2015) on heavy mining truck operators also stated that results evaluated using ISO 2631-1(1997) methods; the 8 hour exposure for RMS evaluation or the A(8) value and 8 hour exposure for VDV method or the VDV (8) approaches, indicated most of the trucks were below the ELV and the vector sum values of each exposure were above an ELV. Meanwhile, the S_{ED} (8) values were below the ELV indicating a difference in health caution evaluation by method used. The ISO 2631-5 (2004) overall method seems to wholly underestimate health risks.

Since a specific duration of measurement is not provided within the ISO health standards, different studies adopt different time measurement periods. A study by Burgess-Limerick & Lynas (2016) has compared VDV (8) and RMS accelerations for a fleet of haul trucks and dozers in an Australian Coal Mine. The study indicated the significance of the measurement period in assessing WBV, highlighted as a shortcoming. However, long sample durations gave more accurate results by exposure commemorating with a larger sample set, while VDV (8) values signifying peak events were generally higher, for longer measurement periods with events of rare occurrence.

Other studies using both ISO 2631-1(1997) and ISO 2631-5(2004) indicated a significant variation in outcomes with ISO 2631-5(2004) greatly underestimating the health risks.

2.3 Human Exposure to Vibrations

Mechanical vibrations exist within most industrial applications such as construction, agriculture and mining, where adverse WBV effects have taken a significant impact.

Kittusamy & Buchholz (2004) focused on previous WBV studies as a function of poor posture, as a major risk resulting in muscular-skeletal disorders with significant health impacts caused by vibration from mobile machine use. The literature suggested that operators who work in heavy construction and earth moving using dozers, loaders, excavators, backhoes, trucks and cranes are exposed to the highest WBV.

The agriculture industry is a major sector in which exposure to WBV has been significant due to the use of mobile equipment and poor ground conditions. A study by Milosavljevic et al. (2011) on a selected sample of 130 rural farmers in New Zealand measured WBV using quad-bikes for farming purposes. The results evaluated, via both RMS and VDV methods, indicated that most individuals of the sample group were within the Exposure Action Limits defined in the EU directives (2002), while some exceeded Exposure Limit Values. Furthermore a dual rear suspension system was observed to reduce vibrations compared to a single suspension system in quad bikes.

The agricultural tractor in wide use operated on-road, off-road and in field applications, exposes an operator to whole body vibration. Ahmed & Goupillon (1997) indicated that older poorly suspended tractor models generated higher WBV effects at low frequency and high amplitude. Servadio et al. (2007) studied the use of different types of tractor tire while measuring vibration at a rear axle and at the driver’s seat showing an increase in speed seemed to reduce vibration in the vertical z-axis. Tires with different numbers of lugs and lug spacing generated varied WBV results. This highlighted that speed and tire/ground interactions have an impact on the in WBV transmitted.

A study by Bovenzi et al. (2002) observed 219 port machinery operators, including 85 straddle carrier drivers, 88 fork lift drivers and 46 crane operators. Average daily exposure A (8) values of 0.64, 0.34 and 0.28m/s^2 via ISO 2631-1(1997) indicated that only the exposure to WBV was within the acceptable action limits for fork lift operators only. Further analysis from this study indicated that even though prolonged poor seating posture was initially not a direct cause of Lower Back Pain (LBP), an exposure to WBV increasing LBP resulted from bending forward and frequent twisting motions enhanced adverse health issues. A study by Brendstrup & Biering-sorensen (1987) indicated similar WBV health related impacts for fork lift operators.

2.4 Exposure to Vibrations within the Mining Industry

In the mining industry, operators of drills and haul vehicles have been identified as the most affected by WBV. A study by Zhao et al. (2013) monitoring a group of wheel loader operators the ISO 2631-1(1997) indicated WBV levels within the “uncomfortable”, with “speed” as a major influencing factor for increasing vibration intensity. In an expansion of this study, Zhao & Schindler (2014) compared WBV for wheel loaders using both ISO 2631-1(1997) and ISO 2631-5(2004), revealing the latter to underestimate WBV health impacts for most operating and road conditions, except for high speeds. The validity of using a RMS approach was questionable as the crest factor values suggested, while compliance when MTTV/a_w and VDV/ ($a_w T^{1/4}$) was warranted as a more viable approach.

An extensive WBV study by Aye & Heyns (2011) within opencast mines in South Africa involved 34 pieces of mining equipment divided into 3 groups; Load Haul Dump (LHD) units, excavators and “other” equipment. This study evaluated both RMS and VDV outcomes based on ISO 2631-1(1997) recorded via accelerometers placed at the seat position. The data was analyzed using health and safety legislation set by the European Union. Results from the assessment indicated that nearly 90% of the evaluated operators of equipment were within the Exposure Limit Values (ELV), but that nearly 50% exceeded the Exposure Action Values (EAV), which highlighted the need for precautionary measures. With regard to specific equipment categories, even though excavators were well within the EU defined Exposure Limit Values; most of the earth moving equipment including haul trucks as well as dozers had WBV triggers within the EU ruled caution zone. Use of a VDV method in addition to the RMS method in this study indicated that WBV was underestimated in some instances to fall within ELV limits.

An evaluation by Howard et al. (2009) used 13 sub classes of equipment and tasks in open pit mines, which defined 3 categories including shovels, falling in a low to moderate health risk zone, 6 categories including graders, small scale haul trucks, tracked wheel loaders, fork lifts and personal vehicles falling in a moderate health risk zone and 4 categories including wheeled dozers and wheeled loaders falling within a moderate to high risk zone. Kress haul trucks were observed to experience the severest WBV levels in the study and all the conventional rear dump haul trucks exceeding WBV limits.

Chaudhary et al. (2015) studied blast hole drill operators in opencast iron ore mines in India. Evaluation of WBV based on ISO 2631-1(1997), using frequency weighted accelerometer readings at seat pans indicated a significantly high WBV level in the vertical z-direction, with some RMS values within the caution limits. All measured VDV values exceeding the upper limit of the caution zone. This study also stated the fact that ISO 2631-1(1997) did not provide a clear indication of the measurement period to be followed, as well as a significant variation in analyzed outcomes.

In a more recent study by Burström (2016), 95 mining vehicles were assessed for exposure to WBV. Using the ISO 2631-1(1997) guidelines, a sample group of haul trucks, drill rigs, wheel loaders, excavators, dozers, graders and mass transport vehicles operating at 3 mines in Finland, Norway and Sweden were analyzed using RMS and VDV methods. The results revealed that wheel loaders and dozers produce WBV within indicated Exposure Action Limits. Even though the VDV and RMS values evaluated for haul trucks were below the indicated limits, the higher exposure duration highlighted the importance for haul road maintenance and training operators to be aware of WBV. The mean A (8) exposure in all the operating vehicles were within the EAVs defined by EU guidelines, further indicating that severe health issues caused by WBV exposures were common in the mining industry.

A study by Burgess-Limerick & Lynas (2016) focused on comparing the effect of duration of WBV exposure measurement in the coal mining industry, where operation of earth moving vehicles such as dozers and haul trucks not only were within the HGCZ, but at the same time exceeded Exposure Limit Values defined by the EU.

2.5 Vibrations in Mine Haul Trucks

A person may get exposed to whole body vibrations through contact with a surface transmitting mechanical vibrations. Though possible when operating static machinery, according to Phillips et al. (2003), the most common mode of exposure is while seated operating heavy mobile machinery.

This section highlights case studies and research focused on analyzing WBV in trucks used for hauling operations within the mining industry. When considering haul trucks; vibration motions commonly occur while travelling under heavy loaded conditions, where these motions are expected to be partly dampened through suspension systems. Chamanara (2013) identified speed, uneven payload distribution, road undulations and other ground conditions to cause significant unfavorable rack, pitch and roll motions transferred to truck suspension, structure and truck body. These adverse motions, in particular rack motion causes a reduction of truck life as well as pitch and roll motions potentially contribute to an increase in WBV to the truck driver, making it vital to continuously evaluate vibrations on haul trucks.

Nitti & Santis (2010) analyzed a data set to develop a statistical model for vibration prediction. Road conditions, truck speed, loaded and unloaded states were studied to predict such truck motion induced vibrations. The effect of each parameter was weighted based on a dummy variable with value of 0 or 1. Even though a model was produced similar to the actual data set; the inability in the findings to explain the physical relationships amongst the dependent and independent variables reduced the usefulness of the discovered empirical relationships. With the complexity involved in vibration mechanics, such studies indicated lack of significance for statistical models to predict vibration.

Bovenzi et al. (2006) conducted a study on 598 professional heavy equipment operators (fork lift, earth moving, truck, bus) and a control group of 30 fire inspectors, where high levels of exposure to WBV within the driver group correlated to experience of high intensities in Lower Back Pain (LBP) . This indicated the impact of vibrations due to several ergonomic risk factors in driving, such as prolonged sitting and awkward posture.

In considering truck drivers, the seating position and posture came under scrutiny in a research conducted by Wikström (1993). When a set of drivers were evaluated in 3 seated postures; (head and body forward, head only rotated 30^0-50^0 degrees leftwards, whole seat rotated in the previous angle from the driving direction); discomfort was identified at the neck-shoulder region and lower back while twisting posture and deviation from the inline driving direction indicated to increase adverse impacts of vibration. This study confirmed that speed was one of the major factors increasing adverse vibration impact. Eger et al. (2008) supported this argument where a non-neutral working posture in combination with WBV was confirmed as a major factor leading to musculoskeletal injury.

A more recent study by Aye & Heyns (2011) indicated that among heavy vehicles and equipment, most haul trucks exceed the EAV for vibration exposure. A study by Paddan & Griffin (2002) using 100 different vehicle classes also indicated dump trucks to exceed EAV interpreted using ISO 2631-1, which was observed to underestimate WBV severity compared to BS 6841 methodology.

Kumar (2004) studied on a set of male and female heavy haul truck (230mt to 350mt capacity) operators in overburden hauling, and concluded that the measurements using ISO 2631-1(1997) exceeded safe working limits significantly, with a need to monitor WBV thereafter. The study further stated that the gender of the driver, truck model and carrying capacity did not correlate significantly to vibration exposure level, but the site or road and operating conditions were observed to have a significant impact.

Mayton et.al (2008) studied aggregate quarry sites and evaluated the effect of WBV for new versus old haul trucks. A fleet of six haul trucks (50-70mt capacity) were used, consisting of 4 old trucks (15-21 years in use) and two new trucks. Vibration readings were measured using tri-axial accelerometers fixed to the rigid body of the truck within the operator cabin and on the operator seat. Comparative measurements from the two accelerometers indicated that older trucks had a higher and variable transmission, amplifying vibrations; while the newer trucks were observed to use more modern seats with low and consistent transmission. When considering the overall results, via ISO 2631-1(1997), older trucks indicated a higher RMS acceleration resulting in a rougher ride experience. While higher VDV indicated in the new trucks, in orthogonal directions was not explained, but was assumed to be a result of newer suspension systems and dampened operator cabin arrangements.

Mayton et al (2015) continued his earlier 2008 study, with a sample of six Haul Trucks (HT) and four wheel type Front End Loaders (FEL) operating at two US aggregate stone quarry sites. The major focus of the evaluation was to discern variation in transmission of WBV from the vehicle frame to the operator through the seat pan. Considering multiple factors, for HTs, the vehicle speed and load did not cause significant variation to transmission but an increase in age of a vehicle and carrying capacity did indicate a decrease in transmission. The dominant axis of vibration was identified as either y or z axis in the case of haul trucks when normalized for 8 hour exposures while it z-axis was noted as dominant when considering separate incidents (without normalizing for 8 hour exposure). It was highlighted to be dominant in x-axis for FELs. Sudden start/stop and bucket filling/emptying tasks during operation of FELs was identified as the reason for this phenomenon. The results for both sets of vehicles indicated that WBV levels for majority of the mobile equipment to be either within the HGCZ or beyond the EU exposure limits, further indicating evidence of adverse WBV in the mining industry.

An open pit coal mine in New South Wales was the subject of a research conducted by Wolfgang & Burgess-Limerick (2014) on a sample of 32 mine haul trucks, consisting of Komatsu 930E (290mt) trucks and smaller Caterpillar 785B/785C/789B units. Measurements were taken at the seat surface with tri-axial accelerometers following ISO 2631-1 (1997), monitored over 5 months, and classified by three defined road conditions; well maintained, rough and a combination of both. The results indicated that the rough and uneven road conditions play a significant role in WBV generation while well maintained conditions led to reduced vibration levels. Truck size was also regarded but significant evidence was not found to show a correlation to WBV. This study also highlighted that most mine haul trucks exceed an 8 hour exposure limit given in the standards and 12 hour shifts commonly used, enhancing the adverse health issues. As a result of this work, the use of electronic equipment to continuously measure and monitor WBV in haul trucks was recommended.

In a more recent study on haul trucks, Johnson et al. (2015) analyzed haul trucks by size; 190mt, 240mt, 320mt; with the vibration data collected at the operator seat interface as well as the floor of the cabin using tri-axial accelerometers. Results indicated the vertical Z-axis as the dominant vibration axis with attenuation from the seat having a significant impact on transmissivity. Furthermore, this trend was observed to decrease with increasing truck size. In considering the other influencing parameters, Z-axis vibrations were not significantly affected by truck size, but X and Y axis vibrations had a tendency to increasing with truck size. As noted earlier, a vector sum of VDV and RMS values tend to exceed the limits indicated in the guidelines, such that the significance of WBV issue in the mining industry was highlighted as a major concern for haul truck operators, while different obtained following existing guidelines, left the most suitable method or standard for evaluation as questionable.

A study conducted on a fleet of Load-Haul-Dump (LHD) trucks, by Eger et al. (2008) in consultation with the Mines and Aggregates Safety and Health Association of Ontario indicated several instances where WBV levels exceeded the limits defined by standards. The monitored seats in the LHDs indicated amplifying vibration when compared to the measurements at the vehicle structure. Research further suggested that when results were compared to ISO 2631-1 (1997), they indicated greater accuracy than ISO 2631-5 (2004), which only considered effects to the lumbar spine region. Eger et al. (2011) then studied a fleet of LHD's indicating exposure within HGCZ limits, where the results highlighted that the empty state operation of LHDs to generated significantly higher WBV level compared to the loaded state.

A similar study on haul truck operators in surface mining, conducted by Smets et al. (2010), using 8 haul trucks ranging from 35mt to 150mt, indicated several instances where WBV levels exceeded exiting standards, and a contradiction in outcomes using ISO 2631-1(1997) versus ISO 2631-5 (2004) standards, indicating an underestimation of whole body health hazards by the latter.

When heavy haul truck operations are considered, the work cycle can be divided into 4 phases as loading, hauling, dumping and returning. Even though the standard does not make it compulsory to consider individual components of a work cycle to calculate WBV exposure, it is important to identify the different types and magnitudes of exposure experience during each of these phases. A study by Mandal et al. (2016), within an Indian metal mine, considered 8 mine haul trucks by operating phase wise impact on WBV during the work cycle. Assessment was conducted following ISO 2631-1(1997), which indicated that the majority of the vehicles were within the EU action limits for WBV. The results further indicated the dominant axis of vibration to be the vertical Z-axis during haul and return phases but varied between X or Y axis directions during loading and unloading activities.

2.6 Worldwide Legislations and Practices for WBV Control

Though standards have been set for WBV evaluation, the lack of more local legislation is a significant factor in mandating the use and leading to an increase of vibration related health issues. According to Berezan (2006), Australia and United States have not implemented a set legislative framework to implement strict regulations related to WBV control and the situation seems very similar in Canada where occupational health and safety legislation set by provincial governments have not specifically required standards related to WBV to be maintained.

According to Phillips et al. (2003), even though ISO 2361-1 was adopted as SABS 2361-1 by the South African Bureau of Standards (SABS) to measure whole body vibration, no exposure limits have been set or legislated to indicate operator health issues.

An initiative taken by the European Union (EU) towards a more legislative approach in handling vibration issues is in process. The EU has defined Exposure Limit Values (ELV) as well as Exposure Action Values (EAV) using both RMS and VDV methods under ISO 2631-1 (1997); which instructs employers to monitor and act to reduce WBV in heavy equipment and vehicles in mine sites. (Aye & Heyns, 2011). Studies such as Burström (2016), within the European mining industry identified instances where significant exposure exceeding Limit

Values stating the need and obligation to take immediate preventive measures for such instances.

The Chaudhary et al. (2015) study of drill operators also indicated an instance where a study has led to identifying WBV, for drilling activities in Indian Iron Ore mines, exceeding limits defined by the ISO standard, but a lack of regulations within the country limits enforcement.

2.7 Research towards WBV reduction

Indications of several studies of WBV have led research to seek solutions. Tiemessen et al. (2007) identified design considerations, operator skills and behavior as major factors in establishing a viable solution to this issue. A preventive strategy decision was suggested, based on combining factors accounting for skill and behavior of operators as well as design considerations. Tiemessen et al. (2007) identified solutions related to seat suspension, cabin suspension, and road design, as significant impacts on design, while speed and driving skill of operators were indicated as important behavioral parameters.

Most research targeting reduction of WBV indicated has focused on modification of seat suspension. Sankar & Afonso (1993) discussed the use of seat suspension integrating both vertical shock absorbance and lateral suspension systems. With special focus on “suspension seats”, Paddan & Griffin (2002) indicated seat dynamics as a major focus factor to reduce WBV in vehicles. Dickey et al. (2010) suggested the development of a laboratory robotic platform to simulate vibrations recorded from forestry, mining, and construction industries. With the use of a similar simulation system, Conrad et al. (2013) worked on a suspension modification for WBV reduction. The effect of seat suspension systems on WBV was considered through a comparative analysis. The study also carried out a simulation of pre-recorded vibration conditions within laboratory conditions, and conducted a comparative evaluation of 3 prototype seats, recording acceleration data from the seat interface and vehicle chassis. This indicated all 3 seats to significantly attenuate input vibration, unlike older existing models in use, which amplified vibration. Comparative results suggested that different seat designs should be used based on the scenario of application. This work also identified the necessity of additional ground and road surface condition maintenance to reduce WBV levels within health guidance accepted limitation.

Dickey et al. (2013) extended the laboratory simulation approach to WBV, using Virtual Reality (VR). 3D VR mimicking physical models measured by Dickey et al. (2010) were used to replicate WBV exposure instances within the laboratory, providing an opportunity for more detailed observation and analysis of relationships between operator posture, directional change in motion and other parameters leading to WBV.

Servadio & Belfiore (2013) analyzed vibration generated by an agricultural tractor which indicated a significant variation in results when different tires were used in the tractor highlighting the importance of tire characteristics as a factor in controlling WBV. This study was evaluated using ISO 2631-1 (1997) and also indicated an increase in WBV with an increase in tractor operating speed.

A comparative study and monitoring program by Wolfgang et al. (2014) in surface coal mines in Australia showed that 30 out of 32 trucks used in the study were within the health caution zone per ISO 2631-1 (1997), highlighting the prevalence of the issue.

Mandal et al. (2016), identified the dominant axis of vibration by using cycle phase for heavy mobile equipment operation; as the Z-axis during hauling and returning phases, contributing to the majority of the vibration dose. The study suggested improvement of haul roads as a major factor to reduce vibration. An increase in WBV was observed proportionally to speed, showing the need to limit vehicle speed in reducing adverse health effects of WBV.

Costa & Arezes (2009) studied operator skills for a sample of forklift operators, which indicated that factors like experience and age play a vital role in operational decision making, having a significant impact on generation of WBV when all other factors were kept constant.

Salmoni et al. (2008) studied on WBV measurement in trucks, indicating the necessity to perform WBV tests continuously in the field and identified difficulties arising while conducting measurements necessary for WBV evaluation using existing standards. Poor understanding of working environments, disturbance to routine activities, and poor control over testing were common issues that occur when measuring WBV in haul trucks; which make it challenging and often uneconomical to focus on continuous health risk assessment.

Berezan et al. (2004) focused on development of a real time onboard indicator system using accelerometer readings to alert haul truck operators to instances of high WBV levels exceeding acceptable limits. This system permitted operator behavior to be self-adjusted as a precautionary measure to reduce WBV. Truck drivers were able to keep in check their usual exposure levels and alter driving patterns accordingly. In this research, a relationship was found between rack motion of the truck frame versus an acceleration equivalent and further analysis recommended to identify correlation between of truck motion parameters and vibration.

Suglo & Szymanski (2014) identified the used onboard information system to provide truck operators with data and warnings with regard to WBV exposure. An Artificial Neural Network (ANN) model was developed using data recorded by Caterpillar’s Vital Information Management System (VIMS) from CAT 797 haul trucks, with a focus to correlating truck parameters such as ground speed, payload, machine rack, roll and pitch to seat vibration data, measured using a tri-axial accelerometer at seat pad interface. Since the study was focused on vibrations in x and y directions, roll motion was found to be the major parameter relating to WBV, while payload was indicated to have the least impact.

The literature has revealed numerous studies stating the importance of continuous measurement of WBV for mining equipment operations. A major roadblock to setup a regulatory framework has in part been the high cost of accelerometers for measurement purposes, but overall lack of agreement in the literature as to how the ensuing analysis should be performed. To overcome such issues research studies have assessed the suitability of other consumer electronic devices to measure tri-axial acceleration. Research work by Wolfgang & Burgess-Limerick (2014) and Burgess-Limerick & Lynas (2014) focused on the use of 5th generation iPod Touch technology to measure WBV. Simultaneous pairs of readings in 32 pieces of mining equipment including dozer, wheel loaders and haul trucks within 3 coal mines were measured using such electronic devices, and standard accelerometers. The results indicated that the ability of the consumer device with a range of ±2g, to measure WBV up to ±0.09 m/s^2 RMS with a 95% confidence and an accuracy up to ±0.06 m/s^2 for measurements in the Z direction.

CHAPTER 03

Preliminary Analysis

This chapter outlines the methodology and reasoning used for selection of suitable truck motion parameters for analysis against accelerometer parameters. The equipment selection for field data collection is discussed followed by the preliminary methods used to analyze the initial sample data and the results observed. Modifications to the analytical parameters beyond initial observations are then discussed.

3.1 Research Approach

When considering real time measurements, mine haul trucks are already equipped with onboard systems, which continuously record a massive amount of data using multiple sensors within the truck. It was identified by Chamanara (2013) that poor road conditions, speed and uneven payload distribution have generated significant unfavorable motions, measured at the truck suspension system. Since such unfavorable motions also lead to WBV, this work analyzes truck suspension data, as a readily available data source from the onboard system.

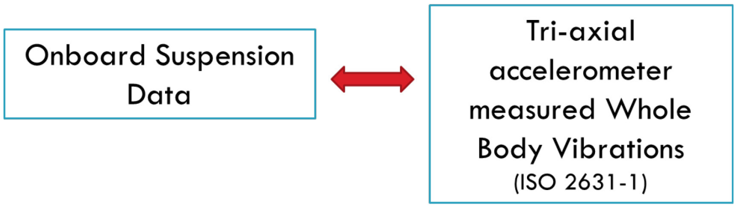


Figure 3.1: Research Approach

Development of a WBV analysis procedure using onboard system data would eliminate the requirement for additional equipment and human resources, while causing no obstruction to mine operations. With the elimination of additional measurement equipment, the operator interference with WBV measurement tools also will no longer be an issue.

Parameters from onboard truck suspension data were selected for analysis against X, Y and Z axis vibrations measured using a tri-axial accelerometer at the operator's seat pan to seek correlation. Figure 3.2 provides a flow chart of the research methodology adapted in this study.

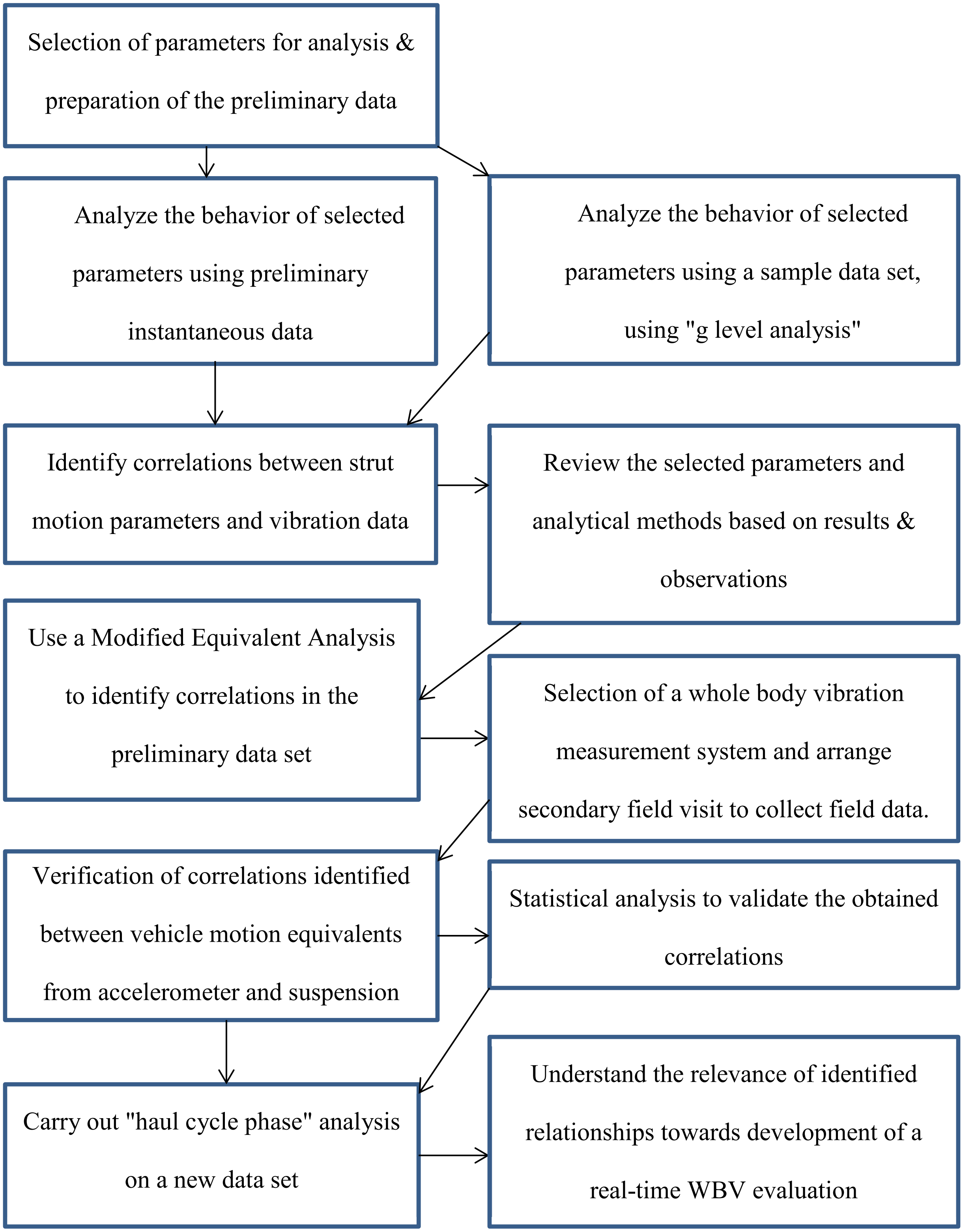


Figure 3.2: Research Methodology

3.2 Selection of analytical parameters

To derive a relationship between truck motions and accelerometer-measured axial vibrations, Pitch and Roll were identified as gross major truck body motions. Pitch motion is the forward motion experienced due to the rotational forces around Y- axis and can be quantified using the difference of front and rear strut forces. Roll motion is experienced perpendicular to the direction of movement due to rotational forces around the X-axis which can be quantified using the difference between left strut forces and right strut forces.

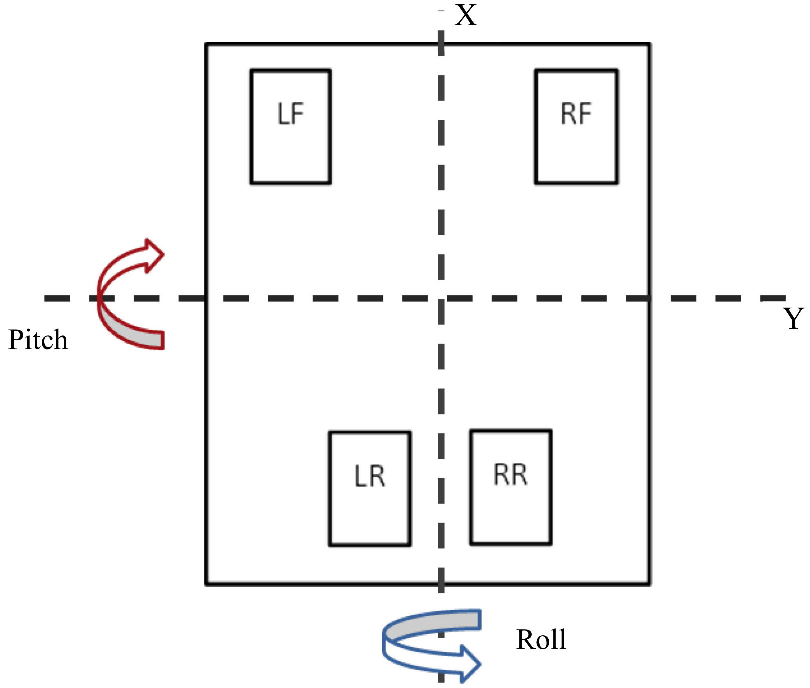


Figure 3.3: Pitch and Roll motion with respective to strut position of a haul truck

Figure 3.3 above shows the directions of each of the motions and equations (3.1) and (3.2) show the standard calculations used to evaluate Pitch and Roll using strut force or g-level. LF, RF, LR and RR denote to the individual strut forces or g-level at each location.

$$\text{Pitch} = (LF + RF) - (LR + RR) \tag{3.1}$$

$$\text{Roll} = (LF + LR) - (RF + RR) \tag{3.2}$$

Based on the directions of motion it was initially assumed that pitch motion caused vibrations along X-axis while roll motions affected Y-axis vibrations. The next objective was to select a similar motion parameter for comparison with Z-axis vibrations.

When considering the strut positions on a mine haul truck, it was observed that the LF strut is situated directly beneath the operators cab and seat, as indicated by the white box in Figure 3.4. Therefore the motion of the LF suspension strut was selected as the parameter to analyze against Z-axis vibrations or vertical accelerations.

Figure 3.4: LF strut positioning relative to operator's seat
Source: https://www.cat.com/en_US/products/new/equipment/off-highway-trucks/mining-trucks/18093014.html

Figure 3.5 shows each of the selected truck motion parameters identified to be analyzed against accelerometer measured operator WBV. Since the suspension strut data from the onboard system is available in pressure units (kPa), their values were converted to force units using the measured inner active bearing surface diameters of the front and rear struts respectively.

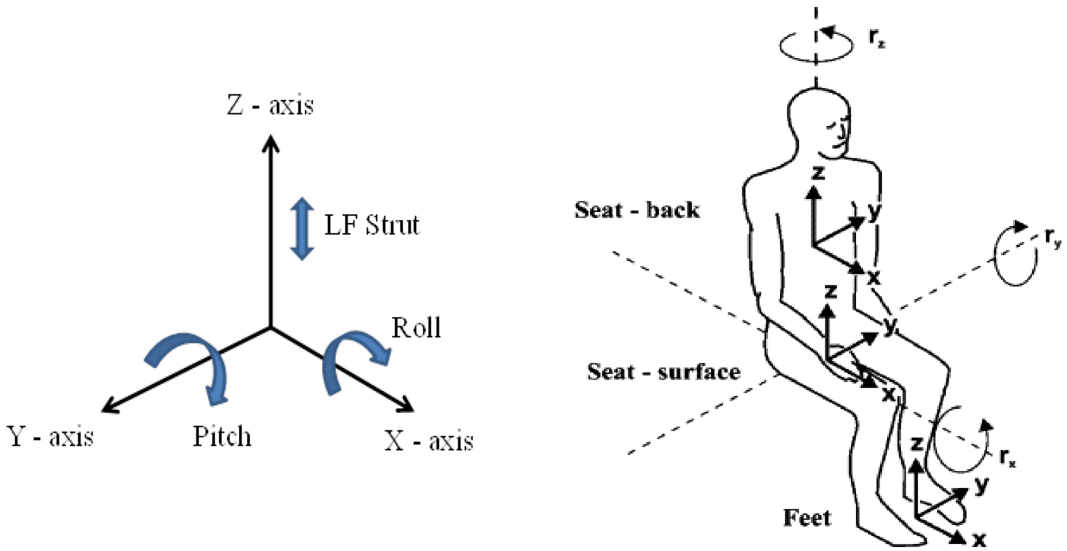


Figure 3.5: Strut motion parameters to be analyzed against each axis of vibration in human body

For the analysis, the truck motion parameters were analyzed using "g-level analysis". G level was obtained by dividing the instantaneous value by the average of the same parameter under similar (equivalent to static) conditions. As a result, for a considered parameter different average values may be derived from instantaneous g-levels, by different phases within the same haul cycle. The resultant "g-level" parameter is unit-less, which permits more focused correlative analysis and future scaling for different size machines.

3.3 Data Collection for Analysis

The general requirement for whole body vibration measurement is a tri-axial accelerometer, a data logger and a laptop computer or mobile device. For the initial analysis, the sample data set was provided by Dr. Tim Joseph. This data was collected and used by Berezan, a former M.Sc. graduate of University of Alberta for a previous study related to whole body vibrations on mine haul trucks. (Berezan, 2004)

The dataset selected for the analysis was recorded on 19th October 2004 at an oil sand mine in Alberta. An ENTRAN EGCS3-D tri-axial accelerometer with a range of ±5g was used for measurement of WBV, while a Larson Davis HVM 100 was used to filter, process and calculate the vibration exposure equivalents. For the duration of the sample data measurement, the onboard data from the VIMS system of a CAT797 360 ton truck was recorded simultaneously.

3.3.1 Data set details

Specifically, the onboard data recorded from the CAT797 haul truck comprised the following parameters.

- VIMS Time (Hrs:Min:Sec)
- Individual Suspension strut Pressures for each of the 4 suspension struts. (in kPa)
- VIMS Payload (t)
- Ground Speed (km/h)
- Longitude & Longitude (in Deg) for vehicle location

Since the onboard strut data set was in pressure units (kPa), the inner bearing surface diameters of the front and rear struts were used to convert to force units (kN).

- Rear Strut Diameter: 0.381m
- Front Strut Diameter: 0.4000m (Source: Berezan, 2004)

The WBV dataset from the accelerometer consisted of x, y, z instantaneous weighted acceleration values and RMS equivalents for each axis.

3.3.2 Data Preparation for analysis

Coordinates were plotted to illustrate the haul cycle path followed by the truck Figure 3.6, to identify haul road, dump and pit regions.

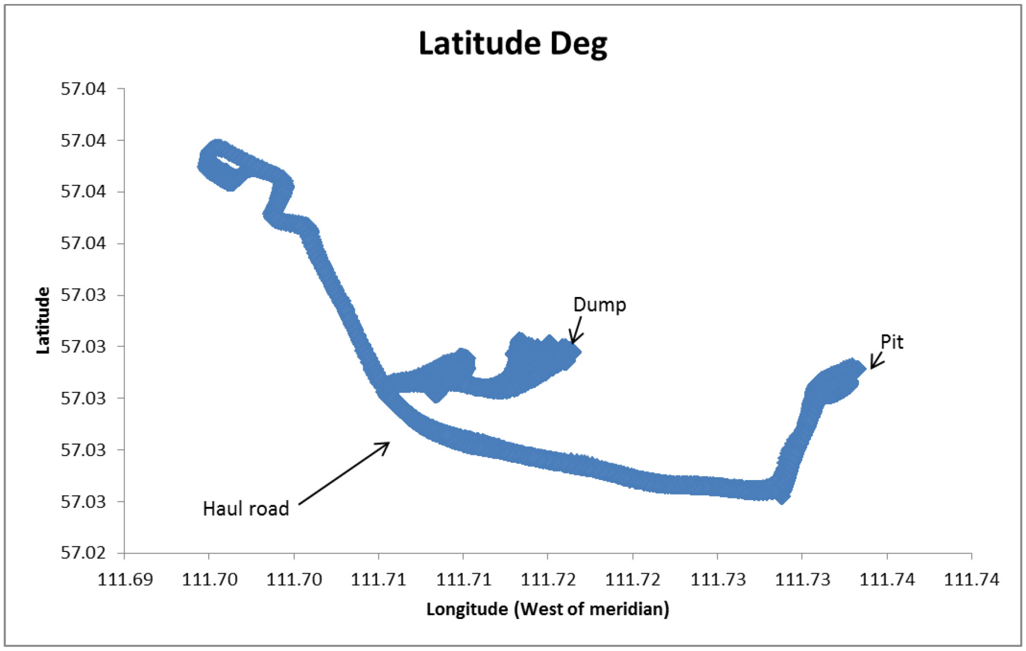


Figure 3.6 : Haul Path plotted using VIMS data

Before comparing the data sets, the time stamps were aligned. Pit and dump locations with high idle time and low vibration levels identified using the GPS locations were used to assist the process. A delay of 91 seconds (difference between data collection clocks) was identified and the acceleration data time was adjusted accordingly to overlap the VIMS time.

During the preliminary analysis it was noted that the accelerometer vibration data set had been recorded at 0.5Hz frequency while the VIMS system on the haul truck had been recorded data at 1Hz frequency. Certain uneven intervals were observed in the data sets likely due to computer recording "drift". In order improve the data match of any instantaneous correlation it was decided to use an interpolation method to in-fill the missing data points, as well as increase the accelerometer data set to the same frequency as the onboard system. Linear interpolation was used, with the code provided in Appendix 1, using version R2015b of MatLab software to interpolate the data files in MS Excel (.xls) format.

3.3.3 Instantaneous correlation analysis

After interpolating the accelerometer data to adjust with the strut pressure data from the onboard information system, the instantaneous values of each of the 6 parameters (a_x vs pitch $_{inst}$, a_y vs roll$_{inst}$, a_z vs LF $_{inst}$) were compared. Absolute values of Pitch, Roll and LF were selected for comparison with X, Y and Z axes accelerations.

A one to one instantaneous correlation was not evident in regression analysis as both data sets recorded at 1Hz, indicated significant deviation or delays, with minimal overlapping.

Summary of sample plots for the instantaneous data are provided in Figures 3.7, 3.8 and 3.9 (a) and (b) plots. Even though an instant event based correlation was not evident, it was evident that a visual correlation could be observed for variation in the selected parameters.

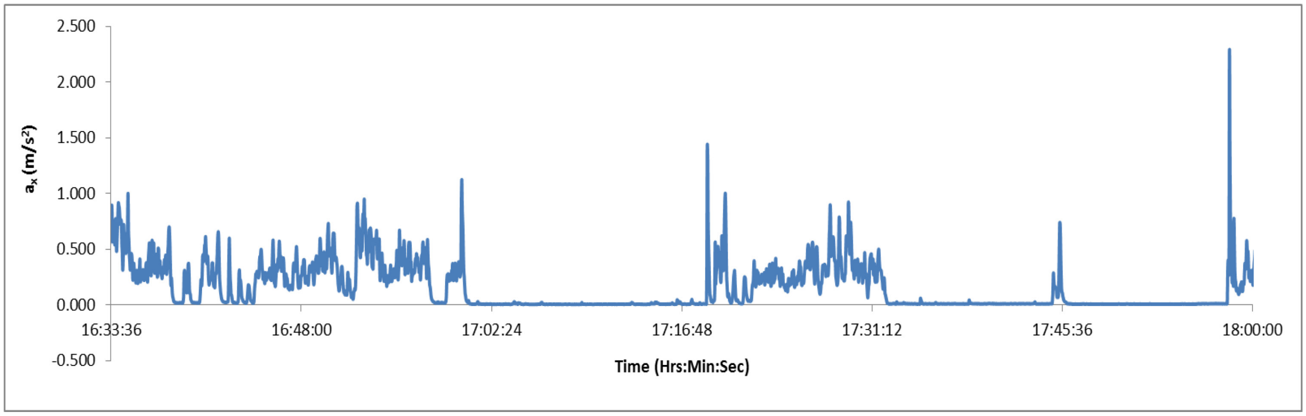


Figure 3.7(a): Instantaneous X-axis acceleration (a_x) vs Time

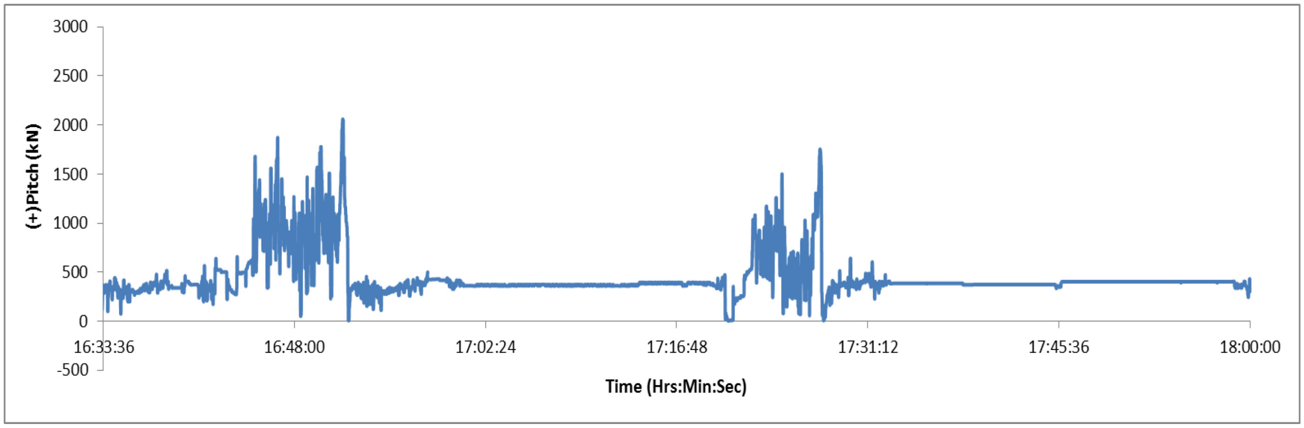


Figure 3.7(b): Instantaneous (+) Pitch vs Time

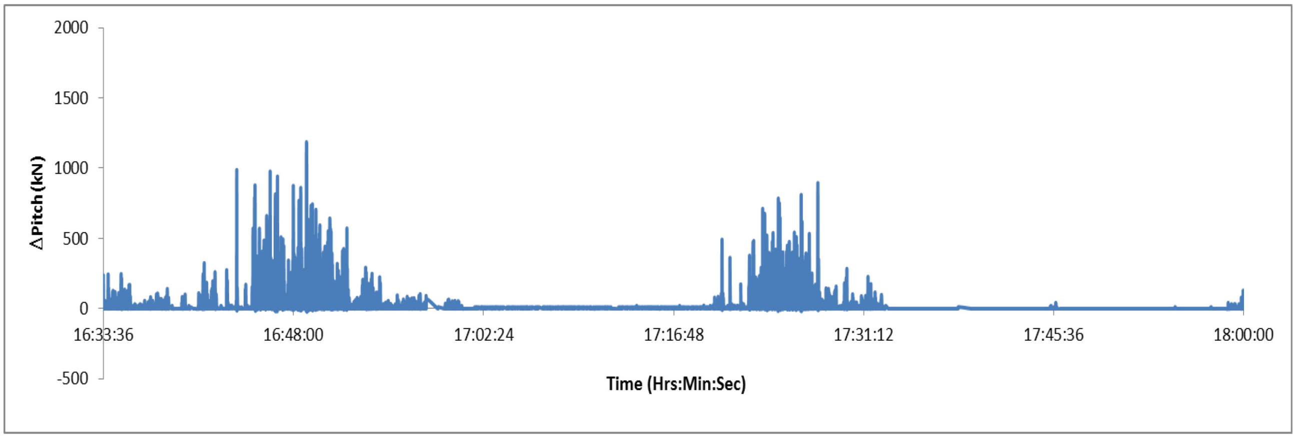


Figure 3.7(c): Instantaneous DPitch vs Time

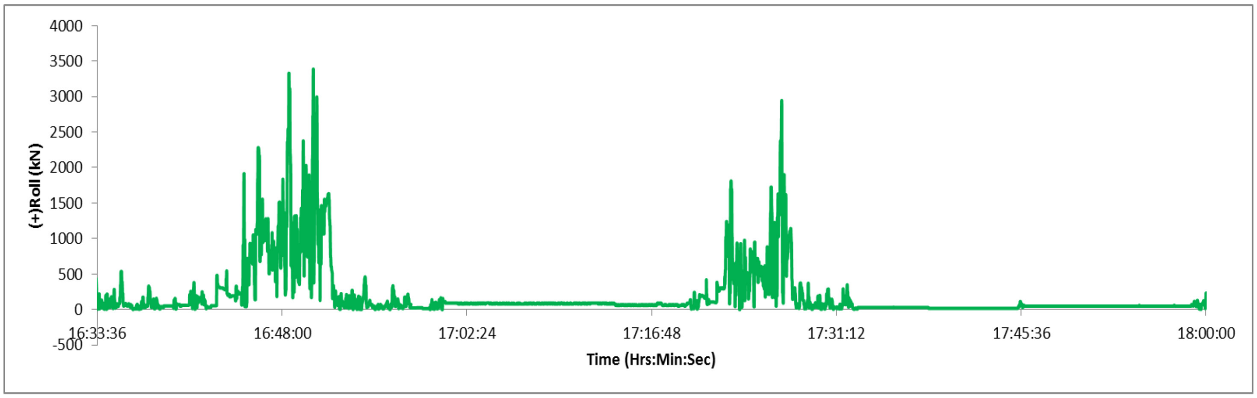


Figure 3.8(a): Instantaneous Y-axis acceleration (a_y) vs Time

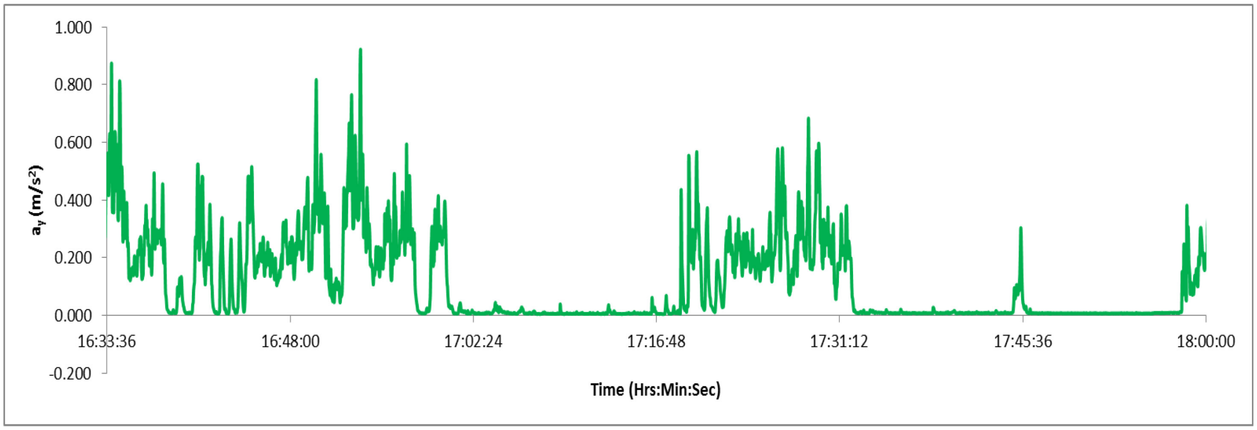


Figure 3.8(b): Instantaneous (+) Roll vs Time

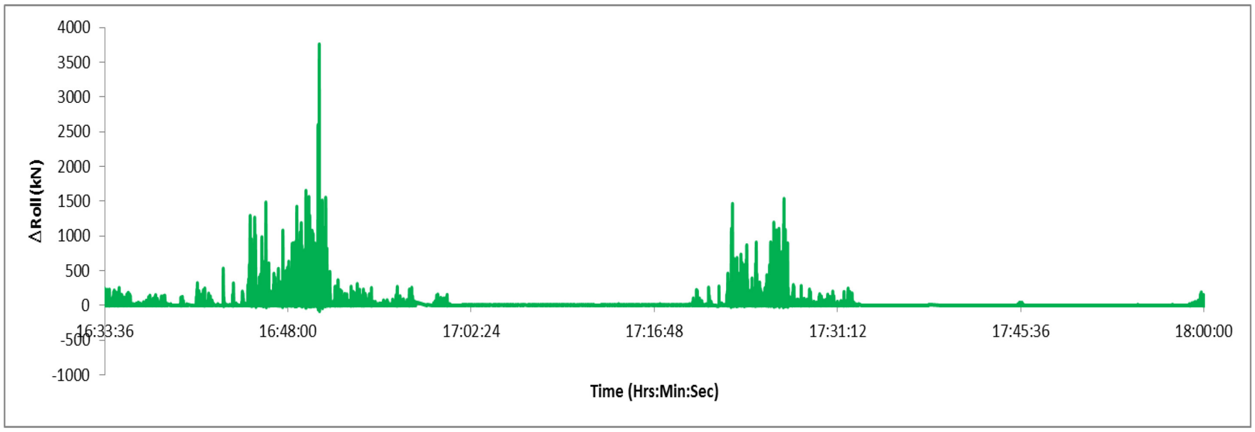


Figure 3.8(c): Instantaneous D Roll vs Time

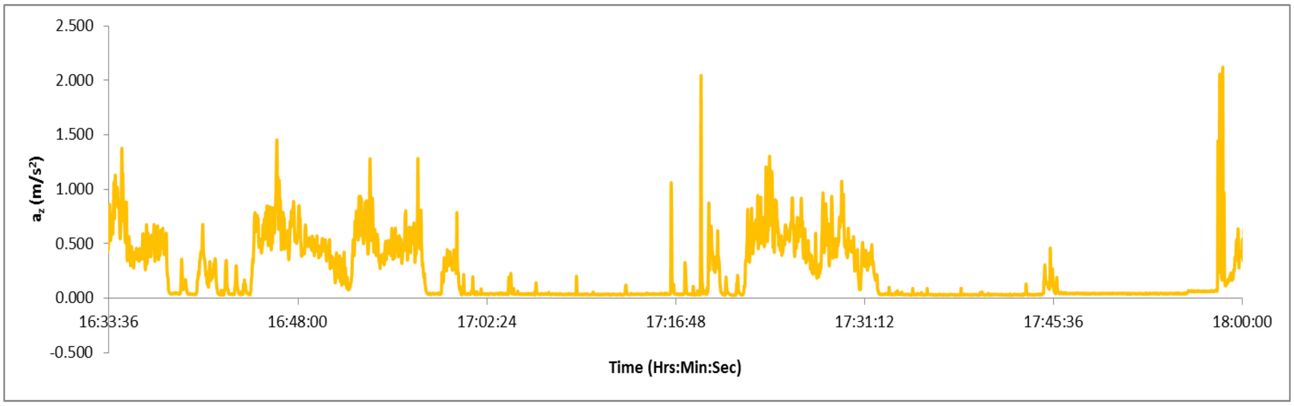


Figure 3.9(a): Instantaneous Z-axis acceleration (a_z) vs Time

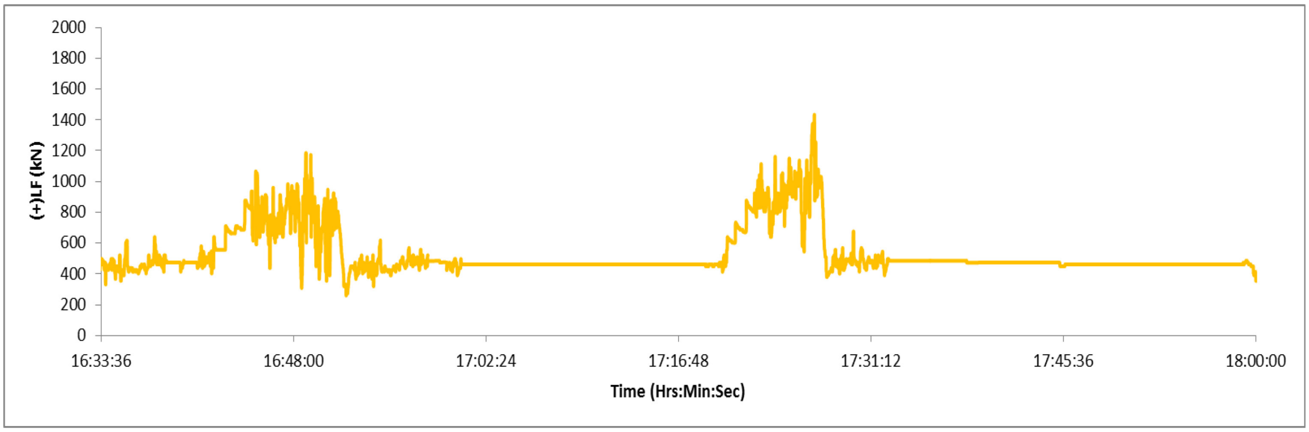


Figure 3.9(b): Instantaneous (+) LF vs Time

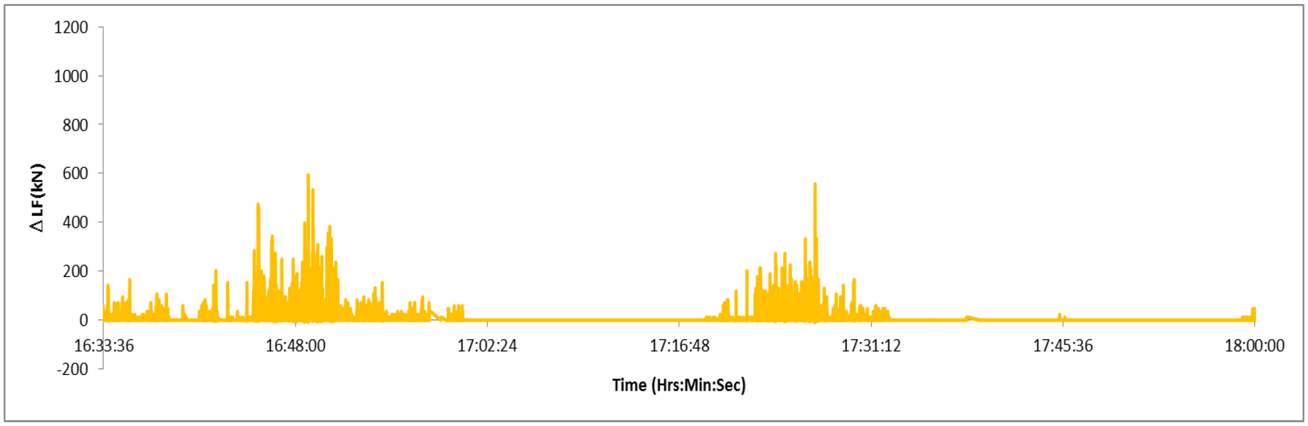


Figure 3.9(c): Instantaneous DLF vs Time

3.3.4 Selection of New Parameters

Use of D Pitch, D Roll and D LF

After the outcome of the preliminary analysis, it was noted that the onboard VIMS system was not very sensitive to small variations in strut pressure resulting in repetitive readings. Therefore instead of considering all raw Pitch, Roll and LF values, D Pitch, D Roll and D LF values > 0 were considered where an actual change in pressure had occurred. The resultant graphs for the modified parameters are indicated in Figures 3.7(c), 3.8(c) and 3.9(c).

Use of Force units instead of G levels

Furthermore, with a real-time measuring procedure necessary, it was decided to proceed with force units for truck motion parameters instead of using G levels which required separate calculations for difference phases of travel. The sole requirement for conversion of strut pressure to force units was to input the inner diameters of the front and rear strut of the truck in which the measurements are carried out.

CHAPTER 04

Modified Equivalent Analysis

Lack of correlation among instantaneous values of each of the truck motion parameter vs the accelerometer parameter led the research to focus more toward an equivalent method, which would signify the vibrations within a specified time duration.

4.1 RMS equivalence analysis

In ISO 2631-1(1997), the standard for measurement of Whole Body Vibration uses a Root Mean Square (RMS) method to evaluate equivalence for vibration exposure for a selected duration.

It was decided to calculate similar RMS equivalents for each of the modified truck motion parameters D Pitch, D Roll and D LF parameters and compare them with the WBV equivalents for the same period evaluated using the accelerometer data. The analysis was carried out using the two data sets recorded for the same haul truck over a period of 4 hours.

The accelerometer measured exposure to Whole Body vibrations involved calculation of the Root Mean Square (RMS) values for each of the instantaneous axial vibration as indicated in equation (5.1), in accordance with ISO 2631-1(1997).

$$a_w = \left[\frac{1}{T}\int_0^T a_w^2\,(t)dt\right]^{\frac{1}{2}} = \left[\frac{1}{T}\sum_{i=0}^{T} a_w^2 . t\right]^{\frac{1}{2}} \qquad (4.1)$$

Where, a_w(t) = weighted acceleration as a function of time (in meters per second squared)

T = duration of measurement

This led to an equivalent acceleration value (a_v), derived for the RMS method, by weighting factors k_x ,k_y= 1.4 for x and y axes and k_z=1 for z axis as per equation (4.2). These k_x and k_y weighting factors indicate a larger human body impact even with relatively smaller vibration exposures along the x and y directions.

$$a_v = \left[k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2\right]^{\frac{1}{2}} \qquad (4.2)$$

In order to calculate similar exposure equivalence using the VIMS strut data set, the difference in each pitch, roll and LF strut pressure event was considered for the analysis as follows.

$$\mathrm{D}\ \mathrm{Roll} = \mathrm{Roll}_{(i)} - \mathrm{Roll}_{(i-1)} \qquad (4.3)$$

$$\mathrm{D}\ \mathrm{Pitch} = \mathrm{Pitch}_{(i)} - \mathrm{Pitch}_{(i-1)} \qquad (4.4)$$

$$\mathrm{D}\ \mathrm{LF} = \mathrm{LF}_{(i)} - \mathrm{LF}_{(i-1)} \qquad (4.5)$$

Where $\mathrm{Roll}_{(i)}$ = instantaneous value of roll at ith second

$\mathrm{Roll}_{(i-1)}$ = instantaneous value of roll at (i -1)th second

$\mathrm{Pitch}_{(i)}$ = instantaneous value of pitch at ith second

$\mathrm{Pitch}_{(i-1)}$ = instantaneous value of pitch at (i -1)th second

$\mathrm{LF}_{(i)}$ = instantaneous value of LF strut pressure at ith second

$\mathrm{LF}_{(i-1)}$ = instantaneous value of LF strut pressure at (i -1)th second

Since the VIMS data set was recorded at 1 Hz, equivalence was determined for each of the parameters using a similar root mean square method reflected in equations (4.6), (4.7) and (4.8).

Time considerations accounted for the instances where variations occurred for each of the truck motion parameters.

$$\Delta Roll_{eq} = \left[\frac{1}{T}\sum_{i=0}^{T} \Delta Roll_i^2 . t\right]^{\frac{1}{2}} \qquad (4.6)$$

$$\Delta Pitch_{eq} = \left[\frac{1}{T}\sum_{i=0}^{T} \Delta Pitch_i^2 . t\right]^{\frac{1}{2}} \qquad (4.7)$$

$$\Delta LF_{eq} = \left[\frac{1}{T}\sum_{i=0}^{T} \Delta LF_i^2 . t\right]^{\frac{1}{2}} \qquad (4.8)$$

Where T= total measurement duration

And t = time for an instantaneous measurement (1second in this case)

In order to consider a correlation between the acceleration and truck motion parameters, the two data sets were initially analyzed under two separate cases for RMS method of evaluation.

Case 01:

Both data sets were divided into segments of 20 minutes for the entire measurement period, and the RMS equivalents Xeq, Yeq, Zeq, D Roll eq, D Pitch eq, D LF eq were calculated for each 20 minute segment.

Case 02:

The procedure followed for case 01 was carried out similarly, but with the use of 60 minute segments from the two data sets.

It was generally considered a minimal coefficient of determination (r^2) of 0.71 is required for a correlation to be acceptable at 50% probability (0.71 x 0.71 = 0.5 for correlation among two independent variables). However, r^2 values greater than 71% will not always be significant evidence for acceptable correlation since the no of data points is an important parameters when considering the validity of a correlation. Due to this reason, the correlations between the RMS acceleration equivalence and truck motion equivalence were considered using regression, correlation coefficients after which the validity of results were experimented through a statistical t-test analysis which considered both the r^2 values as well as the number of data points.

4.2 RMS equivalence analysis results

The initial analysis at 20 minute segments indicated a poor correlation between parameters. In a further analysis, a very high deviation was identified for one of the measurement segments; identified as a period in which VIMS provided the same data continuously. The subsequent data was then removed from both data sets.

The RMS equivalence for case 1 then indicated a high correlation between LF motions and Z-axis vibrations while a possible correlation between roll motion and Y-axis vibrations. X-axis vibration did not indicate any correlation with pitch motion.

When evaluated by 60 minute segments, correlations between Roll vs Y-axis vibration and LF strut motion vs Z-axis vibration increased significantly while X-axis vibration continued to show poor correlation with pitch motion. Since there were only 4 data points obtained from the 60 min segment analysis, the results for Case 01 and Case 02 were plotted together as in Figures 4.1, 4.2 and 4.3 to visually evaluate the combined correlation.

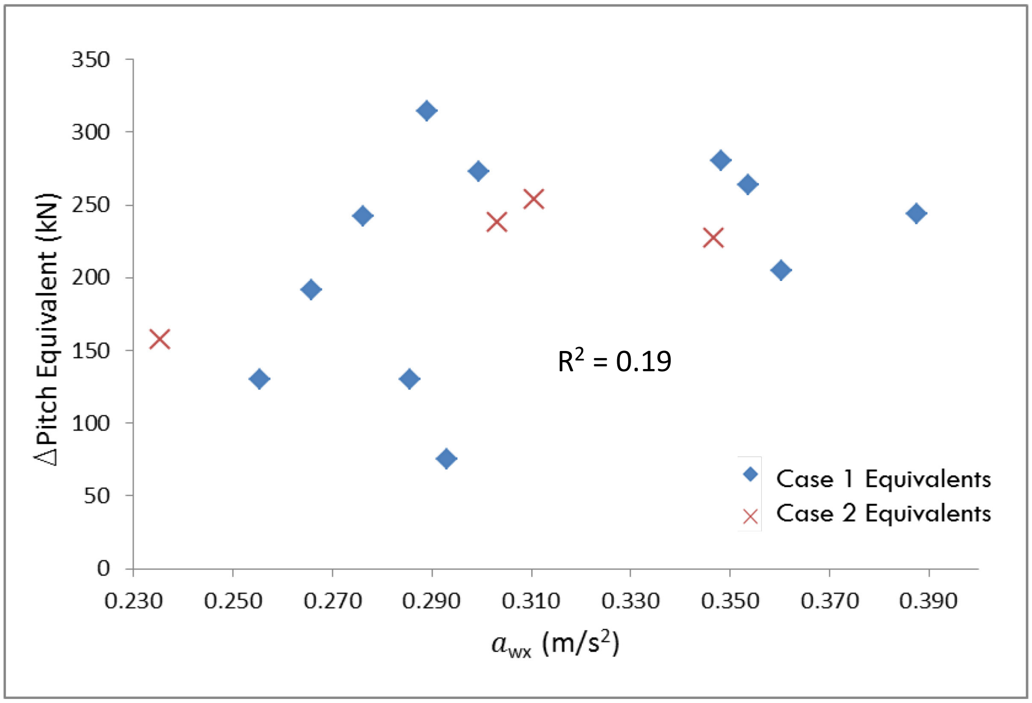


Figure 4.1: RMS Analysis combined for both 20 and 60 minute equivalents (Pitch vs X-axis)

The combined results indicated a poor correlation for X-axis acceleration vs pitch motion as illustrated in Figure 4.1.

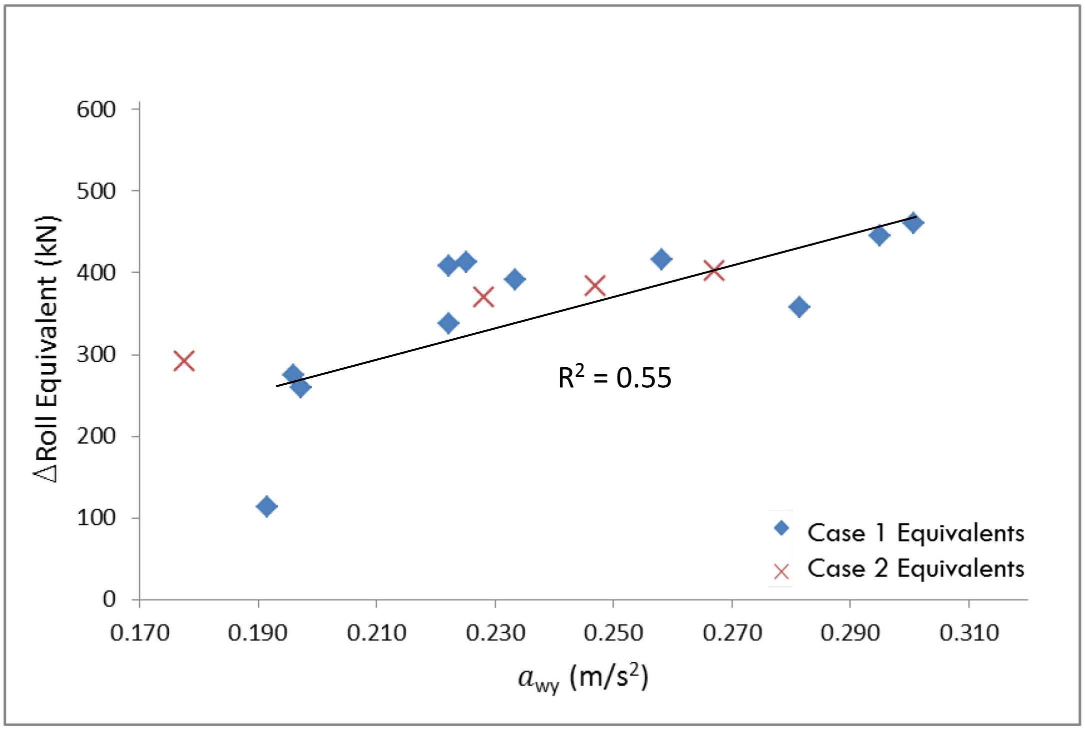


Figure 4.2: RMS Analysis combined for both 20 and 60 minute equivalents (Roll vs Y-axis)

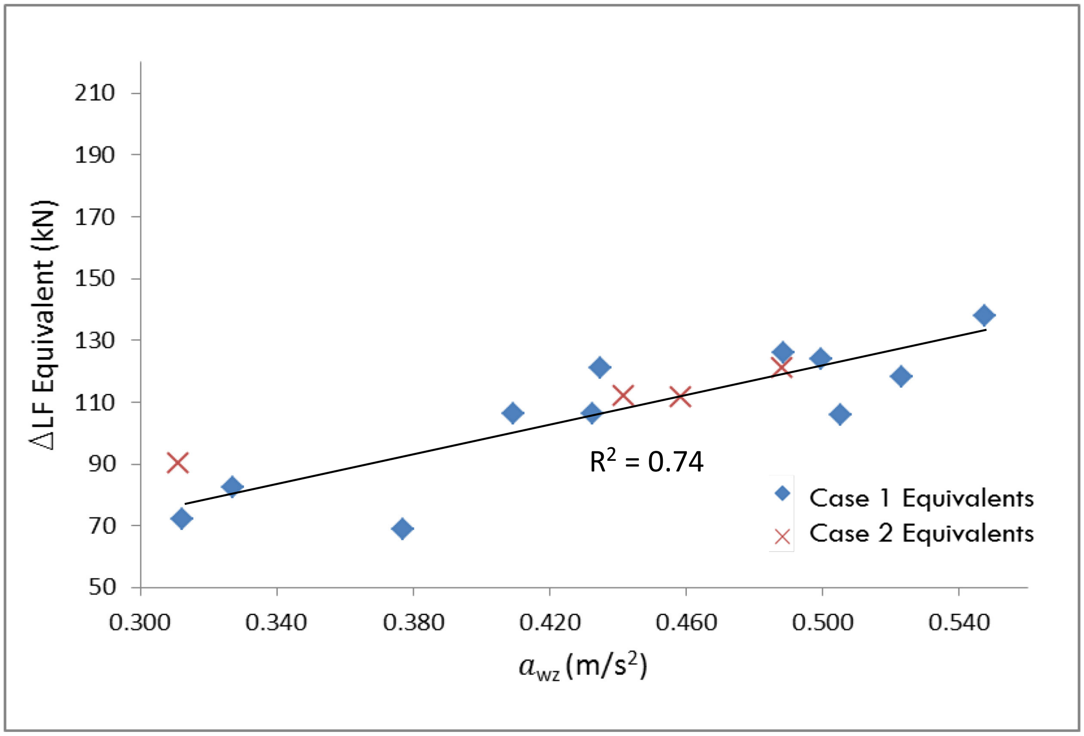


Figure 4.3: RMS Analysis combined for both 20 and 60 minutes equivalents (LF strut vs Z-axis)

In the case of Roll motion vs Y-axis acceleration, a possible correlation was indicated as in Figure 4.2 while a strong relationship was observed in the variation of LF strut and Z-axes equivalence as per Figure 4.3.

4.3 VDV equivalent analysis

A Crest Factor (CF) via ISO 2631-1 was calculated based on the ratio between the maximum instantaneous acceleration in a measurement period (A_{max}) and the RMS value for the measurement period (A_{eq}). In cases where CF >9, the RMS method or a general evaluation was considered to be insufficient in portraying the effects of high magnitude peaks within a sample and hence Vibration Dosage Method (VDV) was used. The VDV method for evaluation is generally used only when the CF for a vibration data set is >9. According to the analysis carried out using the RMS method for an entire set, it was evident that the CF value was less than 9 for all 3 axes,

Table 4.1: Crest Factor (CF) evaluation of the data set

Parameter	**x - axis**	**y - axis**	**z - axis**
$A_{eq}(m/s^2)$	0.3	0.23	0.43
$A_{max}(m/s^2)$	2.27	0.93	2.12
CF (A_{eq}/A_{max})	7.52	4.01	4.93
	< 9	< 9	< 9

Even though the VDV method for evaluation was generally used only when the CF for a vibration dataset was > 9, the vibration data set and truck motion parameters were evaluated to a 4th power averaging method used for VDV in Cases 3 and 4 described below.

$$VDV = \left[\int_0^T a_w^4\,(t)dt\right]^{\frac{1}{4}} = \left[\sum_{i=0}^{T} a_w^4 . t\right]^{\frac{1}{4}} \qquad (4.9)$$

Where, a_w(t) = weighted acceleration as a function of time (in m/s^2)

Equation (4.9) indicates the VDV equivalent for an accelerometer measured axial vibration dataset, while similar VDV equivalence were developed for the truck motion parameters as follows,

$$VDV\ \Delta Roll\ = [\sum_{i=0}^{T} \Delta Roll_i^4 . t]^{\frac{1}{4}} \tag{4.10}$$

$$VDV\ \Delta Pitch\ = [\sum_{i=0}^{T} \Delta Pitch_i^4 . t]^{\frac{1}{4}} \tag{4.11}$$

$$VDV\ \Delta LF\ = [\sum_{i=0}^{T} \Delta LF_i^4 . t]^{\frac{1}{4}} \tag{4.12}$$

Where T= total measurement duration

And t = time for an instantaneous measurement

Case 03:

Similar to Case 01, both data sets were divided into segments of 20 minutes and VDV equivalents VDV_X, VDV_Y, VDV_Z, $VDV_{D\ Roll}$, $VDV_{D\ Pitch}$ and $VDV_{D\ LF}$ were calculated. VDV values for vibration were plotted against the VDVs equivalence for truck motion parameters.

Case 04:

The procedure for Case 03 was repeated but with 60 minute segments.

After the equivalence were plotted and analyzed, correlation was evaluated between the parameters using regression and correlation co-efficient.

4.4 VDV equivalent analysis results

Similar to the RMS analysis, the previous resultant equivalents from cases 3 and 4 were plotted in Figures 4.4, 4.5 and 4.6.

Considering the VDV analysis for 20 minute and 60 minute segments no correlation was indicated when compared X-axis VDV equivalence versus Pitch. The scenario was similar to what was previously observed for RMS equivalence of the two variables.

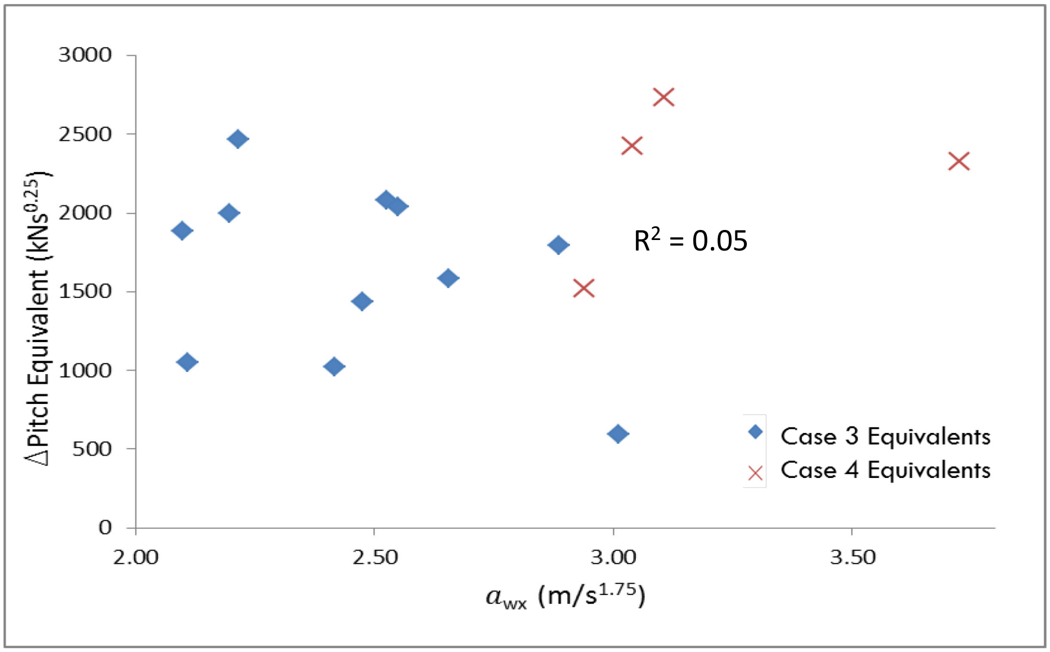


Figure 4.4: VDV analysis combined for 20 and 60 minute segments (Pitch vs X-axis)

In the case of Y-axis vibration vs roll motion and Z-axis vibration vs LF strut motion strong correlations were indicated using VDV equivalence. These resultant plots are indicated in Figure 4.5 and 4.6.

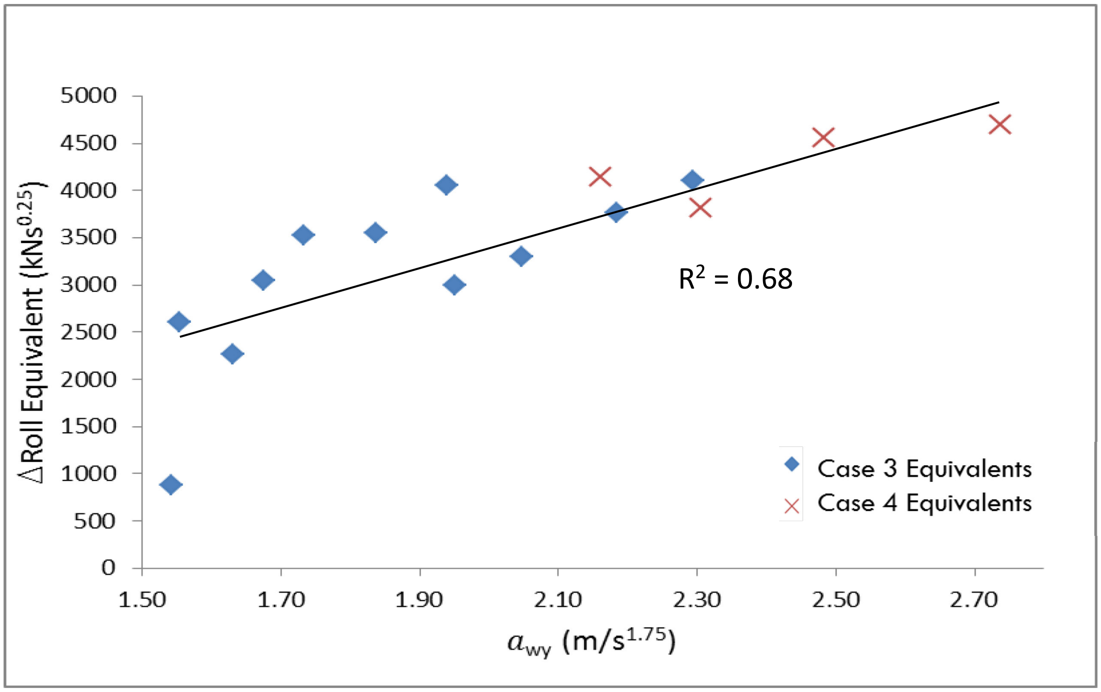


Figure 4.5: VDV analysis combined for 20 and 60 minute segments (Roll vs Y-axis)

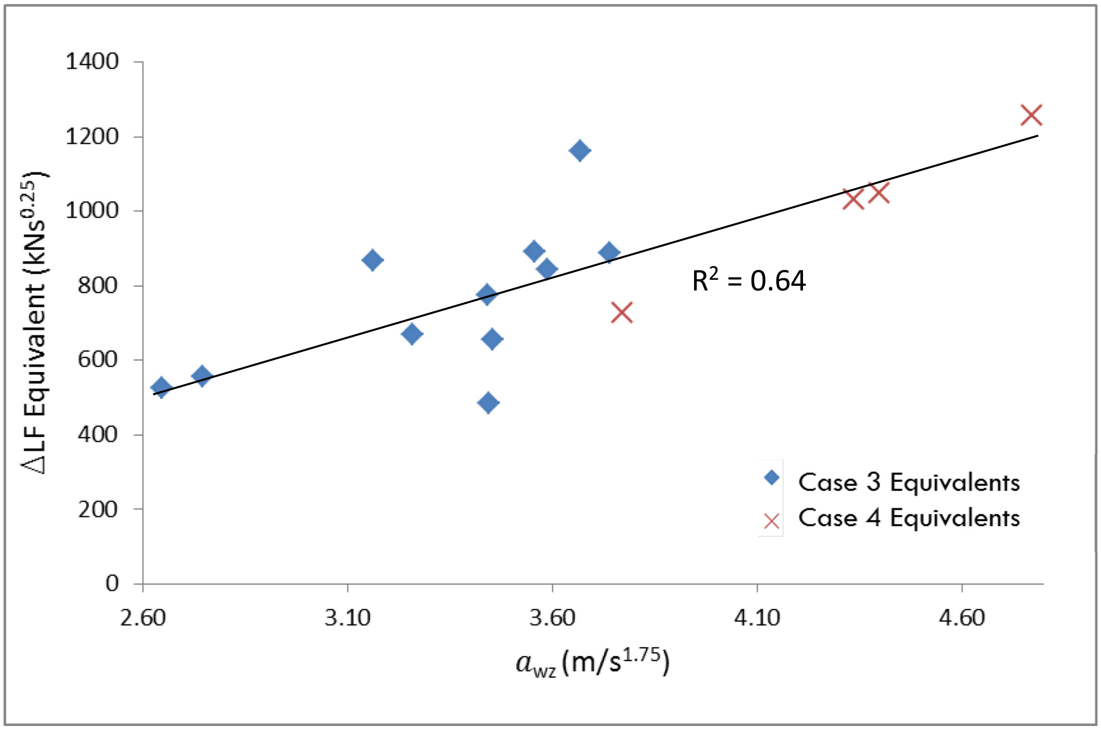


Figure 4.6: VDV analysis combined for 20 and 60 minute segments (LF strut vs Z-axis)

4.5 Validation via statistical evaluation

On discerning the correlations, a statistical analysis was used to determine the degree of acceptability of the observed correlations.

Initially to determine a degree of acceptable correlation, a confidence level was set at 95% ($\alpha = 0.05$).

Variables used for the hypothesis test were defined as follows,

For a Null Hypothesis $H_0 : \rho = 0$

For an Alternative Hypothesis $H_A : \rho \neq 0$

Where ρ is the population correlation coefficient for each instance.

A test statistic for the analysis was calculated using equation (4.13).

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} \tag{4.13}$$

Where n = number of trials

r = Coefficient of Linear Correlation

After calculating the t-value, a corresponding P-value was determined using a t-table with (n-2) degrees of freedom, where (n-2) degrees of freedom was used due to the two variables estimated in a linear correlation of two parameters.

The purpose of the P-value was to determine the likelihood of obtaining a test statistic (t) as a limit if the null hypothesis were found true. The data analysis tool pack in Microsoft Excel was used to calculate the corresponding statistical parameter, with the results summarized in Table 4.2. The P-values were compared with the initially selected $\alpha = 0.05$ (95% confidence level) and extended to an $\alpha = 0.1$ (90% confidence level). In instances where the P-value was smaller than significance level α, the null hypothesis (ρ = 0) was rejected, as concluding evidence was sufficient for a linear correlation between the compared variables. When the P-value was greater than α, a conclusion was made that the evidence was insufficient to suggest a linear correlation among the two variables.

Studying the results shown in Table 4.2, for both RMS and VDV equivalence analysis, it is evident that for all scenarios analyzed, the Pitch motion equivalence vs X-axis vibration does not indicate an acceptable P-value; therefore the null hypothesis is accepted, that no correlation exists.

A comparative analysis for RMS equivalence of roll motion vs Y-axis vibration resulted in a P-value of 0.018 at 20 minute segments and 0.022 at 60 minute segments which indicated sufficient evidence to accept the alternative hypothesis, thus accepting a correlation between the parameters. The Z-axis vibration equivalence vs LF strut force equivalence indicated even smaller P-values of 0.001 and 0.023 for 20 minute and 60 minute segments respectively, indicating again an acceptable correlation between the parameters. When the RMS equivalence from both scenarios were analyzed together, the above indicated correlation between roll motion vs Y-axis vibrations and LF strut motion with Z-axis vibration resulted in acceptable P-values at the selected 95% confidence level, while X-axis vibration continued to indicate poor correlation with pitch motion equivalence. Overall, the RMS results indicated an increase of confidence in correlation for larger time segments. Considering the VDV equivalence for Roll vs Y-axis when again evaluated a high correlation at 20 minute segments, even though there was a decrease at 60 minute segments. Additional calculations performed at the 90% confidence level indicated similar acceptable correlations.

Table 4.2: Statistical validation of results using Student's t-test

Analyzed Scenario	Variables analyzed	Number of Observations (n)	Degrees of freedom (n-2)	R	R^2	Test Statistic (t)	Two taled P- Value	P -Value	(P - α) at Significance Level (α=0.05)	(P - α) at Significance Level (α=0.1)
RMS equivalents (20 min intervals)	a_{wx} vs D Pitch Eq.	11	9	0.390	0.152	1.272	0.235	0.471	-0.421	-0.371
	a_{wy} vs D Roll	11	9	0.741	0.550	3.315	0.009	0.018	0.032	0.082
	a_{wz} vs D LF	11	9	0.870	0.757	5.301	0.000	0.001	0.049	0.099
RMS equivalents (60 min intervals)	a_{wx} vs D Pitch Eq.	4	2	0.805	0.648	1.918	0.195	0.390	-0.340	-0.290
	a_{wy} vs D Roll	4	2	0.989	0.979	9.541	0.011	0.022	0.028	0.078
	a_{wz} vs D LF	4	2	0.989	0.977	9.258	0.011	0.023	0.027	0.077
All RMS equivalents	a_{wx} vs D Pitch Eq.	15	13	0.434	0.188	1.737	0.106	0.212	-0.162	-0.112
	a_{wy} vs D Roll	15	13	0.741	0.549	3.974	0.002	0.003	0.047	0.097
	a_{wz} vs D LF	15	13	0.860	0.739	6.073	0.000	0.000	0.050	0.100
VDV equivalents (20 min intervals)	a_{wx} vs D Pitch Eq.	11	9	0.361	0.130	1.160	0.276	0.552	-0.502	-0.452
	a_{wy} vs D Roll	11	9	0.742	0.550	3.318	0.009	0.018	0.032	0.082
	a_{wz} vs D LF	11	9	0.645	0.416	2.532	0.032	0.064	-0.014	0.036
VDV equivalents (60 min intervals)	a_{wx} vs D Pitch Eq.	4	2	0.286	0.082	0.422	0.714	1.428	-1.378	-1.328
	a_{wy} vs D Roll	4	2	0.795	0.632	1.855	0.205	0.410	-0.360	-0.310
	a_{wz} vs D LF	4	2	1.000	0.999	47.119	0.000	0.001	0.049	0.099
All VDV equivalents	a_{wx} vs D Pitch Eq.	15	13	0.231	0.054	0.857	0.106	0.212	-0.162	-0.112
	a_{wy} vs D Roll	15	13	0.819	0.671	5.149	0.002	0.003	0.047	0.097
	a_{wz} vs D LF	15	13	0.799	0.638	4.785	0.000	0.000	0.050	0.100

🟩 Correlation acceptable according to the Student t-test by significance level

🟥 No significant correlation according to the Student t-test

🟨 No acceptable correlation according to the Student t-test, but a visual correlation evident

Contrary to RMS results, the VDV data indicated a reduced in correlation when evaluated for longer time period segments. This may be a result of the VDV method being more sensitive to high magnitude instantaneous peak values measured. The VDV method also indicated an acceptable P value for Z-axis vibration equivalence vs LF force equivalence at both the 20 and 60 minute evaluated intervals, while the analysis summary containing all VDV equivalence show acceptable P values, indicating a correlation between LF force equivalence vs Z-axis vibration equivalence and Roll motion force equivalence vs Y-axis vibration equivalence.

CHAPTER 05

Verification of results and validation

This chapter contains the details of an independent site data collection and analysis conducted after the initial analysis, in order to verify and validate the correlations suggested. A suitable WBV measurement equipment was selected and calibrated after which, data was collected from two independent mine site visits.

5.1 Preliminary testing of the Whole Body Vibration measurement system

Data was required to confirm the indications of the initial data analysis. A new mine site location was selected and a new WBV measurement tool was acquired.

5.1.1 Selection of new WBV equipment

A tri-axial accelerometer, data logger and the necessary connection cables were identified as the equipment required to measure WBV exposure, purchased through Dalimar Instruments, a subsidiary of the PCB group, specializing in industrial products for acoustics & vibration measurement.

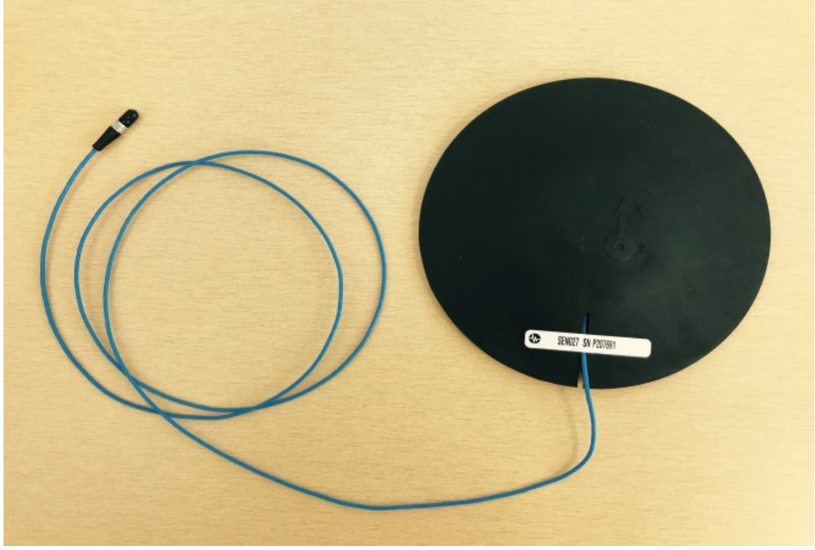


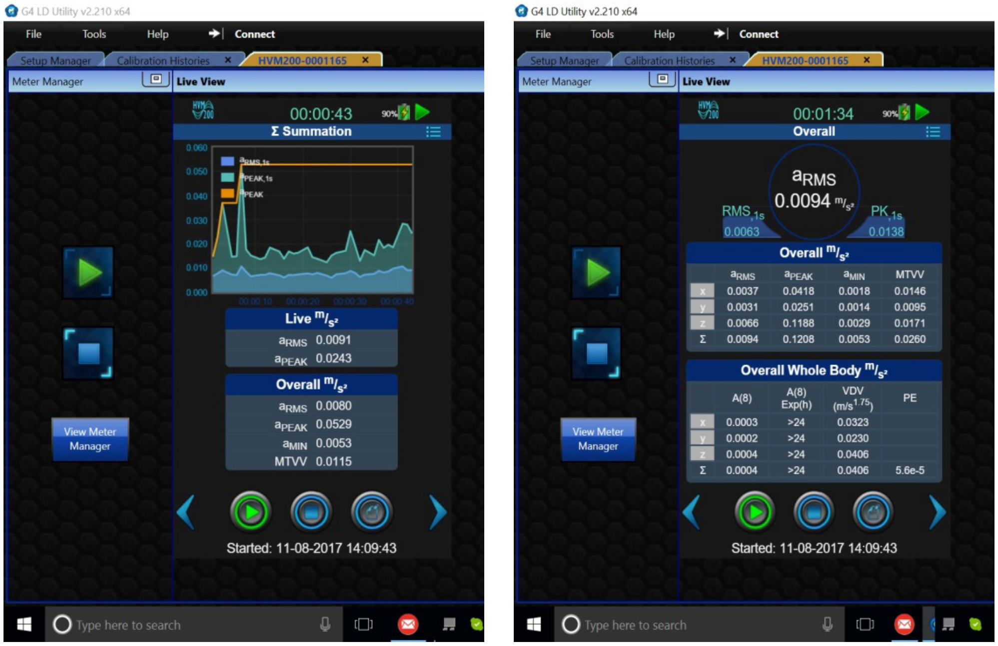
Figure 5.1: Sen 027 Tri-axial Accelerometer

The SEN027 Tri-axial Seat pad accelerometer was selected to match the needs of ISO10326-1 (Mechanical vibration: Laboratory method for evaluating vehicle seat vibration). When selecting the equipment in the similar performance in line with the equipment selected to data collection of the preliminary study was considered to maintain consistency. The design which includes a circular rubber pad casing the accelerometer minimized discomfort to the operator when the equipment was placed on the seat pad for measurement. The accelerometer had a measurement range of ±10g (98m/s$^{2)}$ and permitted frequencies from 0.5 to 1000 Hz to be recorded which was well within the required range for operator health and safety, identified as 0.5 to 80 Hz range. (ISO 2631-1, 1997)

Figure 5.2: HVM 200 Data logger

Figure 5.3: WBV Measurement Kit Setup

The HVM 200 was selected as the data logger which enabled the vibration signal to be filtered, processed and weighted in accordance with ISO 2631-1. The ability to record data in the field without a direct connection to a laptop was identified as a benefit with this device.



Live m/s²
aRMS 0.0091
aPEAK 0.0243

Overall m/s²
aRMS 0.0080
aPEAK 0.0529
aMIN 0.0053
MTVV 0.0115

Started: 11-08-2017 14:09:43

aRMS 0.0094 m/s²
RMS,1s 0.0063
PK,1s 0.0138

Overall m/s²

	aRMS	aPEAK	aMIN	MTVV
x	0.0037	0.0418	0.0018	0.0146
y	0.0031	0.0251	0.0014	0.0095
z	0.0066	0.1188	0.0029	0.0171
Σ	0.0094	0.1208	0.0053	0.0260

Overall Whole Body m/s²

	A(8)	A(8) Exp(h)	VDV ($m/s^{1.75}$)	PE
x	0.0003	>24	0.0323	
y	0.0002	>24	0.0230	
z	0.0004	>24	0.0406	
Σ	0.0004	>24	0.0406	5.6e-5

Started: 11-08-2017 14:09:43

Figure 5.4: Real time monitoring graphical representation (left) and instantaneous measurements displayed (right)

HVM 200 mobile control application was installed on a mobile device with Wi-Fi availability, sufficient to monitor and control the data recording process.

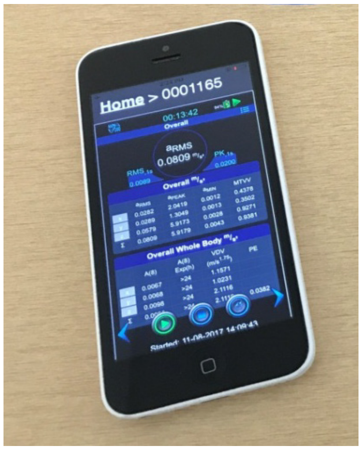


Figure 5.5: HVM200 App Running on a mobile phone

Additionally SWW-UTILITY-G4 software was acquired to monitor the HVM 200 status and for more detailed data analysis purposes on a laptop computer. It enabled the download of data from the HVM 200 and to generate graphs and reports. Full specifications and calibration records for the Whole Body Vibration Kit are appended in Appendix 2.

5.1.2 Calibration and Testing of the WBV measuring kit

Both the HVM 200 and the SEN027 accelerometer were calibrated and certified before purchase which eliminated any immediate need for calibration.

5.2 Site Visit - 1

After preliminary bench testing to verify the calibration was correct, the Whole Body Vibration measurement system was taken to a mine site to record data to clarify the correlations, previously identified using the initial sample data set. Due to site access restrictions because of health and safety concerns, the datasets recorded were carried without the presence of the researcher at the mine site. The site selected for the study was a major Copper Mine in British Colombia. The data was recorded by Finning Canada Ltd. on behalf of the researcher.

A Komatsu 830E truck was used to record experimental data. The strut diameters of the truck were identified to be 0.2794m for the front and rear struts. The onboard strut pressure was made available with KOMTRAX data management system.

5.2.1 Issues faced

Whole body vibrations were planned for measurement at the operator’s seat using a SEN027 tri-axial seat pad accelerometer and the HVM 200 data logger, while a laptop with SWW-UTILITY-G4 software was to be used to monitor the recording process.

Personnel from Finning Canada Ltd. in charge of recording the data were faced with numerous issues due to equipment failure. The onboard monitoring system on the selected mine haul truck had stopped recording data after 35 minutes from the start of the test procedure. As a result only 35 minutes of the total measured 5 hours of Whole Body Vibration data remained useful for comparison with the strut data from on board system. Furthermore the tri-axial accelerometer which needed to be positioned with X, Y axes directions oriented relative to the long axis of the truck, was not properly placed, which resulted in erroneous X, Y vibration data.

Discussions held with the Finning Canada Ltd personnel revealed that the data was also recorded by placing the accelerometer pad on the seat adjacent to the operators’ seat within the cabin, but not directly under the operator, leading to further mishaps surrounding the dataset.

5.2.2 Modified Equivalence Analysis

The two data sets from accelerometer and onboard system was later also identified in two different time zones, which was simply corrected. Further visual analysis was carried out to identify appropriate matches for the two data sets at points of significant identifiable peaks, to timestamp match the data.

Similar to the original dataset, the Copper mine collected dataset was analyzed to discern correlations between accelerometer equivalence and truck motion parameter equivalence. Due to the erroneous nature of X, Y axis orientation of the accelerometer, only the 35 minutes data sets for the Z axis vibration and LF strut force were actually used.

Case 01:

Both data sets were divided into segments of 10 minutes for the whole measurement period and the RMS equivalence Z_{eq} and D LF_{eq} were calculated for each segment. For further analysis on the sensitivity to high magnitude peaks, both data sets were again evaluated using the VDV method as indicated in Case 02.

Case 02:

Similar to Case 01, both data sets were divided to segments of 5 minutes and VDV equivalents VDV_X, VDV_Y, VDV_Z, $VDV_{D\ Roll}$, $VDV_{D\ Pitch}$ and $VDV_{D\ LF}$ were determined. VDV values of acceleration were plotted against the VDVs of truck motion parameters to evaluate correlation.

For each of the 2 cases, correlation coefficients and regression analyses were carried out seeking a viable relationship between the truck motion parameters and accelerometer response.

5.2.3 Results

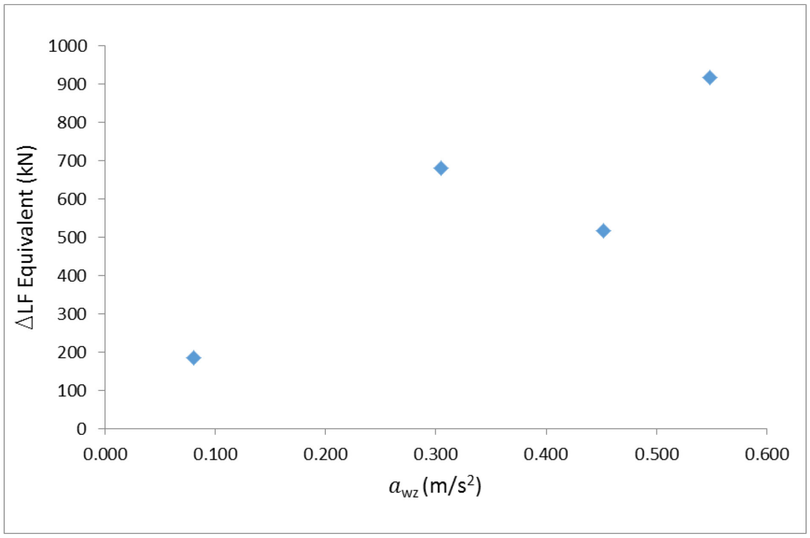


Figure 5.6: RMS Analysis equivalents (LF strut vs Z-axis)

The resultant plots for Cases 01 and 02 are provided in Figures 5.6 and 5.7. Even though a correlation of coefficient (R^2) of 0.75 and 0.89 were obtained respectively, since the analysis results were derived from 4 data segments, more data was needed for substantial outcome verification.

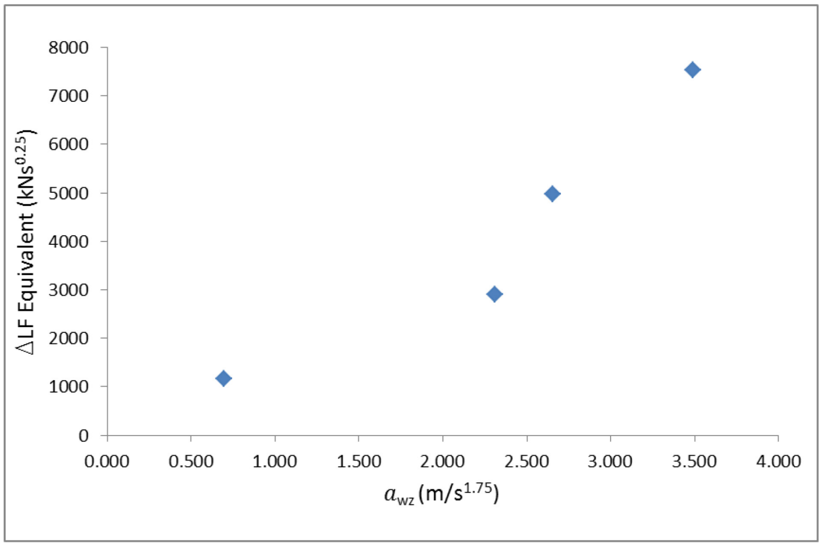


Figure 5.7: VDV analysis equivalents (LF strut vs Z-axis)

5.3 Site Visit -2

The multiple data collection issues that occurred during the first site visit were noted and precautionary measures were discussed with Finning Canada Ltd. and to position the site instrument setup and maximize the amount of productive data collected. The same set of measurement equipment was used for the data recording purpose and the data was recorded by Finning Canada Ltd. personnel at a Copper/Gold mine in British Columbia.

A CAT793F haul truck was used as the focus to record data with VIMS output available for onboard data recording. For pressure to force conversion purposes the Front and Rear Strut diameters were noted as 0.3429m and 0.3175m respectively. Data were recorded from the VIMS and the HVM tool for a period of 2 hours, where after overlapping the data using visual time stamps a reliable 90 minute data set was identified as suitable for further analysis.

5.3.1 Modified Equivalent Analysis

Both accelerometer and onboard suspension force sourced data sets were analyzed at different time intervals as follows, to verify the correlations identified in Chapter 04.

Case 01:

Both data sets were divided into segments of 10 minutes for the whole measurement period and the RMS equivalence X_{eq},Y_{eq}, Z_{eq} , D Roll$_{eq}$, D Pitch$_{eq}$, D LF$_{eq}$ were determined for each 10 minute segment.

Case 02:

The same procedure followed for case 01 was carried out using 30 min. segments from the datasets.

Case 03:

Similar to Case 01, both data sets were divided to segments of 10 minutes and VDV equivalents VDV_X, VDV_Y, VDV_Z, $VDV_{D\ Roll}$, $VDV_{D\ Pitch}$ and $VDV_{D\ LF}$ were calculated. VDV values of acceleration were plotted against the VDVs for the truck motion parameters.

Case 04:

The procedure for Case 03 was repeated with the use of 30 minute segments.

The respective equivalents were then plotted and analyzed for correlation between the identified parameters using regression and the correlation co-efficients.

5.3.2 Results

RMS analysis

Initial results for each of the sets parameters were plotted for all case pairs and due to the lack of segments for the 30 minute analysis data for Cases 01 and 02 were plotted together for each of the parameter sets to obtain a larger data set combined correlation for the RMS equivalence.

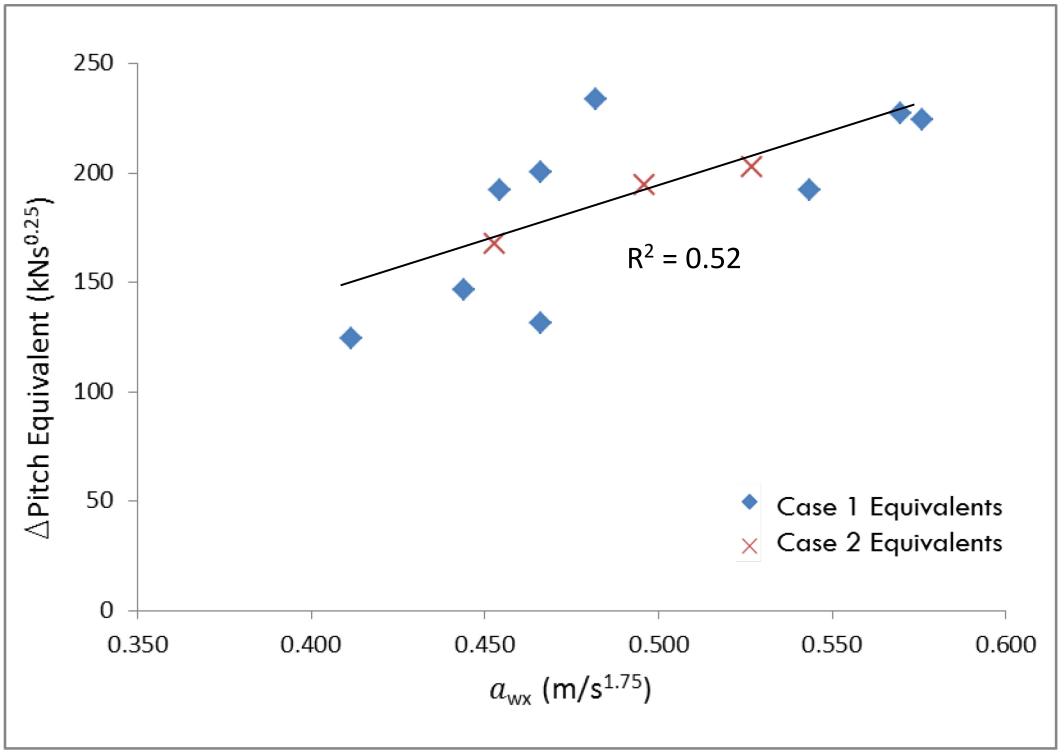


Figure 5.8: RMS Analysis combined for both 10 and 30 minute equivalents (Pitch vs X-axis)

As indicated in Figure 5.8, Pitch motion suggested a promising correlation with X-axis vibration, which was not primarily visible in the original data trialed. In the cases of Roll motion vs Y-axis and LF strut motion vs Z-axis vibrations, the correlations remained strong, in line with the observations of the initial trial study, indicated by Figure 5.9 and Figure 5.10.

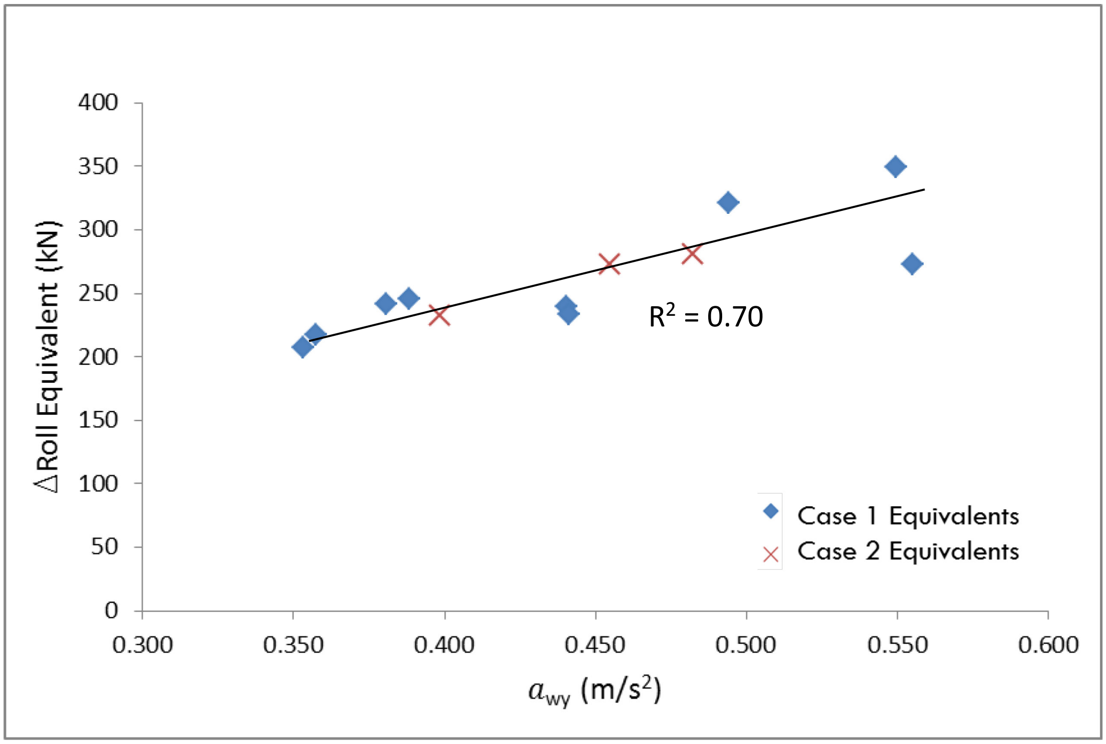


Figure 5.9: RMS Analysis combined for both 10 and 30 minute equivalents (Roll vs Y-axis)

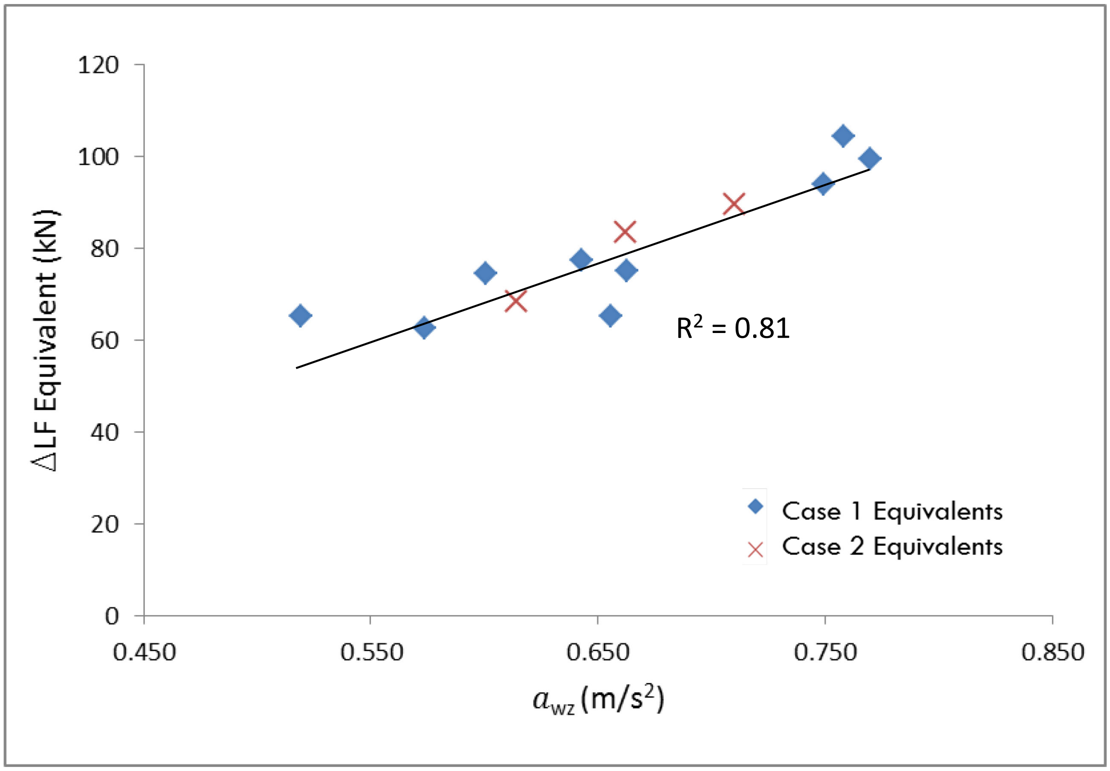


Figure 5.10: RMS Analysis combined for both 10 and 30 minutes equivalents (LF strut vs Z-axis)

VDV Analysis

With regard to the VDV equivalence analysis, it was observed that Roll vs Y-axis vibrations and LF strut vs Z-axis vibrations indicated strong correlations when considered independently at 30 and 10 minute segments. The correlations observed for Pitch motion against X-axis accelerations were poor at 10 minute evaluated segments.

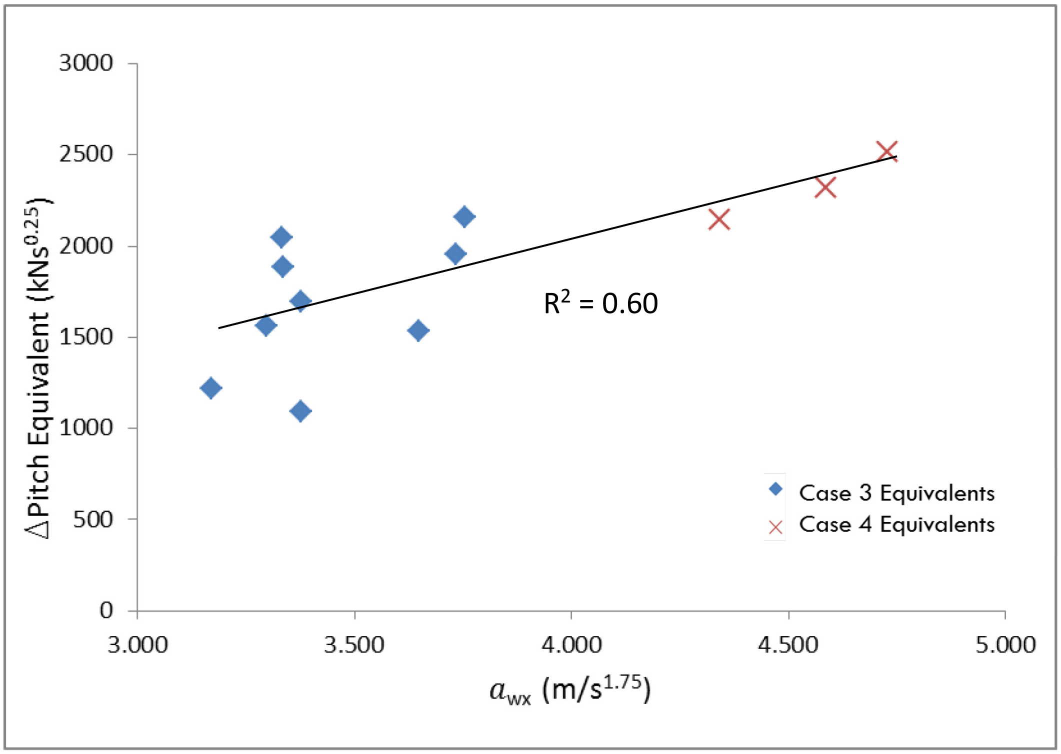


Figure 5.11: VDV analysis combined for 10 and 30 minute segments (Pitch vs X-axis)

An important observation was identified when using the VDV method, such that the value of the equivalence increases significantly with measurement duration; and as a result the equivalence for 10 and 30 minute period outcomes are evident within distant regions when plotted on a combined plot. However, it was noted that both Z and Y axes accelerations have significant linear correlation with LF and Roll motion respectively when in a combined correlation was considered as in Figures 5.11 and 5.12.

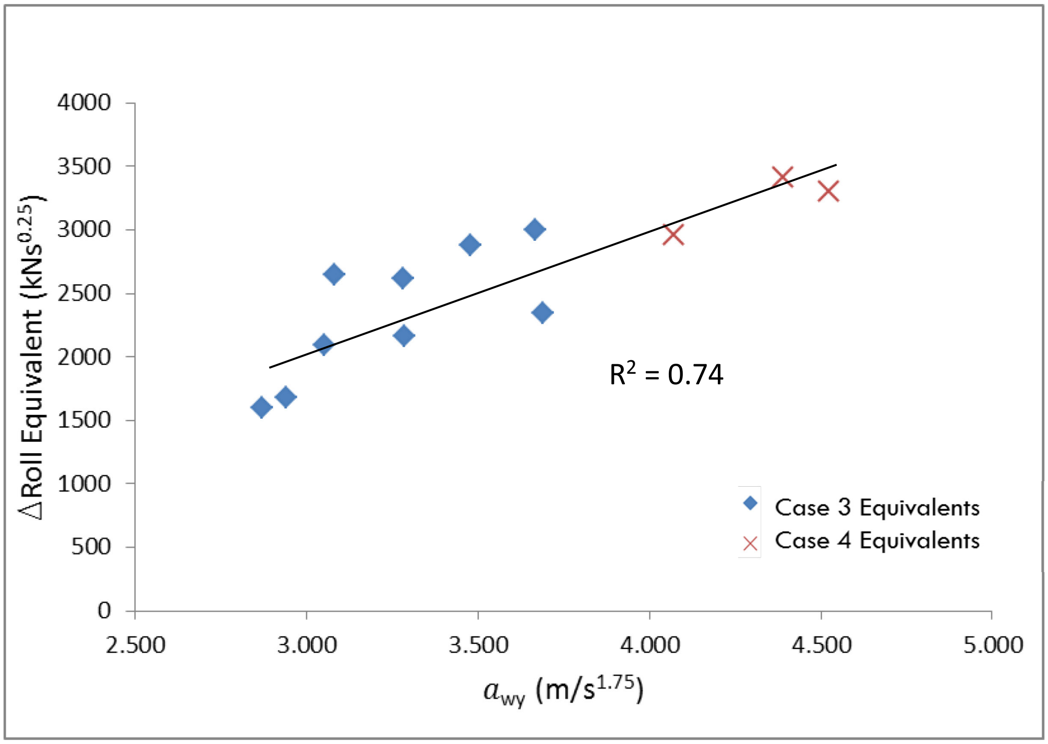


Figure 5.12: VDV analysis combined for 10 and 30 minute segments (Roll vs Y-axis)

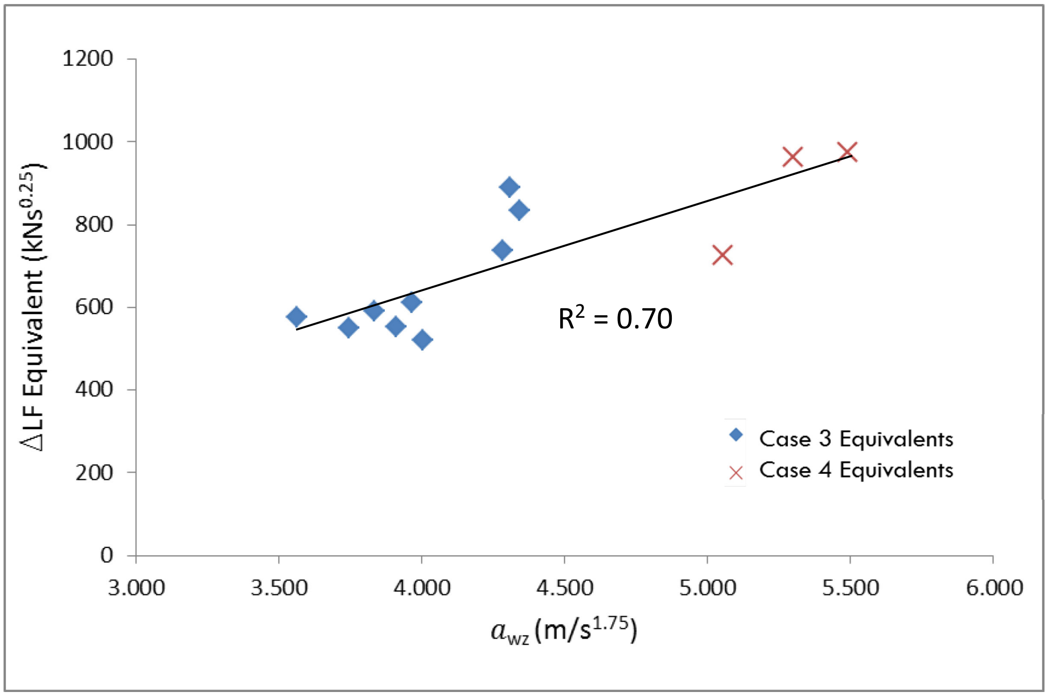


Figure 5.13: VDV analysis combined for 20 and 60 minute segments (LF strut vs Z-axis)

5.4 Validation with Statistical Evaluation

Similar to the t-test statistic approach used in Chapter 04, verification of acceptable results at 95% confidence level ($\alpha = 0.05$) as required for acceptable validity, was performed.

The variables for hypothesis testing were again defined as follows,

Null Hypothsis $H_0 : \rho = 0$

Alternative hypothesis $H_A : \rho \neq 0$

where ρ is the population correlation coefficient for each instant. Test statistic for analysis was calculated using equation (4.13).

After calculating the t-value, a corresponding P-value was again determined using a t-table with (n-2) degrees of freedom. (n-2) degrees of freedom were used due to the two unknowns estimated when determining a linear correlation among two parameters.

In instances where the P-value is smaller than significance level α, the null hypothesis ($\rho = 0$) was rejected concluding evidence is sufficient for a linear correlation between the compared variables. When the P-value was greater than α, a conclusion can be made that the evidence was insufficient to suggest a linear correlation between two variables.

According to Table 5.1 all 3 parameter sets show considerable correlation under both RMS and VDV equivalence analysis. These results indicate and align with strong correlation observed between Z-axis vibration vs LF strut motion and Y-axis vibration vs Roll motion during primarily seen in the initial data study.

Table 5.1: Statistical t-test analysis for correlation validation

Analyzed Scenario	Variables analyzed	Number of Observations (n)	Degrees of freedom (n-2)	R	R^2	Test Statistic (t)	Two taled P- Value	P -Value	(P - α) at Significance Level (α=0.05)
All RMS equivalents	a_{wx} vs D Pitch Eq.	12	10	0.721	0.520	3.291	0.008	0.015	0.485
	a_{wy} vs D Roll	12	10	0.831	0.690	4.718	0.001	0.002	0.498
	a_{wz} vs D LF	12	10	0.900	0.810	6.529	0.000	0.000	0.500
All VDV equivalents	a_{wx} vs D Pitch Eq.	12	10	0.775	0.600	3.873	0.003	0.006	0.494
	a_{wy} vs D Roll	12	10	0.860	0.740	5.335	0.000	0.001	0.499
	a_{wz} vs D LF	12	10	0.837	0.700	4.830	0.001	0.001	0.499

🟩	Correlation acceptable according to Student's t-test at selected Significance level
🟥	No significant correlation according to Student's t-test
🟨	No acceptable correlation according to Student's t-test but visual correlation identified

In addition, a further correlation can be observed between pitch motion and X-axis vibration as well which was not indicated in the initial dataset analyzed. This significant increase in correlation between Pitch motion and X-axis vibration, led the research here towards analyzing, the influencing phases of the haul cycle contributing to this phenomenon.

CHAPTER 06

Operational Phase Analysis

Using the results from of the second field data collection visit, this chapter considers a duty cycle by operational phase analysis approach, where the entire vibration and onboard suspension data sets are divided by operational phase of a haul duty cycle.

6.1 Methodology

The 2nd data collection recorded 3 haul cycles within a duration of 90 minutes. Plots of VIMS payload vs time and dynamic suspended load vs time for this are indicated in Figure 6.1.

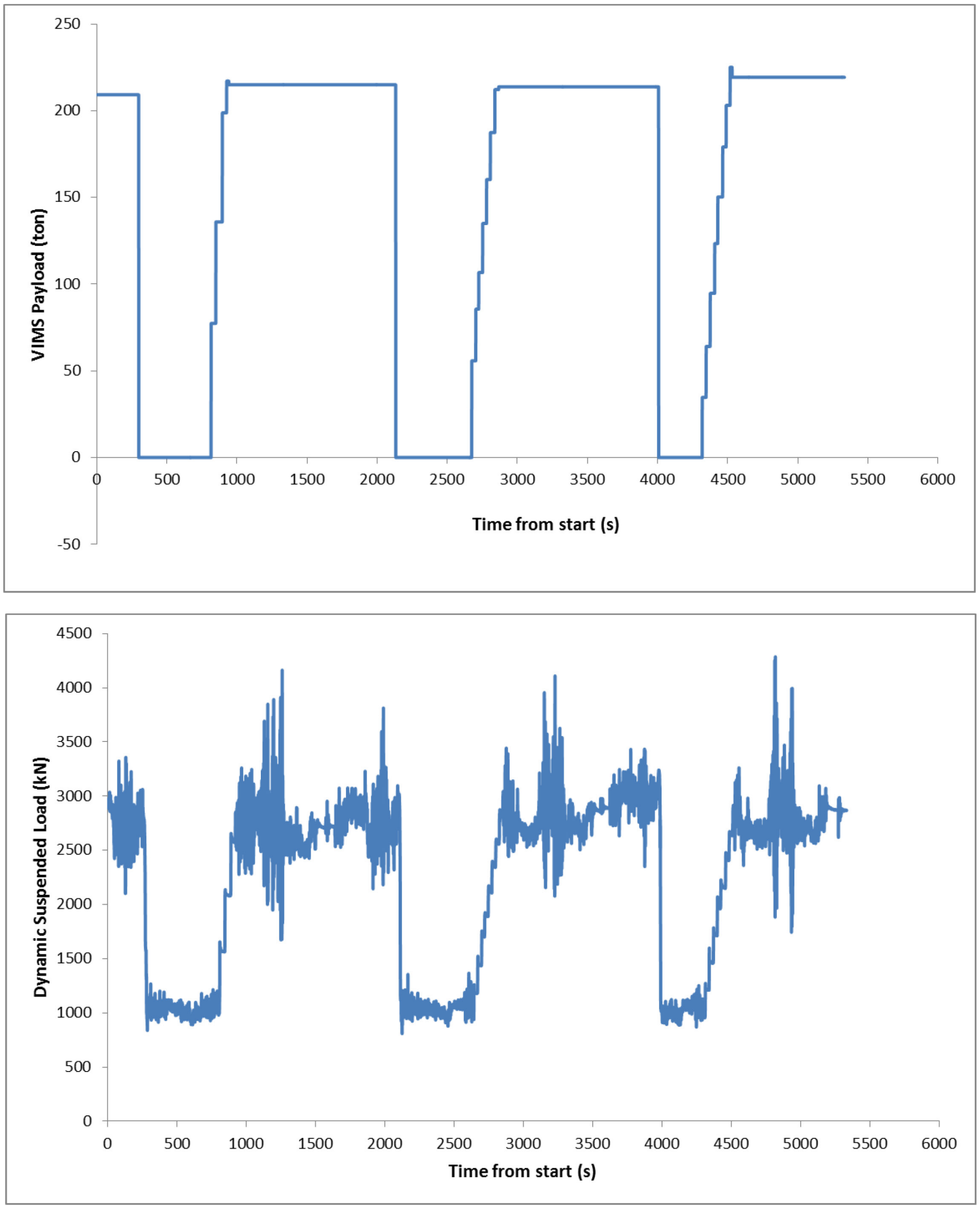


Figure 6.1: VIMS payload and Dynamic Suspended Load plotted against time

"Dynamic" or more accurately "locked-in recorded" load was determined a summation of instantaneous strut forces, since it provides a clear visualization of the forces at the suspension representing loaded and unloaded states.

Each of the three cycles was analyzed separately by duty cycle phase. Since the results were similar for all 3, the sample results indicated here are for one of the three haul cycles. In order to identify the loaded travel, unloaded travel, dumping and loading phases of the selected haul cycle, dynamic payload and ground speed for the truck were plotted in Figures 6.2 and 6.3.

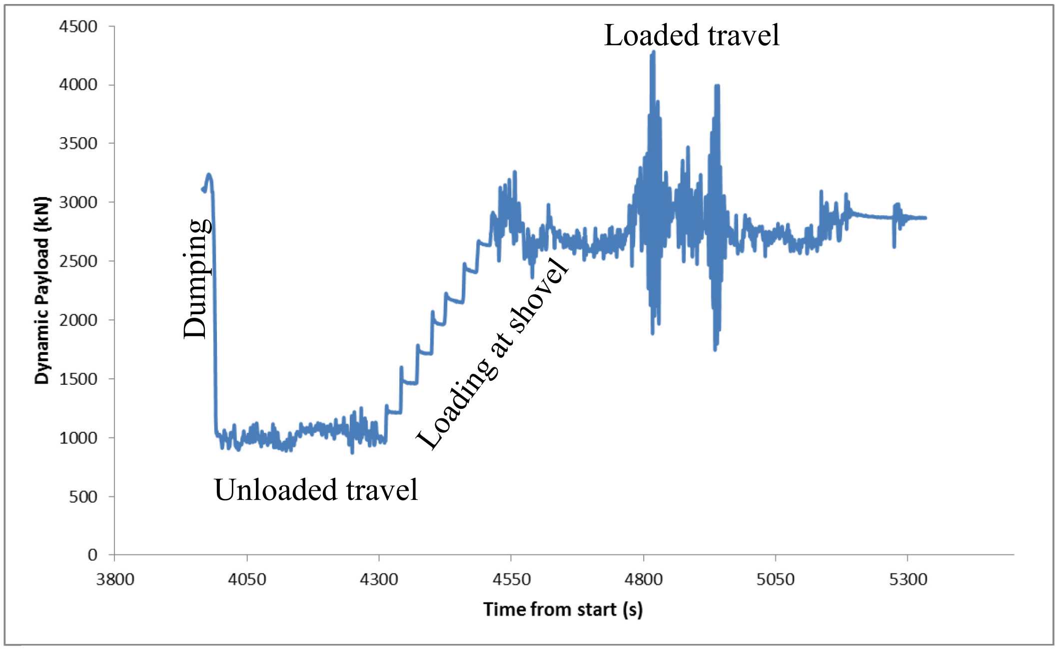


Figure 6.2: Dynamic Payload vs Time for the selected haul cycle

The variables considered for each phase analysis were RMS equivalence for Xeq, Yeq, Zeq, D Roll eq, D Pitch eq, D LF eq, where instead of deriving equivalence for by time segment, continuous RMS equivalence of the entire data set for each variables was considered at 1 second intervals (data recorded at 1Hz).

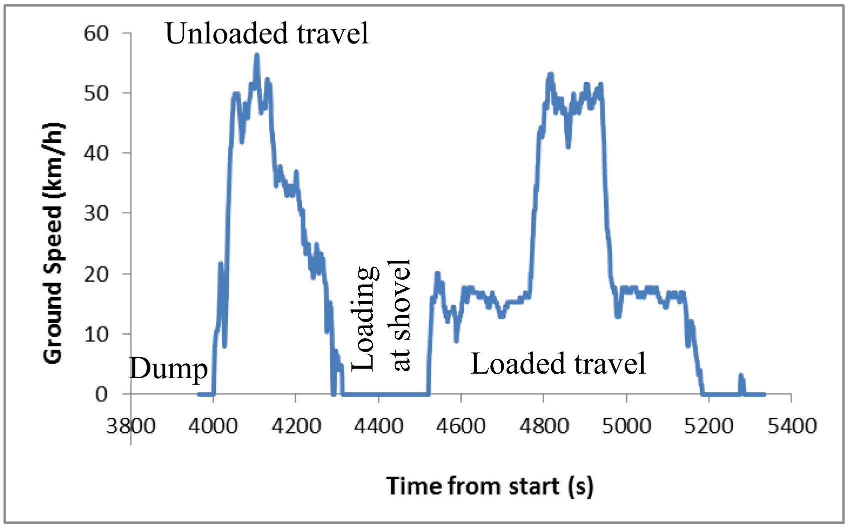
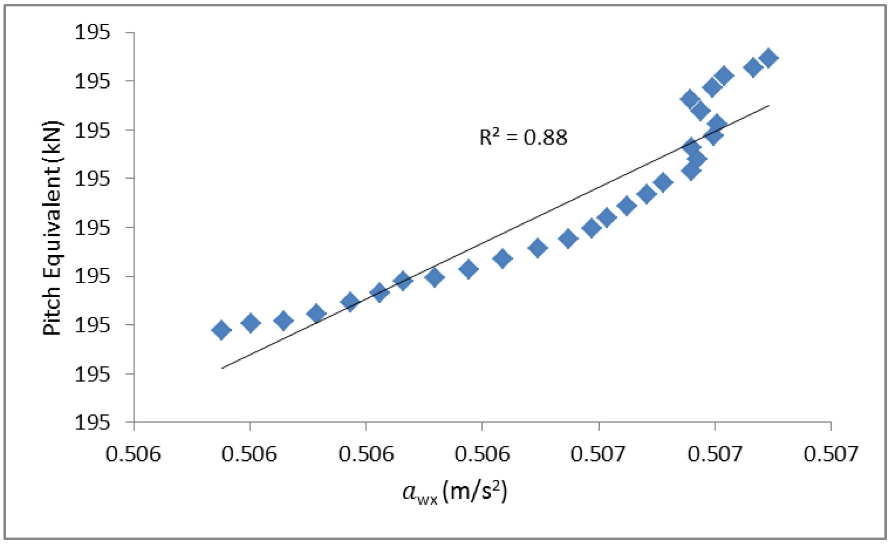


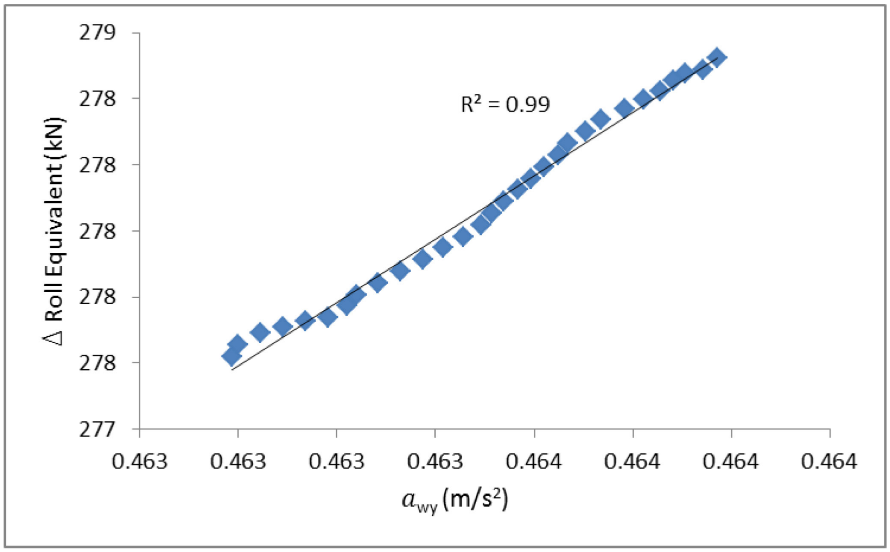
Figure 6.3: Ground speed vs Time for the selected haul cycle

6.1.1 Dumping Phase

Dumping phase of the haul cycle is the shortest time consuming per cycle, identified in the 3962 to 3996 second interval.

Figure 6.4 shows the plots for RMS equivalence for Xeq,Yeq, Zeq vs D Roll eq, D Pitch eq, D LF eq respectively. During the dumping phase, for each of the 3 sets of parameters considered, strong correlations were indicated, with an observed partial deviation in the outcome for of X-axis vibrations versus Pitch motions.





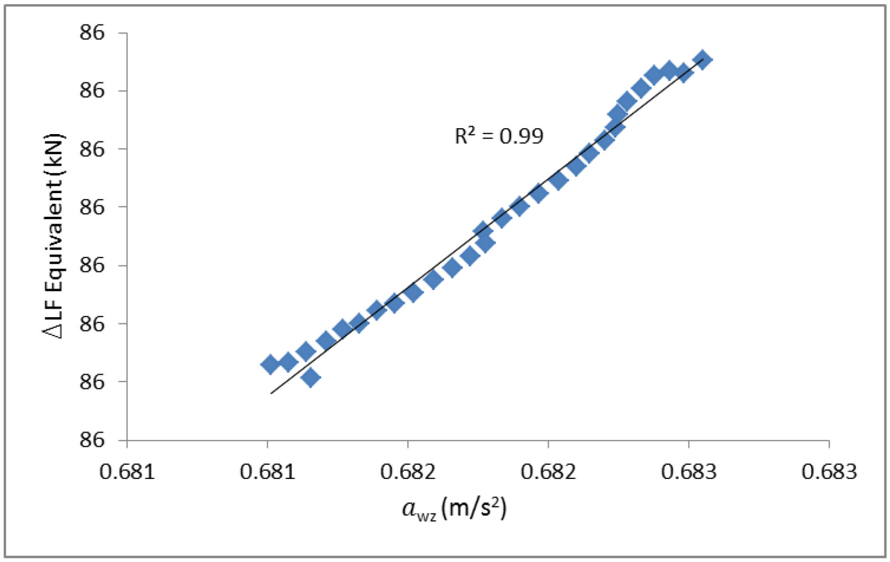


Figure 6.4: Variation of RMS equivalents for suspension parameters against accelerometer meter parameters for the Dumping phase

6.1.2 Unloaded Travel

In the 3995 to 4317 second phase, the truck was noted in motion in the unloaded condition. Per figure 6.5, the motion of the truck is indicated to operate at relatively high speed, continuously accelerating and decelerating throughout the phase, indicating changing road and operating conditions from dump to pit.

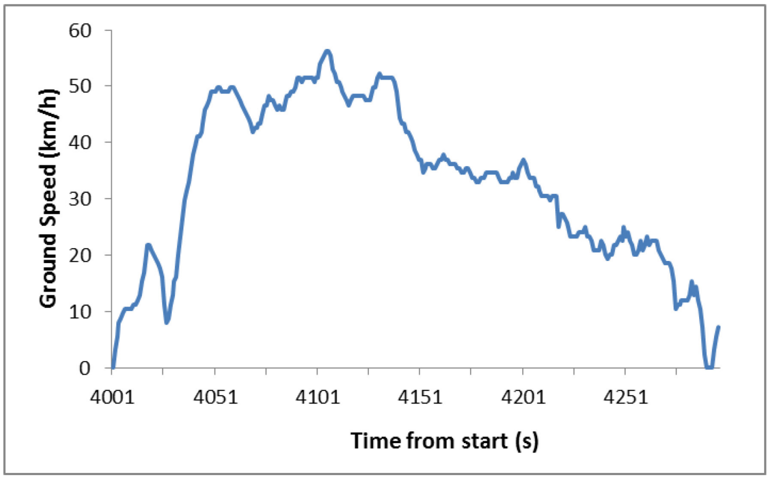


Figure 6.5: Ground Speed versus Time for the Unloaded Travel condition

Based on accelerations, decelerations and travelling at constant velocity the travel was divided into 4 regions of analysis.

- **3995 to 4050 second interval**

This sub phase of travel includes accelerations and decelerations with speeds ranging from within 8 to 23 kmph. It is evident that only part of the motion indicates that a correlation exists for X and Y axes vibrations versus pitch and roll motions, but not an acceptable correlation to be discerned. In the case of Z-axis vs LF strut motion a strong correlation exists per Figure 6.6.

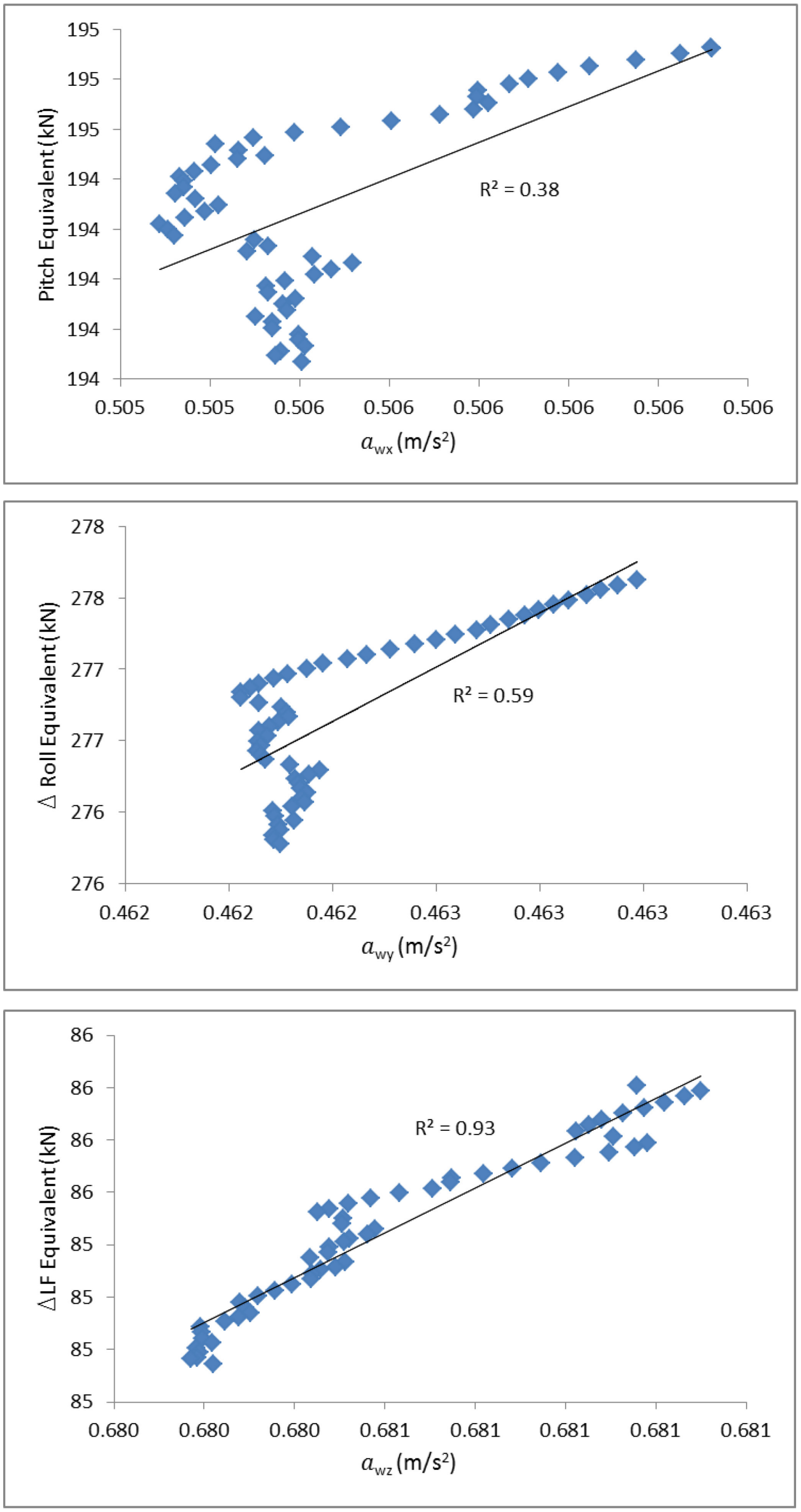


Figure 6.6: Correlation analysis for 3995 to 4050 seconds interval of unloaded travel

- **4050 to 4150 second interval**

This sub-phase of unloaded travel indicated a period of acceleration in which the haul truck speed increased from 20kmph to about 56kmph. During this phase of reach relatively higher velocity, all three parameter sets indicated strong correlation with a strong relationship visible for both Y and Z axis vibrations versus Roll and LF strut motions as per Figure 6.7.

- **4150 to 4250 second interval**

In this sub-phase, the speed of the truck ranges from 33 to 37 kmph in which the motion is effectively at constant speed. As indicated in Figure 6.8, the Z axis vibration indicated a strong positive correlation with LF strut motion, while X and Y vibrations indicated good similar correlations for a significant part of the motion.

- **4250 to 4317 second interval**

The last sub-phase of unloaded travel was deceleration motion, in which X and Y axis vibrations indicated a strong correlation to pitch and roll motions per Figure 6.9, while a poor correlation exists between Z axis and LF strut motion which may be a result of the additional effect extracted by braking, on the measuring equipment.

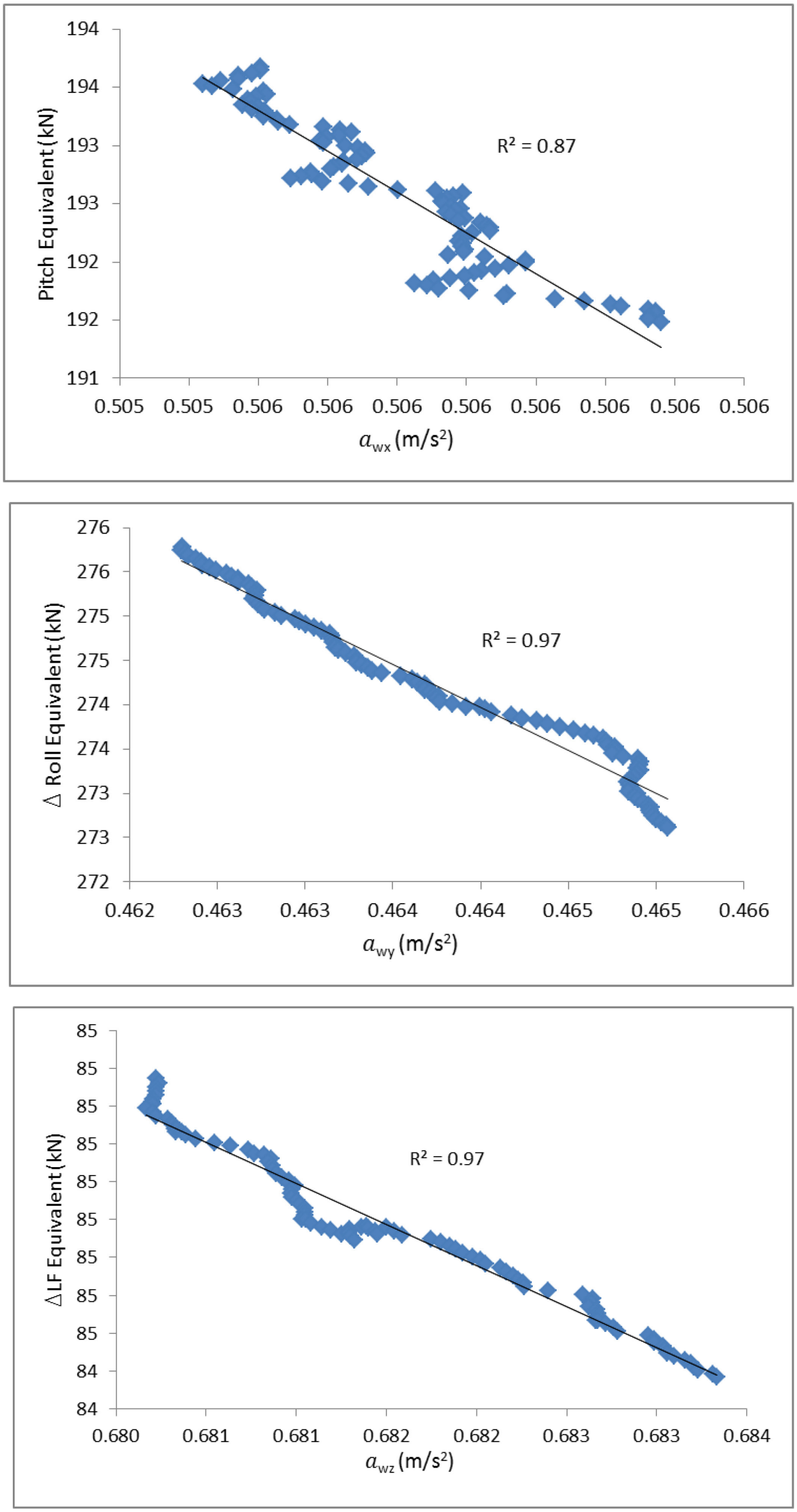


Figure 6.7: Correlation analysis for 4050 to 4150 seconds interval of unloaded travel

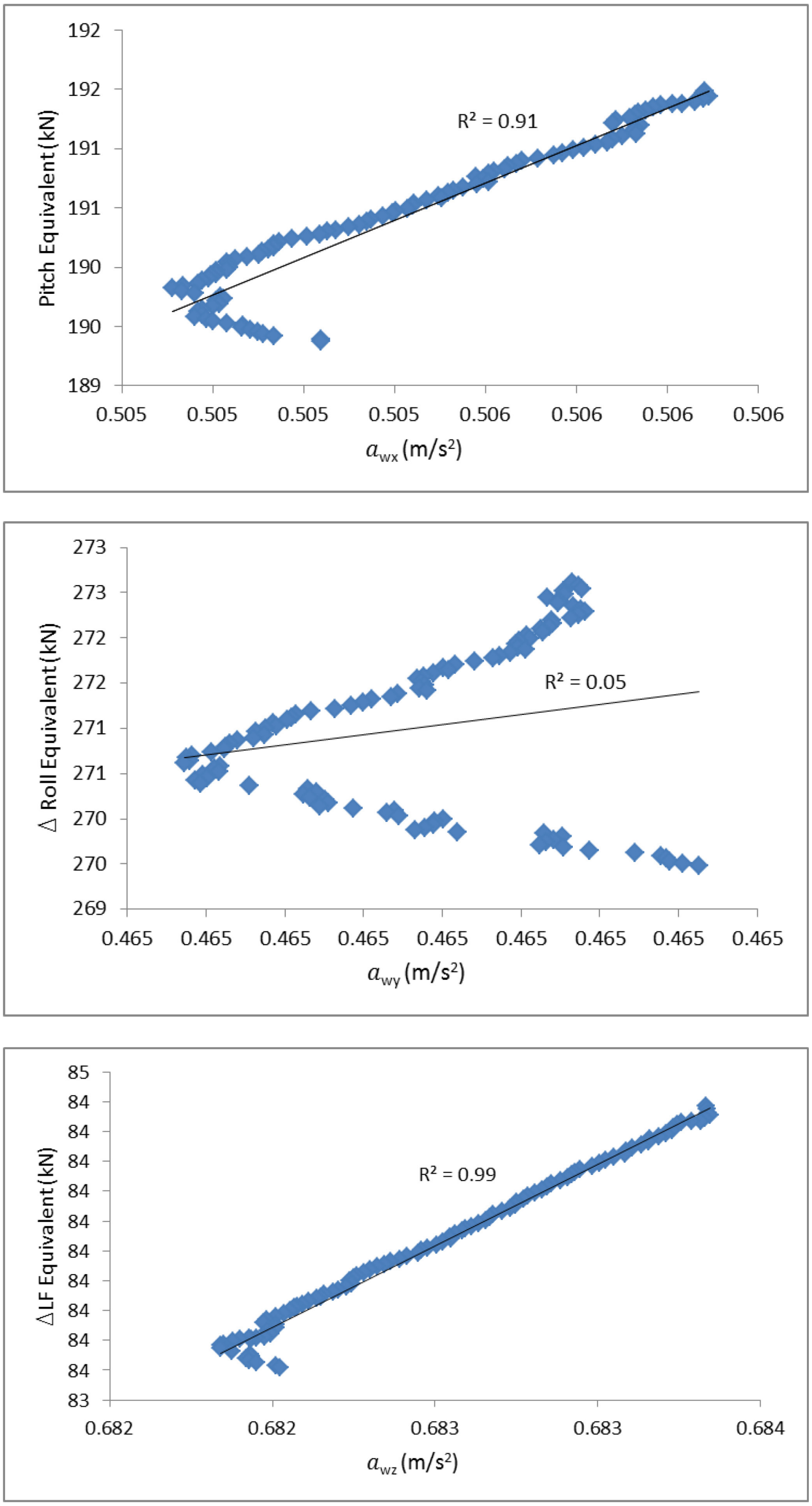


Figure 6.8: Correlation analysis for 4150 to 4250 seconds interval of unloaded travel

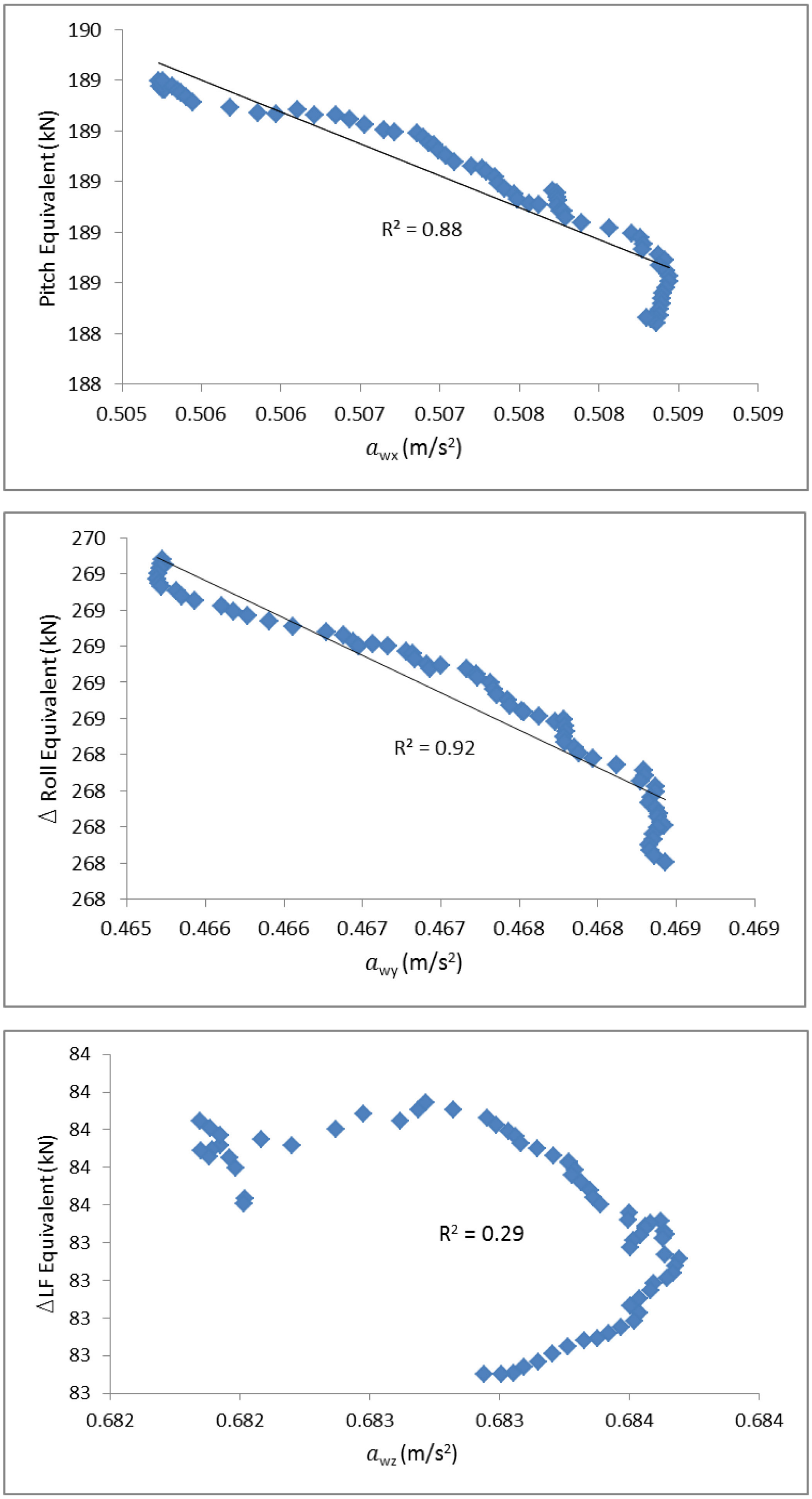


Figure 6.9: Correlation analysis for 4250 to 4317 seconds interval of unloaded travel

6.1.3 Loading Phase

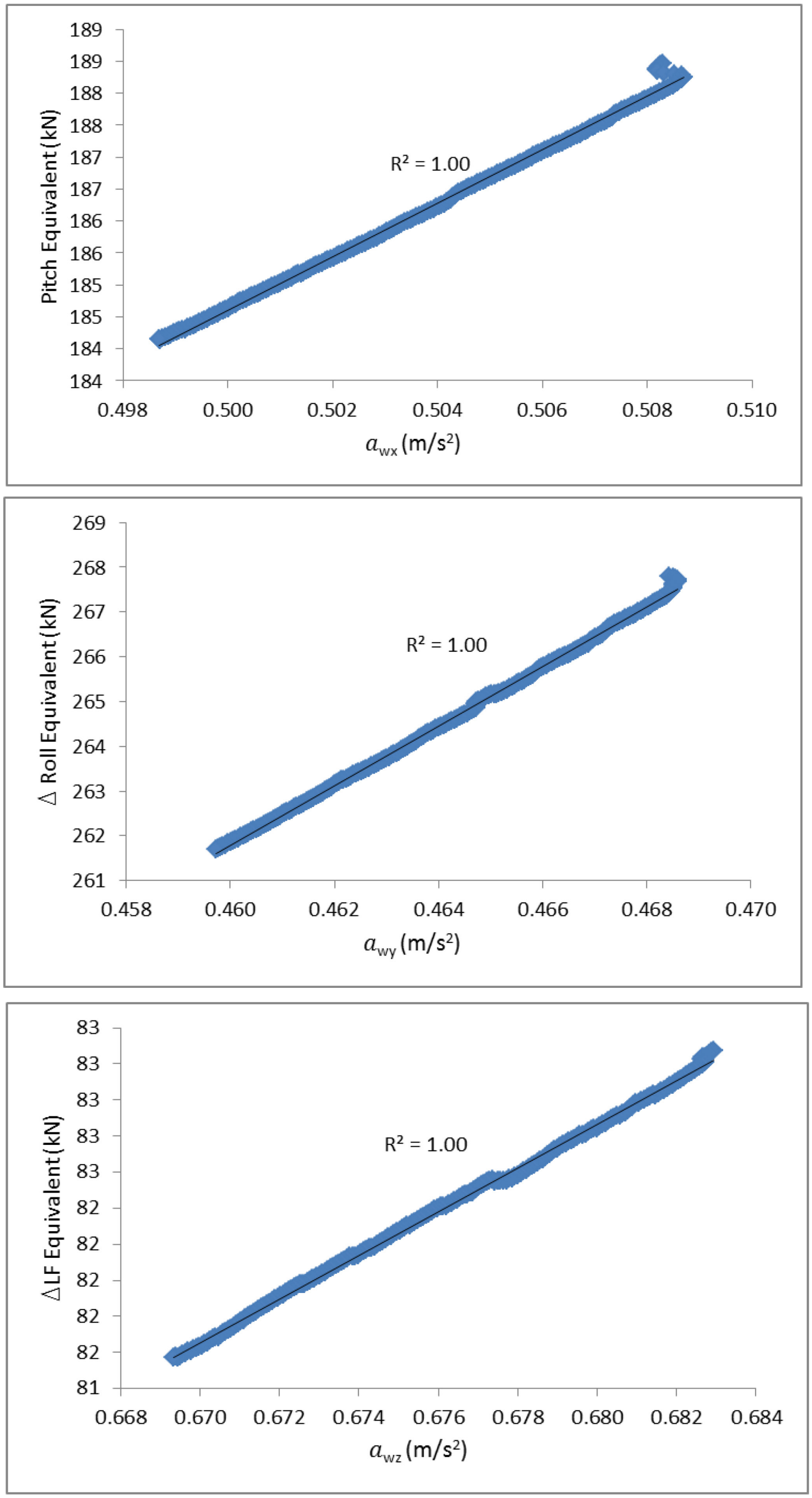


Figure 6.10: Correlation analysis for the phase of Loading

The loading phase was considered for the period when the truck is stationary in the pit while being loaded by an excavator. The time interval between 4313 to 4521 seconds was identified as the loading phase. The plots in this case also, in Figure 6.10, indicate strong correlations for all 3 sets of truck motion parameters vs the respective accelerometer axial vibration data.

6.1.4 Loaded Travel

The loaded travel phase was identified between 4525 to 5184 seconds, using ground speed vs time indicated in Figure 6.11.

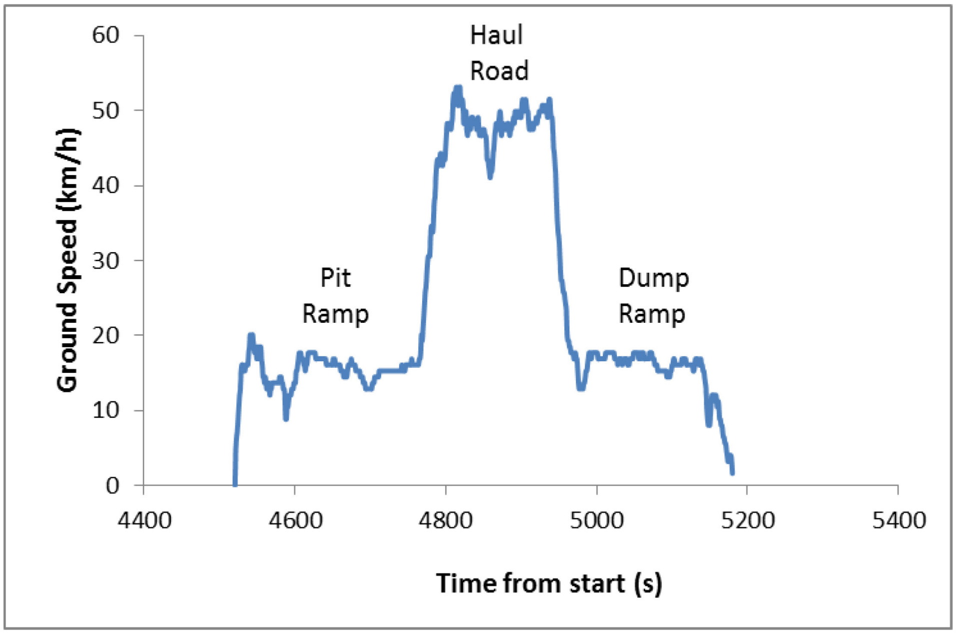


Figure 6.11: Ground Speed versus Time for the Loaded Travel condition

Based on Figure 6.11, 3 sub-phases of loaded travel within the loaded travel phase were identified. Each of the truck motion parameters and accelerometer equivalence were analyzed for the 3 sub-phases as follows.

❖ 4525 to 4760 second interval (on well-constructed pit ramp)

Within this interval the haul truck travels at an average speed of about 13kmph with speeds ranging from 8 to 20 kmph. Most of the travel time is experiencing minor accelerations and decelerations within the given speed range, typical of travelling on a ramp with switchbacks.

When considering this phase of loaded travel, it was evident that a strong correlation exists between all 3 of the considered parameter sets as per Figure 6.12.

❖ 4760 to 5003 second interval (along mine haul road)

Within this sub-phase the truck achieves an average velocity of about 47kmph with speeds ranging from 40 to 54 kmph. Decelerations and accelerations are also visible through this phase, likely due to operator's reactions to road conditions. Resultant graphs of the analysis are indicated in Figure 6.13.

Results indicated poor to no correlation between X-axis and Y-axis vibrations vs Roll and Pitch motion when travelling at high speeds. However, a correlation remained between Z-axis acceleration versus LF strut motion.

❖ 5003 to 5184 second interval (on the dump ramp)

Within this sub-phase the haul truck travels at an average speed of about 16kmph with speed ranging from 8 to 18 kmph. Similar to the first scenario of loaded ramp travel, a strong correlation exists between all 3 sets of variables considered in the analysis, as per Figure 6.14.

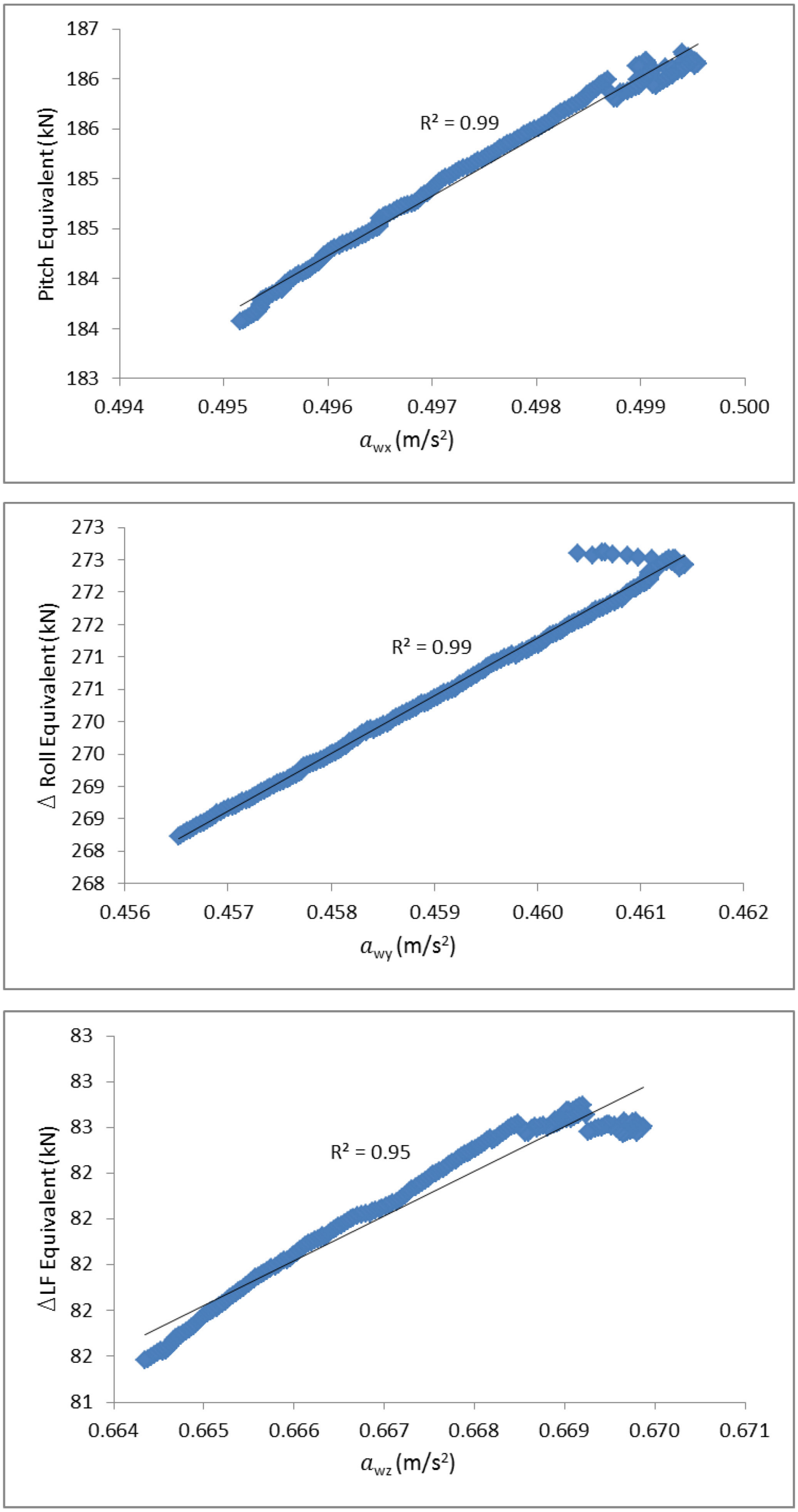


Figure 6.12: Correlation analysis for 4525 to 4760 seconds interval of loaded travel

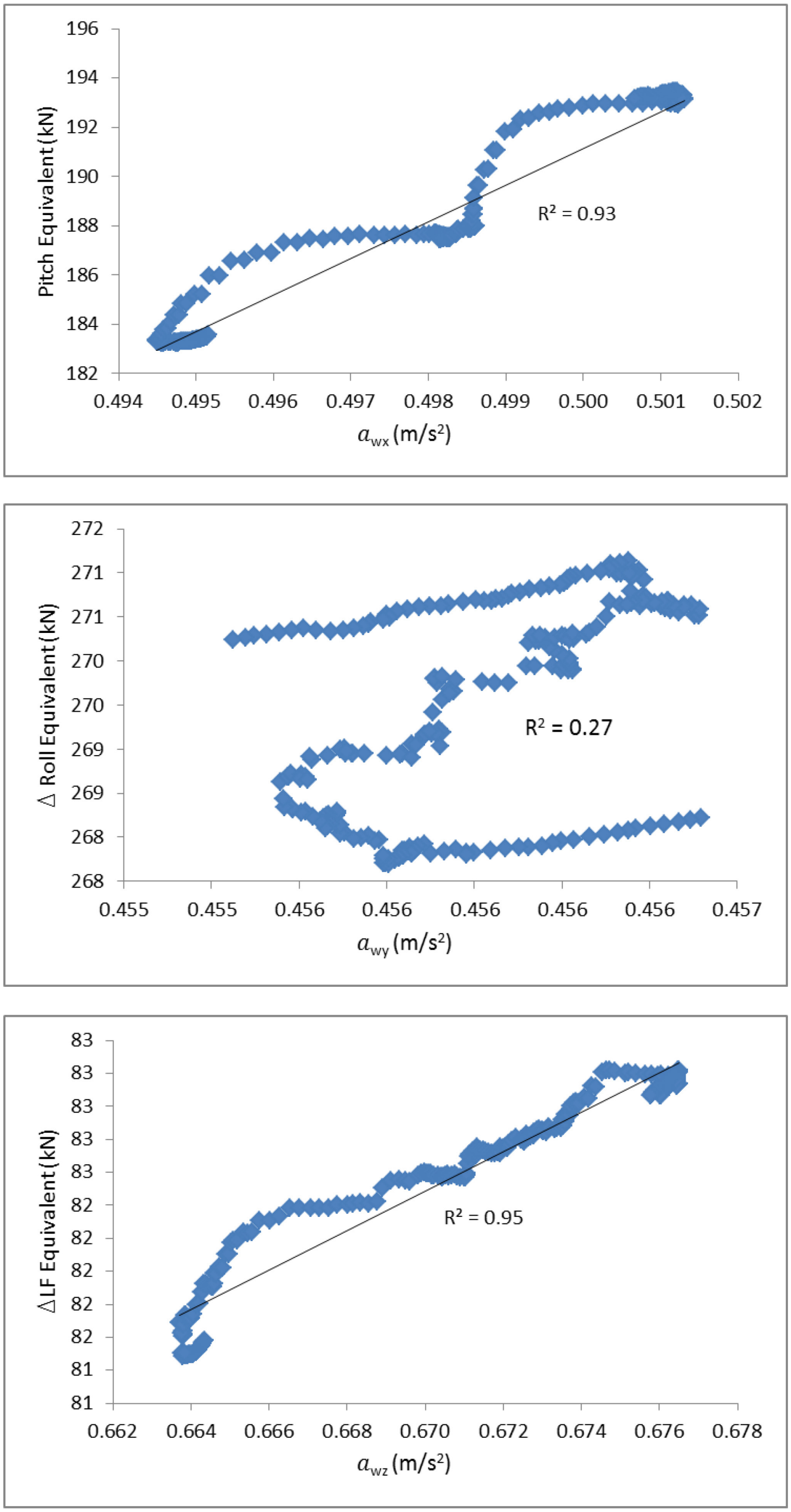
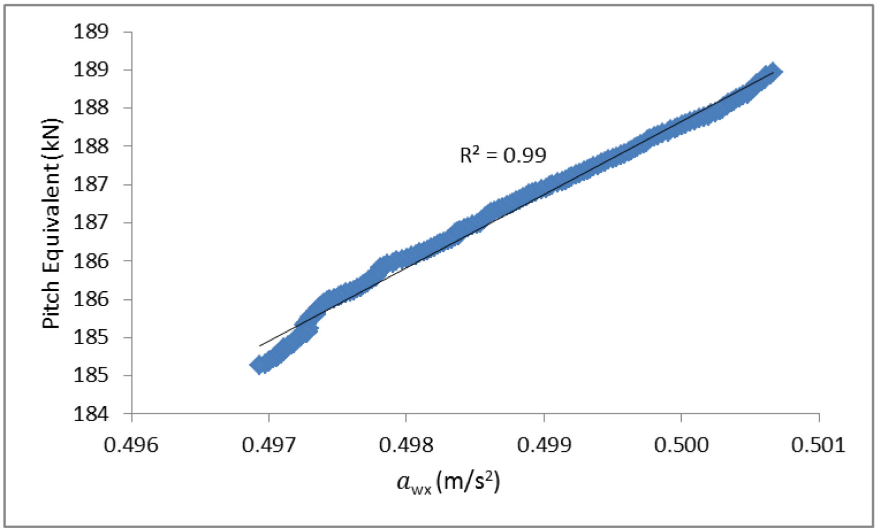
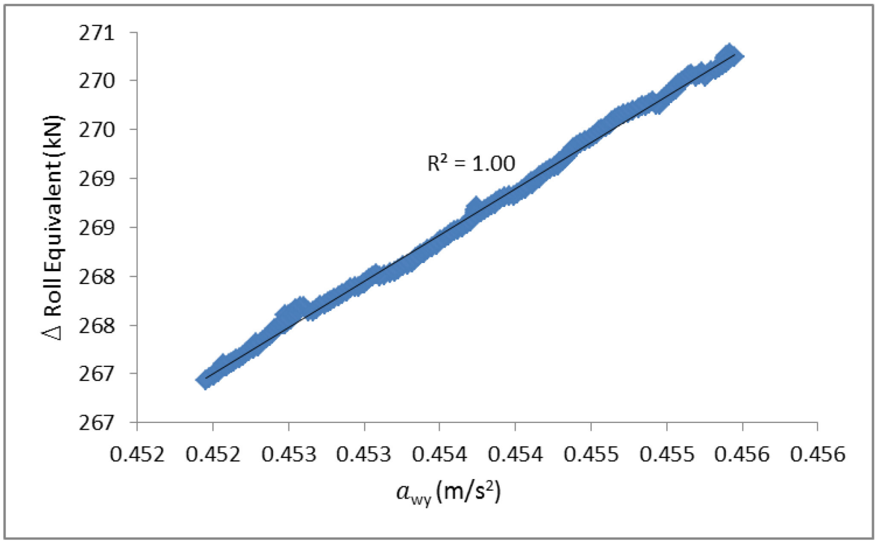


Figure 6.13: Correlation analysis for 4760 to 5003 seconds interval of loaded travel





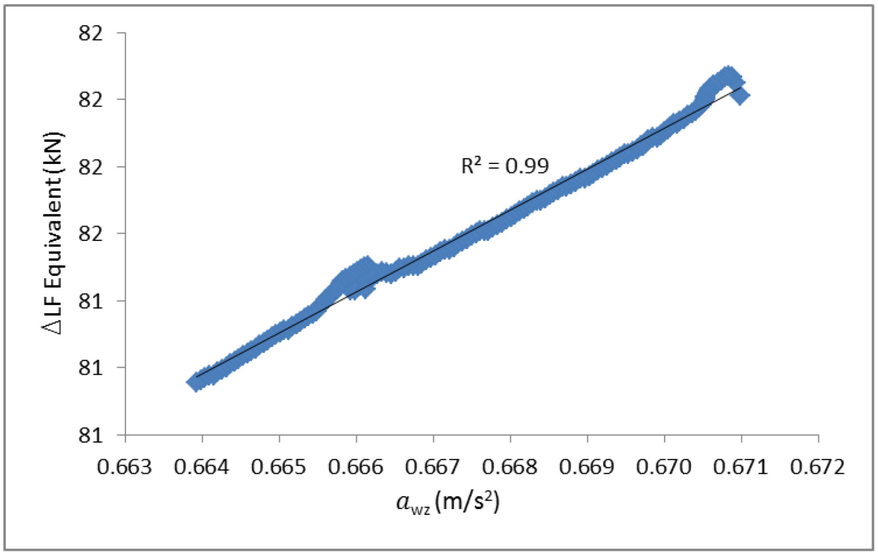


Figure 6.14: Correlation analysis for 5003 to 5184 seconds interval of loaded travel

6.2 Summary

The phase analysis was carried out with the objective of analyzing which phases of the travel result in good correlation of each of the 3 sets of strut motion and accelerometer parameters considered. It was observed that all 3 considered variables indicated perfect correlation during loading and dumping phases of the cycle when the truck is stationary. For loaded travel state on a well-constructed road, at relatively lower velocities up to 35kmph, strong positive correlations were indicated for all 3 parameters, while at higher velocities on these mine haul road sections only Z axis indicates strong correlation with LF strut motion.

Further, considering the phase of unloaded travel, the speed of the truck was observed to be relatively higher approximately in the 50kmph region, with reasonable correlation only noted for LF strut vs Z-axis vibration analysis, similar to period at constant speed. It is noted for phases of acceleration and deceleration; correlations between the variables are significantly reduced.

An attempt was made to achieve this through subtracting g-level equivalence for acceleration and deceleration of the vehicle from the overall vibration value but the results did not improve the correlations significantly. If the additional g-force could be analyzed and isolated during acceleration/deceleration phases, the accuracy in all 3 correlations may potentially be improved, which could be suggested as a recommendation for future research.

When the complete haul cycle is considered as a whole it was determined that 87% of the time the Z-axis accelerations strongly correlate with LF strut motion, while acceptable strong correlations are observed between X axis vs pitch motion and Y axis vs roll motion for only approximately 53% and 68% of the travel time respectively.

CHAPTER 07

Conclusions

Even though a quantified physics based engineering relationship has not been previously derived, worldwide research has previously indicated that Whole Body Vibration (WBV) is a significant impact to operator health and safety in terms of short term exposure and discomfort as well as long term serious injuries. Numerous studies have indicated instances where harmful levels of WBV have been measured in operation of heavy mobile equipment in agriculture, mining, construction and other earth moving industries. The literature suggests that workers, involved in the mining industry have a high tendency to experience adverse health effects due to being exposed to WBV, mainly when performing tasks such as drilling and material haulage using a range of heavy mobile equipment such as dump trucks and dozers. For mine haul trucks, studies have indicated the significance of truck speed, operator posture, seat and suspension system, ground conditions and driving practices contributing to the intensity of WBV.

Several case studies in the mining industry itself, provide evidence that, WBV levels related to heavy mining vehicles, and especially haul trucks frequently exceed the limitations set by ISO standards. It was evident that more attention should be focused towards a system easily applicable for mine haul trucks to continuously measure WBV levels without disrupting routine mining tasks or requiring greater capital cost for monitoring system for each piece of equipment. Studies on existing standards (ISO 2631-1 through ISO 2631-5) indicated difficulty in measurement procedure, due to the need for human resource and tools, as well as costly delays to mine operations which highlighted the need for a novel WBV evaluation methodology.

Ergonomic solutions in the form of measuring tool design solutions, as well as studies focused on behavioral solutions seem to lack awareness of the severity of the issue, which has caused a development gap in research towards WBV reduction. Evidence with regard to worldwide standard implementation suggests the need to reinforce standards with a suitable legislative frame-work, especially in countries like Canada, Australia and USA where mining has a vital role in the overall economy. With research mostly focused towards ergonomic seat designs, to provide more comfort to operators, the necessity for a convenient vibration measurement system with minimal interference to operations was concluded as a solution towards tackling operator health and safety issues with regard to WBV in mine haul trucks. This research has focused on developing the analysis that will permit using onboard measurement tools to evaluate such values of WBV exposure.

The research approach adapted here endeavored to seek a correlation for accelerometer measured axial vibrations versus onboard system suspension strut data indicative of truck motions. Such an analysis was initially unsuccessful when instantaneous values of the identified parameters were considered. However, since a visual correlation was apparent, a modified equivalent analysis in accordance with ISO2631-1(1997) was created to evaluate equivalence to Pitch, Roll and LF strut data, comparable to X, Y and Z axes equivalence using RMS and VDV methods. When the results of this preliminary analysis were validated using a statistical t-test, both Z and Y axes indicated acceptable strong correlation versus LF and Roll motions of the truck, while the no or poor correlations were identified for X-axis vibration versus Pitch motion.

Secondary field collected data provided the opportunity to verify initially indicated correlations, where the results of the modified equivalent analysis reinforced an acceptable relationship between Y-axis vibration and Roll motion, and a strong correlation between Z-axis vibration and LF strut motion. Compared to the initial analysis performed, the secondary field data also indicated correlations between X-axis and Pitch motion.

A phase analysis was performed to determine which segments of a haul truck duty cycle result in acceptable correlation for each of the parameters analyzed and moreover where correlation does not exist. The results of the study indicated dumping, loading and travelling at constant speed during the haul cycle creates a strong correlation for all 3 sets of the parameters analyzed for both loaded and unloaded conditions. However, it was noted that at speeds of 50kmph mark during empty state travel, accelerations and decelerations resulting in negative correlations, possibly a result of the unbalanced external forces acting on the suspension system during these phases. This may be due to the additional impact of acceleration and braking picked up by the accelerometers. During the unloaded travel phases even at higher speeds, a correlation remained between Z-axis vibration and LF strut motion and it was stronger during loaded travel phases where operator was effectively at constant velocity.

The phase analysis summary indicated that for 87% of the time, in a haul cycle, Z axis acceleration equivalence maintained a strong correlation versus LF strut motions; even though the corresponding values were relatively low at 68% and 53% for X and Y axes vibration respectively versus Pitch and Roll motion. The acceleration and deceleration of the truck indicated an additional impact on the truck suspension to that generated by vibration measurement. If the additional g force could be analyzed and isolated during these acceleration/deceleration phases, the accuracy in all 3 correlations potentially may be improved, which could be suggested as a recommendation for future research. The literature study as well as the results from the field data in this study revealed that the Z-axis is the dominant axis in WBV evaluation; with strong correlations identified between Z-axis vibrations and LF strut motions, the work here directly indicates a firm step towards development of a convenient and continues WBV measurement system with the use of (a) an available onboard system data, (b) the analysis shown in this thesis and more over (c) with no additional instrumentation necessary for measurement.

As highlighted in literature findings, the ISO2631-1(1997) does not specify time duration for measurement and other literature suggests the use of a significant duration to collect a representative WBV exposure measurement. However, with the use of the correlation analysis used in the modified equivalent method, there is a possibility to analyze at multiple different data segments and the effect of duration towards exposure evaluation. Using this methodology a specific optimal measurement duration could be defined upon which the correlation between the analyzed variables reach $r^2>0.9$ providing a more systematic procedure of measurement.

When considering the external noise on data recording, the discomfort in using a tri-axial accelerometer may cause the operators adjust their body position time to time causing these instances to include in vibration data. In the case of using onboard strut data for WBV evaluation, the different seat dampening mechanism used in haul trucks are not accounted for. In the case of requiring measuring the dampening effect of the seat, accelerometers can be fixed simultaneously on the seat pad as well as somewhere on the rigid operator cabin to observe the difference in the exposure readings.

When observing from an industrial point of view, the use of a real time WBV measurement system carries additional benefits. Since the system indicates continuous measurements for a selected vehicle, an increase in WBV exposure could be useful in identifying poor road conditions, issues with the truck suspension performance as well as a comparative analysis between a truck fleet at a mine site could provide data related to driving patterns and behaviors of operators. Such an analysis would be significant in providing training to operators as well as fostering disciplined driving patterns to prolong equipment health while reducing maintenance costs. When a convenient WBV evaluation system is continuously used to measure the WBV exposure, it provides strong evidence for the company to have fulfilled the responsibility of proving a health hazard free working environment.

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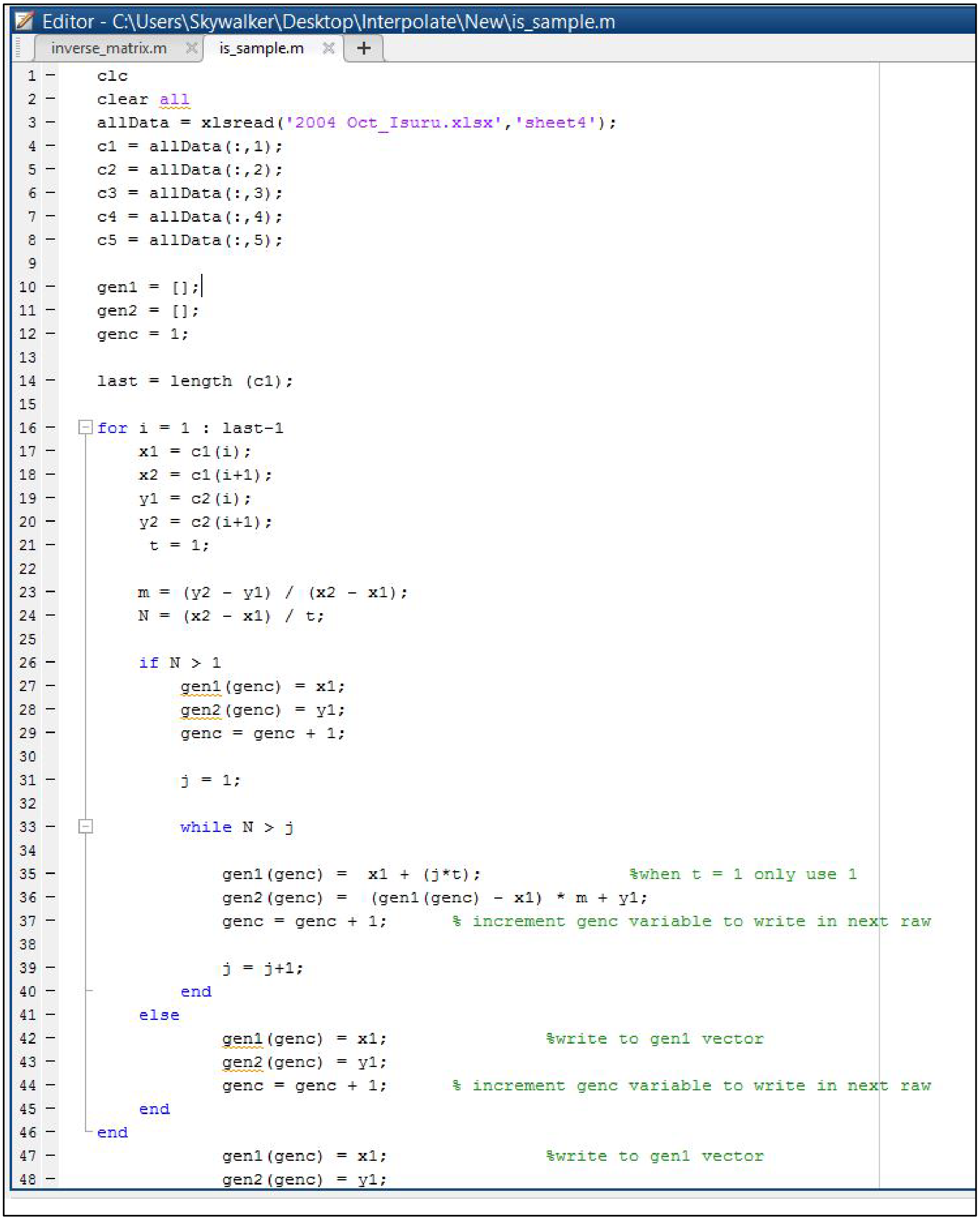
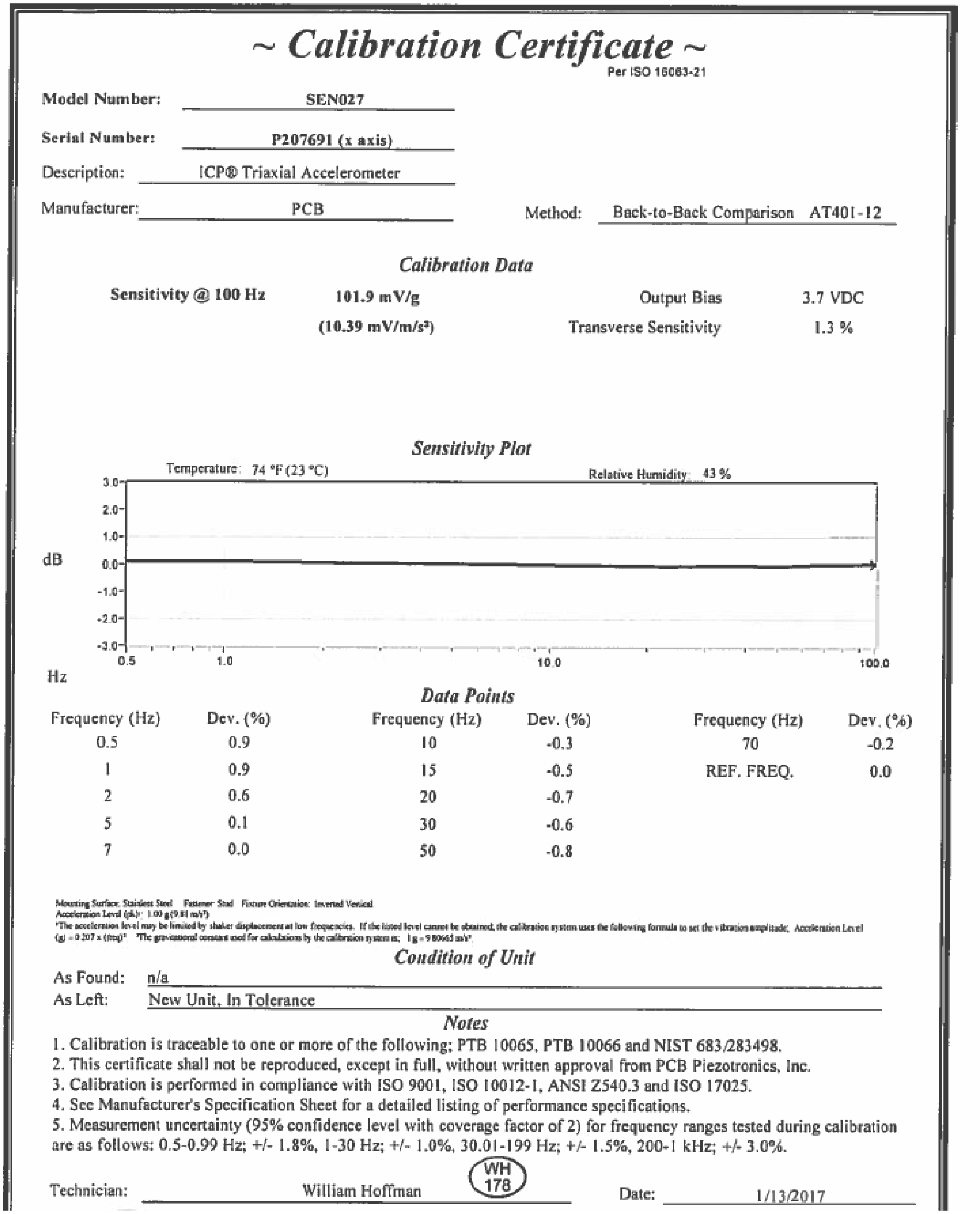
Appendices

Matlab code for linear interpolation of missing VIMS data



```
clc
clear all
allData = xlsread('2004 Oct_Isuru.xlsx','sheet4');
c1 = allData(:,1);
c2 = allData(:,2);
c3 = allData(:,3);
c4 = allData(:,4);
c5 = allData(:,5);

gen1 = [];
gen2 = [];
genc = 1;

last = length (c1);

for i = 1 : last-1
    x1 = c1(i);
    x2 = c1(i+1);
    y1 = c2(i);
    y2 = c2(i+1);
     t = 1;

    m = (y2 - y1) / (x2 - x1);
    N = (x2 - x1) / t;

    if N > 1
        gen1(genc) = x1;
        gen2(genc) = y1;
        genc = genc + 1;

        j = 1;

        while N > j

            gen1(genc) =  x1 + (j*t);              %when t = 1 only use 1
            gen2(genc) =  (gen1(genc) - x1) * m + y1;
            genc = genc + 1;      % increment genc variable to write in next raw

            j = j+1;
        end
    else
            gen1(genc) = x1;               %write to gen1 vector
            gen2(genc) = y1;
            genc = genc + 1;      % increment genc variable to write in next raw
    end
end
            gen1(genc) = x1;               %write to gen1 vector
            gen2(genc) = y1;
```

Calibration reports of the HVM 200



~ Calibration Certificate ~

Per ISO 16063-21

Model Number: SEN027

Serial Number: P207691 (x axis)

Description: ICP® Triaxial Accelerometer

Manufacturer: PCB

Method: Back-to-Back Comparison AT401-12

Calibration Data

Sensitivity @ 100 Hz	**101.9 mV/g**	Output Bias	3.7 VDC
	(10.39 mV/m/s²)	Transverse Sensitivity	1.3 %

Sensitivity Plot

Temperature: 74 °F (23 °C)

Relative Humidity: 43 %

Data Points

Frequency (Hz)	Dev. (%)	Frequency (Hz)	Dev. (%)	Frequency (Hz)	Dev. (%)
0.5	0.9	10	-0.3	70	-0.2
1	0.9	15	-0.5	REF. FREQ.	0.0
2	0.6	20	-0.7		
5	0.1	30	-0.6		
7	0.0	50	-0.8		

Mounting Surface: Stainless Steel Fastener: Stud Fixture Orientation: Inverted Vertical
Acceleration Level (pk)¹: 1.00 g (9.81 m/s²)
¹The acceleration level may be limited by shaker displacement at low frequencies. If the listed level cannot be obtained, the calibration system uses the following formula to set the vibration amplitude; Acceleration Level (g) = 0.207 x (freq)² ²The gravitational constant used for calculations by the calibration system is; 1 g = 9.80665 m/s².

Condition of Unit

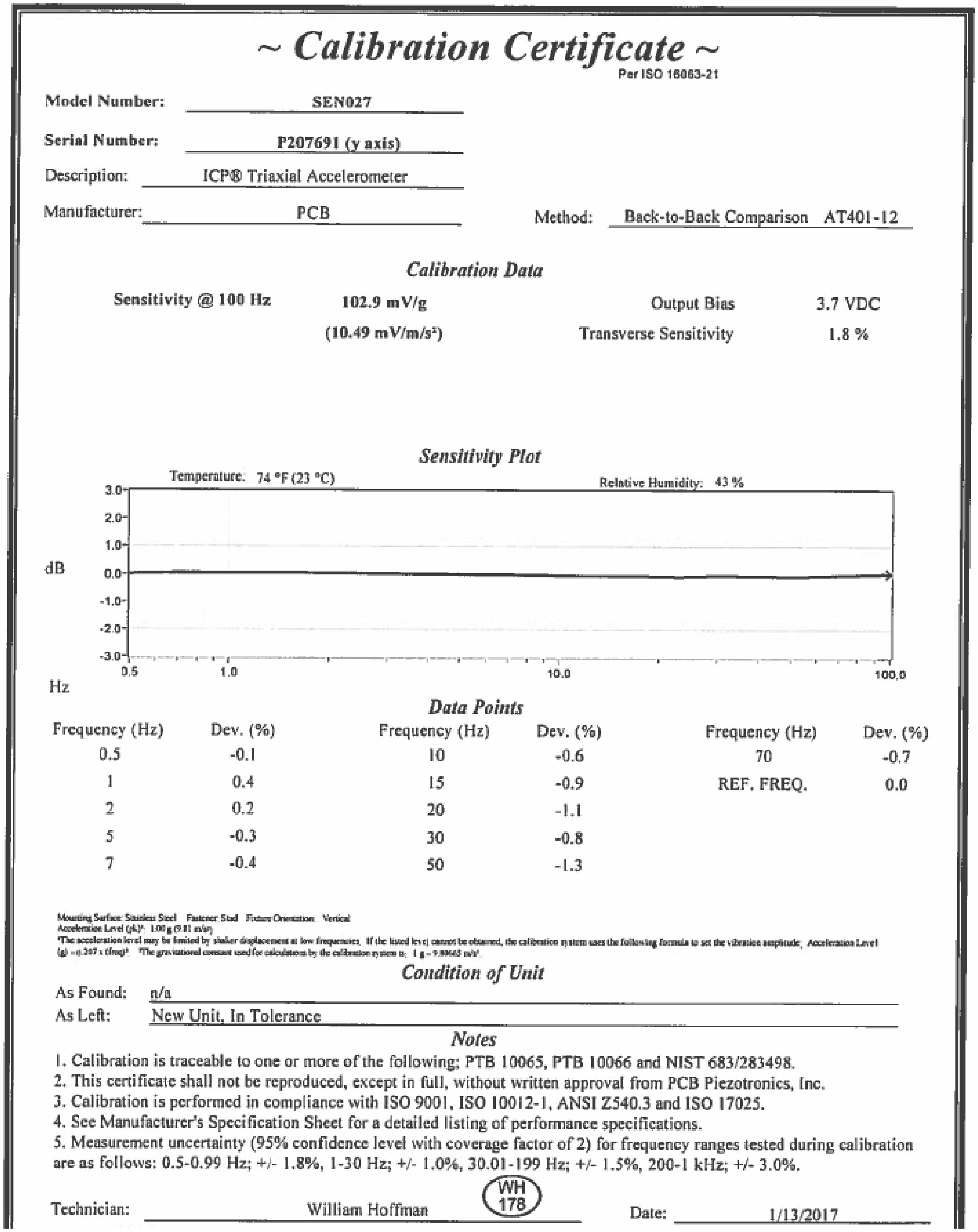
As Found: n/a

As Left: New Unit, In Tolerance

Notes

1. Calibration is traceable to one or more of the following; PTB 10065, PTB 10066 and NIST 683/283498.
2. This certificate shall not be reproduced, except in full, without written approval from PCB Piezotronics, Inc.
3. Calibration is performed in compliance with ISO 9001, ISO 10012-1, ANSI Z540.3 and ISO 17025.
4. See Manufacturer's Specification Sheet for a detailed listing of performance specifications.
5. Measurement uncertainty (95% confidence level with coverage factor of 2) for frequency ranges tested during calibration are as follows: 0.5-0.99 Hz; +/- 1.8%, 1-30 Hz; +/- 1.0%, 30.01-199 Hz; +/- 1.5%, 200-1 kHz; +/- 3.0%.

Technician: William Hoffman WH 178 Date: 1/13/2017



~ Calibration Certificate ~

Per ISO 16063-21

Model Number: **SEN027**

Serial Number: **P207691 (y axis)**

Description: ICP® Triaxial Accelerometer

Manufacturer: PCB

Method: Back-to-Back Comparison AT401-12

Calibration Data

Sensitivity @ 100 Hz	**102.9 mV/g**	Output Bias	3.7 VDC
	(10.49 mV/m/s²)	Transverse Sensitivity	1.8 %

Sensitivity Plot

Temperature: 74 °F (23 °C)

Relative Humidity: 43 %

Data Points

Frequency (Hz)	Dev. (%)	Frequency (Hz)	Dev. (%)	Frequency (Hz)	Dev. (%)
0.5	-0.1	10	-0.6	70	-0.7
1	0.4	15	-0.9	REF. FREQ.	0.0
2	0.2	20	-1.1		
5	-0.3	30	-0.8		
7	-0.4	50	-1.3		

Mounting Surface: Stainless Steel Fastener: Stud Fixture Orientation: Vertical
Acceleration Level (pk)¹: 1.00 g (9.81 m/s²)
¹The acceleration level may be limited by shaker displacement at low frequencies. If the listed level cannot be obtained, the calibration system uses the following formula to set the vibration amplitude: Acceleration Level (g) = 0.207 x (freq)² ²The gravitational constant used for calculations by the calibration system is: 1 g = 9.80665 m/s².

Condition of Unit

As Found: n/a

As Left: New Unit, In Tolerance

Notes

1. Calibration is traceable to one or more of the following: PTB 10065, PTB 10066 and NIST 683/283498.
2. This certificate shall not be reproduced, except in full, without written approval from PCB Piezotronics, Inc.
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Technician: William Hoffman WH 178

Date: 1/13/2017

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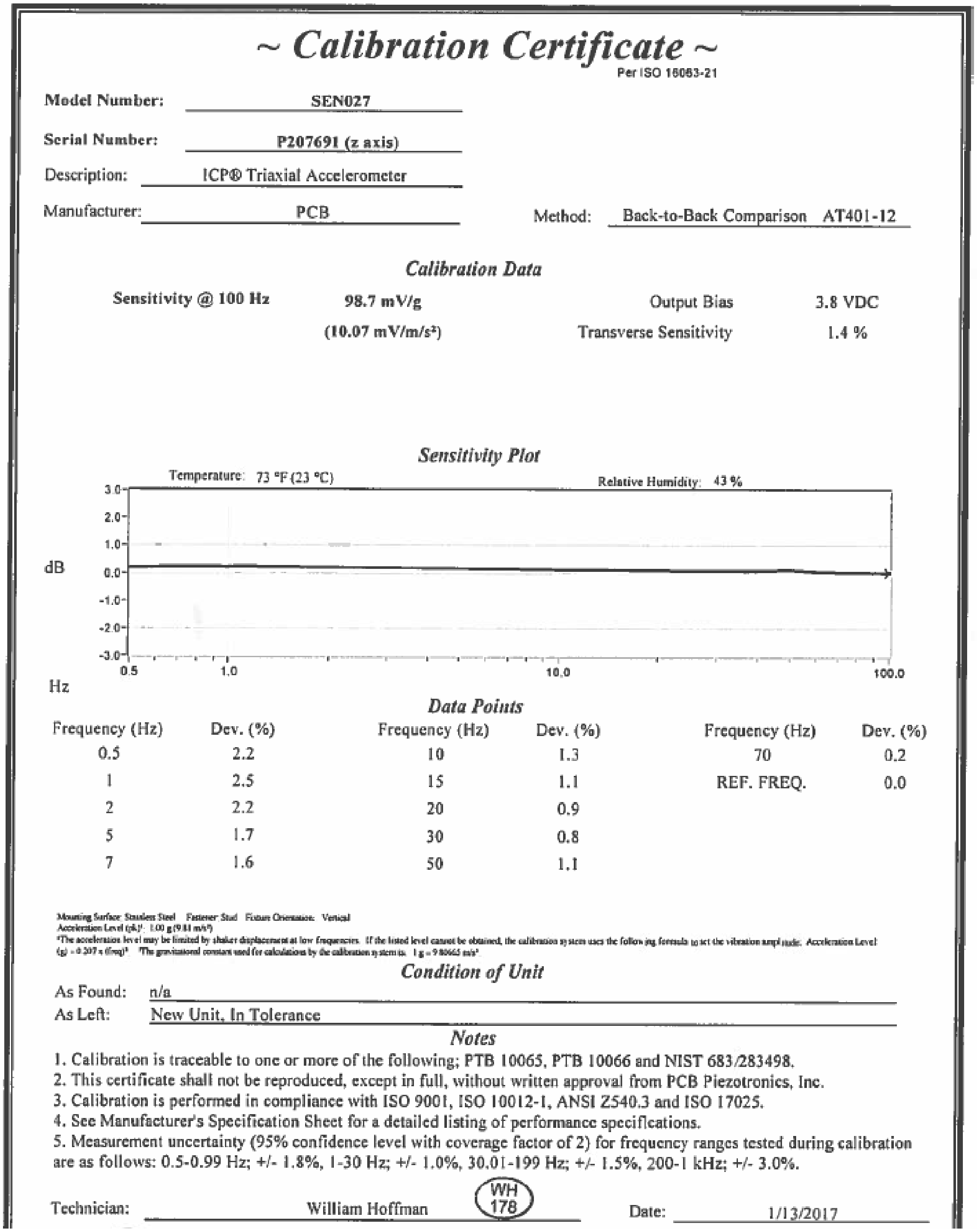

~ Calibration Certificate ~

Per ISO 16063-21

Model Number:	SEN027
Serial Number:	P207691 (z axis)
Description:	ICP® Triaxial Accelerometer
Manufacturer:	PCB

Method: Back-to-Back Comparison AT401-12

Calibration Data

Sensitivity @ 100 Hz	**98.7 mV/g**	Output Bias	3.8 VDC
	(10.07 mV/m/s²)	Transverse Sensitivity	1.4 %

Sensitivity Plot

Data Points

Frequency (Hz)	Dev. (%)	Frequency (Hz)	Dev. (%)	Frequency (Hz)	Dev. (%)
0.5	2.2	10	1.3	70	0.2
1	2.5	15	1.1	REF. FREQ.	0.0
2	2.2	20	0.9		
5	1.7	30	0.8		
7	1.6	50	1.1		

Mounting Surface: Stainless Steel Fastener: Stud Fixture Orientation: Vertical
Acceleration Level (pk)¹: 1.00 g (9.81 m/s²)
¹The acceleration level may be limited by shaker displacement at low frequencies. If the listed level cannot be obtained, the calibration system uses the following formula to set the vibration amplitude: Acceleration Level (g) = 0.207 x (freq)². The gravitational constant used for calculations by the calibration system is: 1 g = 9.80665 m/s².

Condition of Unit

As Found: n/a

As Left: New Unit, In Tolerance

Notes

1. Calibration is traceable to one or more of the following; PTB 10065, PTB 10066 and NIST 683/283498.
2. This certificate shall not be reproduced, except in full, without written approval from PCB Piezotronics, Inc.
3. Calibration is performed in compliance with ISO 9001, ISO 10012-1, ANSI Z540.3 and ISO 17025.
4. See Manufacturer's Specification Sheet for a detailed listing of performance specifications.
5. Measurement uncertainty (95% confidence level with coverage factor of 2) for frequency ranges tested during calibration are as follows: 0.5-0.99 Hz; +/- 1.8%, 1-30 Hz; +/- 1.0%, 30.01-199 Hz; +/- 1.5%, 200-1 kHz; +/- 3.0%.

Technician: William Hoffman WH 178 Date: 1/13/2017