8-24-2015 12:00 AM

Evaluation of Suspension Seats Under Multi-Axis Vibration Excitations - A Neural Net Model Approach to Seat Selection

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A thesis submitted in partial fulfillment of the requirements for the Doctor of Philosophy degree in Kinesiology

EVALUATION OF SUSPENSION SEATS UNDER MULTI-AXIS VIBRATION EXCITATIONS – A NEURAL NET MODEL APPROACH TO SEAT SELECTION

(Thesis format: Monograph)

by

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Graduate Program in Kinesiology

A thesis submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy

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Abstract

Whole-body vibration describes vibrations that are transferred from a supporting surface to the human body. Low back injury is a major health issue amongst heavy machine operators and seat selection is important for reducing vibration exposure. Modeling the vibration attenuation properties of seats is one approach for predicting the performance of seats in different vibration environments. An efficient neural network (NN) algorithm identified the vibration attenuation properties of five suspension seats that are commonly used in the Northern Ontario mining sector. Each of the NN seat models strongly predicted vertical seatpan r.m.s. accelerations from the chassis accelerations and a measure of driver anthropometrics. We implemented the developed NN models to evaluate the performance of industrial seats for a variety of skidders from the forestry sector and load-haul-dump vehicles from the underground mining environment. Our results demonstrated that seat selection is not universal. The performance and rank orders of industrial seats varied between vibration environments based on the calculated equivalent daily exposure ($A(8)$) values. We performed a sensitivity analysis to evaluate the influence of specific vibration frequency components on the predicted daily exposure values. This analysis revealed that each of the industrial seats responded differently to specific vibration frequencies and explained why the seat selection algorithm matched particular seats to specific vibration environments. We also evaluated the performance of the new No-Jolt™ air-inflated cushion with multi-axis vibration exposures and vertical jolt exposures. The vibration attenuation properties were assessed for two seat suspensions (with relatively good and poor initial performance) when their foam cushions were replaced with the air-inflated cushion. The air cushion only improved the vibration attenuation properties of the seat that initially had good performance. We also observed that operator's anthropometrics and sex influenced the performance of the air-inflated cushion in certain cases when vibration environment includes jolt exposures. All of our findings emphasize the importance of matching the specific seat/cushion to the particular vibration environment in order to reduce heavy machine operators' vibration exposure and minimize their health risks.

Keywords

Whole-body vibration, seat selection, cushions, attenuation, neural network, *A*(8), *VDV*, health guidance caution zone, sensitivity analysis, jolt.

Acknowledgments

I am grateful to thank my supervisor Dr. James P. Dickey. I have extremely benefited from him by countless academic communications during work. His scientific and precise manner of doing research not only has inspired in many aspects of my dissertation, but also set up a life example that I wish to follow in my future career. I really appreciate that he spent tons of time and patience to read my manuscripts. His valuable suggestions greatly improved the quality of my dissertation.

I would like to thank Dr. Alan Salmoni, Dr. Ana Luisa Trejos, Dr. Dave Walton and Dr. Subhash Rakheja (Concordia University) as my dissertation examiners; Dr. Daniel J. Bechard and Dr. Tammy R. Eger (Laurentian University) as my comprehensive committee members; Dr. Alan Salmoni and Dr. Michael J. Katchabaw as my advisory committee members. Thanks also go to all biomechanical lab mates, and all the volunteers in my research studies.

Finally, I am grateful to thank my parents forever. I could not have done this without their constant support throughout these many years. Millions of thanks will be given to my wife Xin Gao. Her encouragement and assistance is my most motivation when I faced difficulties in these years. I also appreciate that my wife gave me a priceless gift – my little angel Olivia. She brings me endless happiness.

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List of Abbreviations

BMI	Body mass index
BMI Prime	BMI/25
CAT	Caterpillar
dB	Decibel
df	Degree of freedom
DF	Dominant frequency
EEG	Electroencephalogram
FE	Finite element
Hz	Hertz
HGCZ	Health guidance caution zone
IMU	Inertial measurement unit
ISO	International Standard Organization
ISSA	International Social Security Association
LBP	Low back pain
LHD	Load-haul-dump
NN	Neural network
r.m.s.	Root-mean-square
SD	Standard deviation
S.E.A.T.	Seat effective amplitude transmissibility
VDV	Vibration dose value
WBV	Whole-body vibration

Dedication

To my parents and my wife.

Chapter 1

1 Introduction

1.1 Whole-body vibration

1.1.1 Physical responses by whole-body vibration

Human health is a universally important topic. People's physical health is a function of their diet, exercise, and living environment. However, some risk factors are embedded into one's daily activities, such as the whole-body vibration (WBV) exposure that occurs during transportation or as part of work.

WBV is a generic term used to describe vibrations that are transferred from a supporting surface to the human body. WBV is transmitted from the chassis of vehicles to human bodies by buttocks, feet, hands or back. The international organization for standardization (ISO) classify WBV into three types based on the individual's body posture: seated, standing and lying down (ISO 2631-1, 1997).

Heavy mobile machinery operators drive vehicles over rough terrain and uneven surfaces for a large portion of their workday (Griffin, 1990). Many occupational vibration exposures include large shocks and jolts, which are particularly deleterious to human health (ISO 2631-5, 2004). Excessive exposure causes various physical responses in the cardiovascular, respiratory, endocrine and metabolic, motor processes, sensory processes, central nervous system, and skeletal (Griffin, 1990). These responses are outlined in the following sections.

Cardiovascular responses:

Vibrations at specific magnitude and frequency cause the changes of cardiovascular varied. For example, Guignard (1965, as cited in Griffin (1990)), observed that the cardiovascular response produced by the moderate to high level of vertical vibration in the frequency range from 2 to 20 Hz was similar to that which occurs during moderate exercise. Other research indicated that heart rate, blood lactate, systolic blood pressure increased, but the diastolic pressure dropped when young healthy subjects stood on a vibrating exercise platform at 26 Hz (Rittweger et al., 2000). Similar exercise-like changes occur in heart rate; it was significantly higher during squat exercises at 20 Hz vibration than that without vibration (Rosenberger et al., 2014).

Respiratory responses:

Specific vibrations cause increased ventilation. For example, Ernsting (1961, as cited in Griffin (1990)), observed that 9.5 Hz vibration at 1 g amplitude caused an increased in oxygen consumption compared to vibration at 1.7 Hz. Vibration also caused increased hyperventilation at all frequencies. The effects of hyperventilation were greatest at the highest frequencies in the range 2-10 Hz when subjects were exposed to constant displacement sinusoidal vibration (Hoy et al., 2005; Sharp et al., 1975, as cited in Griffin (1990)). These effects were also observed when individuals were exposed to WBV while exercising; WBV increased oxygen consumption when it was applied with the squatting exercise (Rittweger et al., 2001; Serravite et al., 2013).

Endocrine and metabolic responses:

The initial study discovering the metabolic and endocrine responses to WBV was performed in dogs (Blivaiss et al., 1964); they discovered that the changes in circulating hormones and metabolites in plasma varied as a function of the magnitude and duration of the WBV. Another study also indicated that the growth hormone levels were acutely altered by WBV, which may indirectly influence bone remodeling (Bosco et al., 2000). In terms of muscle metabolic rates, higher vibration frequency (28 Hz) resulted into a significantly higher metabolic rate than lower frequency vibrations (10 and 17 Hz) for the gastrocnemius medialis and vastus lateralis muscles during standing (Friesenbichler et al., 2013).

Motor processes:

The pioneering study revealing the phenomenon of the reflex muscle tension to the vibration was Matthews (1966); he discovered that the certain amplitudes and frequencies of vibration caused reflex muscle tension. However, a conflicting motor effect was observed when individuals were exposed to WBV during exercising; a 7% reduction in the maximal voluntary knee extension force occurred after a single short-term 90 second vibration exposure when subjects exercised on a vibrating plate with standing/sitting positions at 30 Hz and amplitude of 8 mm (De Ruiter et al., 2003). Moreover, another study reported that a 45-minute occupational type WBV exposure at 3 Hz with an amplitude of 0.7 m/s^2 caused a significant delay in the response of erector spinae muscle when subjects were perturbed (Arora and Grenier, 2013).

Sensory system responses:

Vibration exposure can lead to hearing impairments; one study reported that there was a significant risk of hearing deficits for sound tone frequencies between 4 and 8 KHz for the subjects exposed to occupational vibration (induced white finger) compared to subjects without vibration (Iki, 1994). Furthermore, he reported that hearing ability was significantly deteriorated for sound tones at 2 and 4 KHz for at least five years in the subjects with occupational vibration exposure (induced white finger). Vibration also causes damage to the structure of peripheral nerves (Stromberg et al., 1997) or reduces finger blood flow (Bovenzi et al., 2000) in workers exposed to vibrations. A similar observation in animals was reported by Raju et al. (2011). They observed a reduction in the number of nerve terminals, and a reduced sensitivity to a heat stimulus, in the tails of rats that were exposed to impact vibrations.

Central nervous system:

Vibration causes rhythmic changes in the electroencephalogram (EEG). For example, one study reported that the cerebral rhythms were strongly influenced by vibration when the cats and monkeys were exposed to 2 g vibrations between 9 and 15 Hz (Adey et al., 1961). Vibration may also disrupt individuals' ability to sustain their attention. For example, the reaction time of responding to the arrow direction on the screen was degraded to the subjects when they were exposed WBV exposures in the vertical and fore-and-aft directions at the flat frequency spectra (1-20 Hz) with a twisted posture (Newell and Mansfield, 2008). Similarly, a reduction in alertness occurred when people were exposed to vibrations at r.m.s. equal to 0.3 m/s^2 for 20 mins (Azizan et al., 2014).

Skeletal system:

Various influences of vibration on the skeletal system have been reported. The lumbar vertebrae may exhibit fatigue failures after intense prolonged WBV (Hansson et al., 1991). Low back disorders may be caused by high level shocks, such as from the top and/or bottom end stop impacts of the seat suspension (Rebelle, 2004). Long-term exposure to vibrations that include multiple shocks are one of the main factors that cause severe effects on the lumbar spine. Multiple shocks cause large transient accelerations, which generate excessive pressure at the lumbar vertebral endplates and diffuse the nutrition of the disc issue (ISO 2631-5, 2004).

1.1.2 Characteristics of whole-body vibration

The extent of physical responses to vibration (e.g. degraded comfort, motion sickness, and severe low back pain) depends on the magnitude, frequency, and duration of exposures. Vibration frequency is one of the significant properties of WBV, and it strongly influences the effects of WBV on human health. The resonant frequencies for the human torso are between 4 and 6 Hz for the entire torso with the lower spine and pelvis, and between 10 and 14 Hz for the upper torso with forward flexion movements of the upper vertebral column respectively (Brammer, 2010). The dominant frequency of vibrations transmitted through the seat to a seated person is often below 20 Hz (Griffin, 1990). Discomfort increases with acceleration from 2 to 6 Hz in the vertical and fore-and-aft vibration, and the sensitivity of lateral accelerations is approximately the same between 1 and 2 Hz (Griffin, 1990). At very low frequencies (less than 0.5 Hz) the principal effect of vibration is motion sickness (ISO 2631-1, 1997). The vibration frequencies that affect health, activities and comfort are between 0.5 to 80 Hz (ISO 2631-1, 1997).

The magnitude of WBV exposures is another primary factor which impacts human health. Vibrations that are below 0.01 m/s^2 are rarely felt, and vibrations above 10 m/s^2 are assumed to be hazardous (Griffin, 1990). When the vibration r.m.s. magnitude exceeds 2.0 m/s^2, people feel extremely uncomfortable (ISO 2631-1, 1997).

The duration of WBV exposures also modulates the effects of vibration on human body (Griffin, 1990). ISO 2631-1 (1997) mentions that the increased magnitude and duration of vibration increase health risks for the individuals exposed to WBV. The duration of WBV is also reflected in the health guidance caution zone (ISO 2631-1, 1997); the magnitude of the upper limit of the HGCZ decreases as the duration of the exposure increases due to the energy of vibration exposure being equivalent. Accordingly, longer duration of acceleration with lower magnitude can be equivalent to shorter duration with a larger magnitude of acceleration.

1.1.3 Whole-body vibration causes low back pain

Approximately 4 - 7% of all employees are annually exposed to potentially hazardous levels of WBV in North America and some European countries (International Social Security Association (ISSA), 1989). Approximately 7 million employees in the United States are annually exposed to WBV (Wasserman et al., 1997), and approximately 7.2 million male and 1.8 million female employees in Great Britain are exposed to occupational WBV (Palmer et al., 2000).

Health impacts associated with WBV have been reported in various studies. For example, excessive exposure to WBV is a prevalent occupational risk factor that may cause severe effects on health in heavy machine drivers (e.g. fork-lift trucks, lorries, tractors, loaders and cranes) and in helicopter pilots (Bovenzi and Hulshof, 1999). These symptoms may include musculoskeletal injury (Bovenzi, 1996; Hagen et al., 1998; Hulshof et al., 2002; Jack et al., 2008; Johanning, 2011; Lis et al., 2007; Milosavljevic et al., 2012a; Punnett et al., 2005; Waters et al., 2008; Wilder and Pope, 1996; Wilder, 1993), motion sickness (Beard and Griffin, 2014b; Griffin, 1990), muscle fatigue (Baig et al., 2014; Magnusson and Pope, 1998; Meng et al., 2015), gastrointestinal tract problems (Ishitake et al., 1998; Miyashita et al., 1992), and nervous system dysfunction (Harkonen et al., 1984; Sutinen et al., 2006).

Low back pain (LBP) is consistently considered to be the most common complaint among heavy machinery operators exposed to long-term WBV (Bovenzi and Betta, 1994; Davis and Jorgensen, 2005; Seidel, 2005). An European Standardization reported that prolonged occupational exposures to WBV from heavy mobile vehicles result in an increased risk of LBP amongst drivers (Comite Europeen de Normalisation , 1996). This is common in North America too. More than 25% of the employees from a large utilities corporation in Ontario are affected by LBP every year (Lee et al., 2001).

Due to high prevalence, LBP leads to lost work time (Bovenzi and Betta, 1994; Seidel, 2005), and large economic burden in terms of lost wages and medical expenses (Ivanova et al., 2011; Miller et al., 2002). Over the past 10 years (2003-2012), two Canadian provinces (Ontario and British Columbia) report that LBP has consistently represented the most commonly injured body symptom, and low-back claims represent appropriately 20% of lost time claims (Workplace Safety and Insurance Board of Ontario, 2013; WorksafeBC, 2012). In the United States, the total costs for the treatment of LBP are over $100 billion per year (Crow and Willis, 2009; Frymoyer and Cats-Baril, 1991).

Epidemiologic studies have identified that several factors contribute to lower back symptoms when operators are exposed to WBV. For example, low back injuries may occur when WBV is associated with prolonged sitting with a twisting posture (Bovenzi, 1996). High magnitude of WBV in load-haul-dump (LHD) vehicles resulted in operator's rate of LBP being 4.25 times more prevalent than subjects that were not exposed to vibration (Mandal and Srivastava, 2010). Other modulating factors include terrain types, vehicle types, driving speed, driver/seat contact area, vehicle mass, suspension systems, tire pressure and the state of vehicle maintenance (Donati, 2002; Eger et al., 2011a; Eger et al., 2011b).

1.2 Suspension seats

Seating is one of the easiest engineering controls that can significantly influence vibration exposure transmitted to the heavy machine operators, and reduce health risks (Griffin, 1978). Some studies have shown significant differences in vibration attenuation between seats in laboratory and field studies; this is presumably due to their differing characteristics. For example, malfunctioning or worn-out seats may amplify the low-frequency vibration exposures for drivers (Dentoni and Massacci, 2013). Conrad et al. (2014) noted differences between the vibration attenuation properties of three different suspension seats during laboratory studies with vibration exposures derived from pot haulers in the steelmaking industry. Similarly, Jonsson et al. (2015) noted that an air seat amplified the WBV more than the static seat in the high floor bus; however they also noted that there was no significant difference between the vibration attenuation of these air-suspension and static pedestal seats in the low floor bus.

Most commercial industrial seats incorporate a passive mechanism comprising a damper and some type of spring. The spring element usually consists of steel spring or a pneumatic cylinder. The principal intent of these mechanisms is to reduce the vibration to the vehicle occupants (Paddan and Griffin, 2002). However, measurements from a wide range of vehicle seats revealed that suspension seats frequently amplify vibration exposures (Cation et al., 2008; Dentoni and Massacci, 2013; Donati, 2002; Paddan and Griffin, 2002). Various factors influence the performance of suspension systems. For example, variations in the body weights, foot support position, contact with backrest, arm support, energy absorption by the body and driving conditions can influence the vibration attenuation properties of suspension seats (Corbridge, 1987a, as cited in Griffin (1990); Politis et al., 2003). The transmissibility of the seat varies depending on the frequency of the vibration, and the dynamics of seats and human body (Griffin, 1990). There were significant differences of transmissibility between six suspension seats at the resonance frequency approximately 2 Hz (Corbridge, 1987b, as cited in Griffin (1990)). Moreover, the optimum seat for one vehicle is not necessarily suitable for another vehicle (Griffin, 1990; Paddan and Griffin, 2002). Thus, seat performance is complex due to the frequency-dependent properties of each seat (Conrad et al., 2014; Gunaselvam and Van Niekerk, 2005; Wilder, 1993). Industrial seats should be selected or adjusted appropriately for the specific vehicles or particular vibration environment.

Correctly adjusting the seat suspension can reduce the vibration exposures transmitted to the operators (Paddan and Griffin, 2002). Three basic criteria for adjusting seats are listed below:

1) Suspension travel:

The lower the vibration frequency, the larger the required seat suspension travel. Some study has suggested suspension travel distances for particular vibration environments. For example, Donati (2002) recommended a travel distance of 3 cm for vibrations above 3 Hz, and up to about 15 cm for vibrations at 1.5 Hz.

2) Suspension adjustment:

Suspension seats should be properly adjusted for the operator's weight to reduce the transmitted vibration. Weight adjustment changes the spring tension so the seat is close to its central position when the operator is seated (Donati, 2002). This reduces the likelihood of the seat suspension bottoming out, or topping out. The vertical suspension distance on most commercial suspension seats is less than about 10 cm (Griffin, 1990). Accordingly this amount of suspension travel is adequate for higher frequency vibration environments, but may not be adequate for low frequency vibration environments.

3) End-stop impacts:

Suspension systems must be fitted with bottom end-stop buffers to prevent the suspension from bottoming out when the seat is exposed to high magnitude shocks (Donati, 2002). Several studies have evaluated the vibrations associated with the end stop impacts in suspension seats. For example, Wu and Griffin (1996) emphasized the importance of center-position adjustment for suspension seats. They observed that end-stop impacts occurred as the input magnitude increased when the suspension seat was not set at the center-position. They observed 28% increases in the vibration dose value (*VDV*) ratios when the suspension was set below the center-position compared to the suspension that was set at the center-position with the same input magnitude equal to 2 m/s^2. Some studies have suggested to choose an optimal end-stop buffer to decrease the end-stop impacts. For example, Rakheja et al. (2004) discovered that low stiffness end-stop buffers were important to reduce the severe accelerations by analyzing seat effective amplitude transmissibility (S.E.A.T.) and *VDV* ratios based on their two degree of freedom lumped parameter model. Similarly, Rebelle (2004) observed that the acceleration magnitude was decreased by approximately 73% at the largest shock impact when he replaced the original end-stop buffer with an optimal one.

1.3 Cushions

Seat cushions are an important factor for seat performance (Wu and Griffin, 1996). The damping and stiffness characteristics can differ significantly between cushions (Kolich et al., 2005; Smith, 1998). Various studies have compared the characteristics between foam cushions by analyzing operators' comfort levels. For example, cushions with softer foam were thought more comfortable than the cushions with harder foam (Griffin, 1990). However, he also reported that cushions being too soft can bottom out under the extreme vibrations. Other study evaluated the static comfort of various seat cushions by measuring the pressure at the interface between the ischial tuberosities and the seat cushions (Ebe and Griffin, 2001). They determined that the cushion with less pressure in the sitting area were more comfortable than the cushion with greater pressure. In addition, various studies evaluated foam cushions by analyzing their vibration attenuation properties. For example, there were significant differences of the vertical transmissibility among ten alternative cushions (six of ten were foam cushions) using the same vibration condition (a random exposure with the r.m.s. magnitude of 0.6 m/s^2) and the same subject (Corbridge et al., 1989). Seats with thin and compliant foam had a significantly higher vibration levels (Kolich et al., 2005). However, seat cushion material composed of high density polyurethane was good for attenuating the transmitted vibrations based on evaluating nine commercially seat cushion materials for a tractor seat (Mehta and Tewari, 2010). Some study has also evaluated supplementary cushions. For example, there was a significant reduction in the vertical vibration magnitude when taxi drivers used an extra seat cushion (Chen et al., 2003). Thus, modifying seat cushion design has the potential to affect the static and dynamic discomfort of the seat occupants (Beard and Griffin, 2014a).

Several studies have suggested replacing original manufacturer cushions with air cushions as they can evenly distribute pressure over the seatpan/buttocks interface, reduce pinch points and lower pressures under the ischial tuberosities (Griffin, 1990; Huston et al., 1999; Seigler, 2002). In addition to these contact pressure issues, several studies have shown that air cushions can attenuate WBV more than foam cushions (Chen et al., 2015; Dewangan et al., 2015; Huston et al., 1999; Seigler, 2002; Van der Merwe, 2007). However, some studies did not show that air cushions performed better than foam cushions in terms of their vibration attenuation properties. For example, the air cushion had the similar results of r.m.s. acceleration ratios as that of the foam cushion when participants drove an instrumented wheelchair over nine obstacles (DiGiovine et al., 2000). Another study clearly reported that air cushion had a poorer vibration attenuation performance than that of the foam cushion at the frequency range between 0.5 and 20 Hz with three vertical vibration levels and under the sitting condition without back support (Dewangan et al., 2015). It seems likely that the performance of air cushions may vary depending on the characteristics of the vibration environment.

1.4 Modeling methods

In order to evaluate vibration transmissibility properties of industrial seats, often people switch seats and drive the same vehicle over a standard course (for example, Dentoni and Massacci, 2013; Jonsson et al., 2015). One difficulty is keeping the input accelerations the same, although typically these studies measure the chassis acceleration to evaluate whether the input accelerations are consistent. Another typical challenge for the workplace measurements of WBV is the expensive equipment and software that is required (Thalheimer, 1996; Trask et al., 2007).

Many excellent biomechanical models have been developed to describe the complex structure and dynamic response of seat-human systems, such as nonlinear lumped parameter method in which the human body and seat are represented by a combination of lumped masses, springs and dampers (Chen et al., 2013; Cho and Yoon, 2001; Fairley and Griffin, 1986; Kim et al., 2005; Rakheja et al., 1994; Srdjevic and Cveticanin, 2012; Wei and Griffin, 2000). Rakheja et al. (2003) developed a two degree of freedom lumped parameter model to evaluate the vibration transmission properties of three seats under large magnitude excitations. Their biomechanical model included several component models (e.g. seat cushion, seat suspension, damper and elastic motion limiter), and it presented good agreements with the measured data in terms of parameters such as transmissibility and the magnitudes of the acceleration power spectral density. Although, they considered the possibility of losing contact between the seated subjects and the cushion in their model, typically lumped parameter methods simplify the complex contours at the seatpan/human interface, and ignore the variations in cushion properties and dynamic responses of subjects (Zhang et al., 2015).

Finite element (FE) is another modeling methodology for the dynamic response of seat-human systems (Grujicic et al., 2009; Kitazaki and Griffin, 1997; Zhang et al., 2015). Although FE can overcome the limitations of nonlinear lumped parameter method, FE models are complex to develop, they are computationally expensive and are difficult to calibrate and optimize (Zhang et al., 2015).

Neural network models (NNs) have been utilized in a wide range of applications because of their versatility for describing relationships between variables (Calvo et al., 1995; He et al., 2012; May et al., 2012; Odom and Sharda, 1990; Smith and Demetsky, 1994; Tian and Collins, 2005; Widrow et al., 2013; Won et al., 2010; Zadpoor et al., 2013). They perform capably in noisy environments and can operate with faulty and missing data. They also do not require accurate estimates of the parameters (e.g. stiffness, damping coefficient, etc) like some other biomechanical models. NNs can model complex nonlinear relationships between the measured system's input and output signals by adjusting the inter-connections (weighting factors) among network nodes (neurons) to optimize the predictions or to target a given performance.

1.5 International Organization for Standardization (ISO) 2631-1 (1997)

ISO 2631-1 describes the measurements and analysis for evaluating the vibrations transmitted to the human body through the supporting surfaces, such as the feet, buttocks and back of a seated person, the feet of a standing person, or the supporting area of a lying down person. ISO 2631-1 defines the methods to measure random, periodic and transient WBV, which is relevant to human health, comfort, perception and motion sickness.

1.5.1 Direction of measurement

Three translational axes of an orthogonal coordinate system are defined for expressing the directions of vibration transmitted to the seated human body, namely sagittal (x-), lateral (y-) and vertical(z-) axes. Three rotational movements are defined as roll (rotating around x-axis), pitch (rotating around y-axis) and yaw (rotating around z-axis) (Figure 1-1).

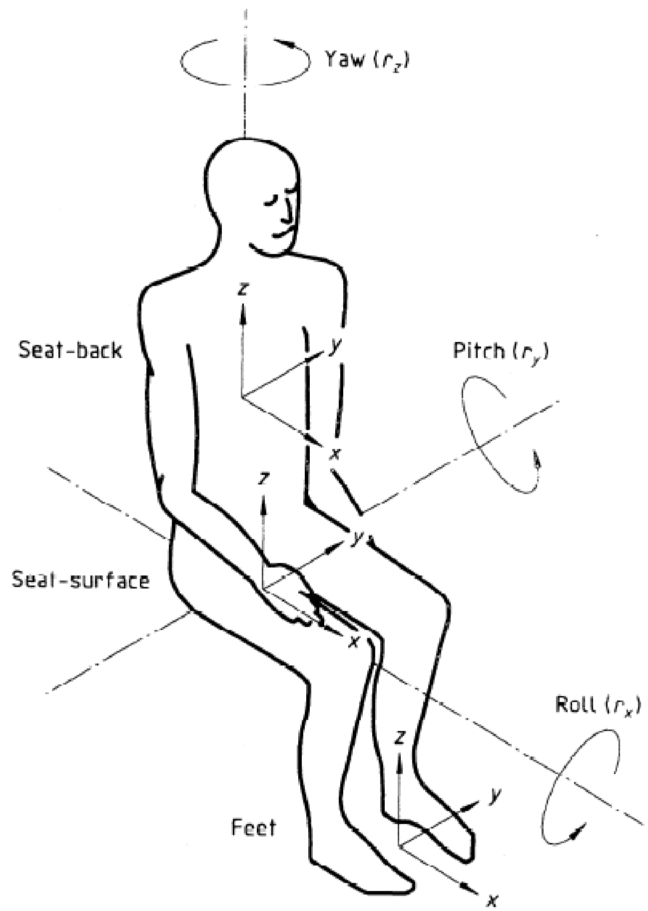


Figure 1-1. Basicentric axes of the seated human body. Adapted from ISO 2631-1 (1997).

1.5.2 Frequency weighting

The vibration frequencies that affect health, activities and comfort are between 0.5 to 80 Hz (ISO 2631-1, 1997). Frequencies below 0.5 Hz and above 80 Hz are considered not important for health evaluation. Accordingly, frequency weightings are needed to filter the vibration signals on different axes. Two main frequency weightings relative to health are often used. W_k filter is used for the vertical direction and W_d filter is used for the two horizontal directions (Figure 1-2).

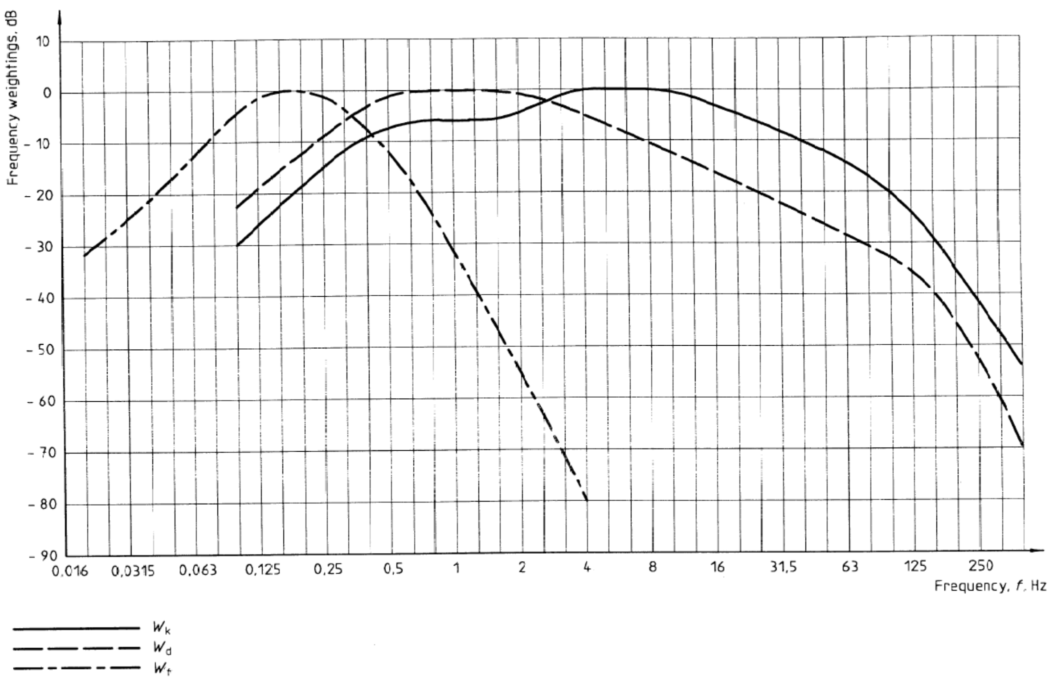


Figure 1-2. Principle frequency weighting curves adapted from ISO 2631-1 (1997).

The frequency-weighted acceleration in each axis is filtered by the corresponding frequency weightings, and multiplies weighting factors *k*:

k=1.4 for the x- and y- axes;

k=1 for the z-axis.

1.5.3 Vibration evaluation

1.5.3.1 The weighted root-mean-square (r.m.s.)

The magnitudes of vibration measurements are commonly calculated as the weighted r.m.s. acceleration (ISO 2631-1, 1997), expressed in m/s^2 for translational vibration and rad/s^2 for rotational vibration. The weighted r.m.s. acceleration is calculated according to the Equation 1-1.

$$a_w = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{\frac{1}{2}} \qquad (1\text{-}1)$$

where $a_w(t)$ is the weighted acceleration as a function of time, and T is the duration of the measurement.

1.5.3.2 The fourth power vibration dose value (*VDV*)

The *VDV* method is more sensitive to the vibration peaks than the basic r.m.s. evaluation method. It uses the fourth power instead of the second power of the time-dependent acceleration defined as Equation 1-2. The unit of *VDV* is in m/s$^{1.75}$ or rad/s$^{1.75}$.

$$VDV = \left\{\int_0^T [a_w(t)]^4 dt\right\}^{\frac{1}{4}} \qquad (1\text{-}2)$$

where $a_w(t)$ is the instantaneous frequency-weighted acceleration, and T is the duration of the measurement.

1.5.4 Health

ISO 2631-1 is primarily applied to seated health persons who are exposed to WBV at work. Two health guidance caution zones (HGCZs) are displayed in Figure 1-3, which are commonly used to evaluate the health risk of WBV exposure to participants. These two HGCZs are formed by two different Equations 1-3 and 1-4.

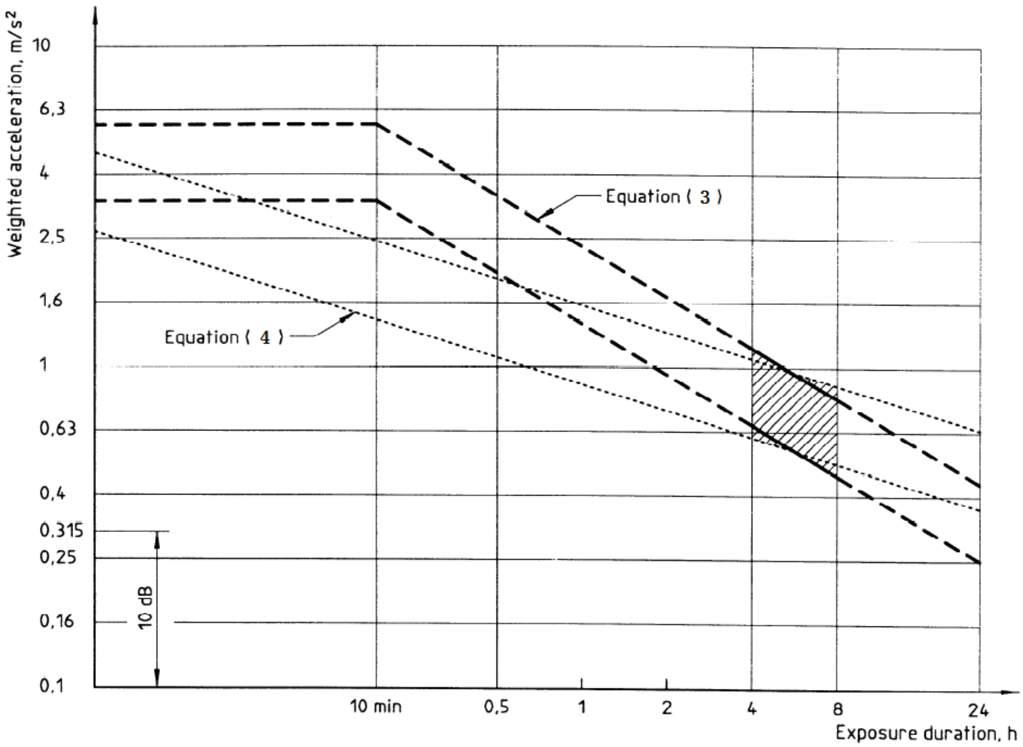


Figure 1-3. Health guidance caution zones. Adapted from ISO 2631-1 (1997).

Assuming the energy of weighted r.m.s acceleration and time duration is constant for each day, then the Equation 1-3 is represented by:

$$a_{w1} \cdot T_1^{1/2} = a_{w2} \cdot T_2^{1/2} \qquad (1\text{-}3)$$

where a_{w1} and a_{w2} are the weighted r.m.s. accelerations for the two daily exposures respectively, and T_1 and T_2 are the corresponding vibration durations.

Equation 1-4 indicates a time dependence by the following relationship:

$$a_{w1} \cdot T_1^{1/4} = a_{w2} \cdot T_2^{1/4} \qquad (1\text{-}4)$$

Both HGCZs for Equations 1-3 and 1-4 are approximately the same when the vibration durations are between 4 and 8 hours (the shading areas).

ISO 2631-1 indicates that health risks have not been clearly observed for the vibration exposures below the HGCZ (dashed lines, indicated by Equation 3). For vibration within the HGCZ, potential health risks may occur and therefore caution is indicated. However, above the HGCZ, health risks are likely. This recommendation is primarily relevant for exposures in the range of 4 to 8 hours.

1.5.5 Daily vibration exposure values

Daily vibration exposure can consist of more than one period of exposure with different magnitude and duration. In order to characterize vibration exposure, the 8-hour frequency-weighted acceleration, $A(8)$, can be calculated. This equivalent vibration magnitude can be evaluated corresponding to the overall duration of exposure (Equation 1-5).

$$a_{we} = \left[\frac{\sum a_{wi}^2 \cdot T_i}{\sum T_i}\right]^{\frac{1}{2}} \qquad (1\text{-}5)$$

where a_{we} is the equivalent vibration magnitude, and a_{wi} is the individual acceleration for the exposure duration T_i.

1.6 Thesis organization

After the introduction as described in this Chapter, the remainder of this thesis is organized as follows: A neural network (NN) mathematical modeling algorithm is introduced in the Chapter 2. This method is implemented in the following three Chapters (3-5).

In the Chapter 3, we successfully identified the vibration attenuation properties for each of the five industrial seats based on this intelligent NN method. We evaluated their performances for each of the eight sample skidder vehicles in the forestry environment.

In the Chapter 4, we expanded this NN approach to evaluate the influence of different seats on the WBV exposures from load-haul-dump (LHD) vehicles in the underground mining environment. We performed a sensitivity analysis to evaluate the influence of the individual vibration frequency components on the *A*(8) results for each of the seat models.

In the Chapter 5, a No-Jolt^{TM} air-inflated cushion was selected to evaluate its vibration attenuation properties. We predicted the seat/cushion performances in different environments by using this NN modeling approach. We also evaluated the seat/cushion transmissibility with jolt vibration exposures to determine the effectiveness of the new No-Jolt^{TM} air-inflated cushion.

Finally, some conclusion remarks as well as the future directions are presented in the Chapter 6.

Chapter 2

2 Neural network (NN) seat models

A neural identification network was developed to model the system dynamics of each seat (Figure 2-1). We used a 5-layer network in which each node performs a particular activation function for the incoming signals. The input nodes in layer 1 consisted of the recorded time series chassis vibration data; these nodes transmitted the recorded translational chassis acceleration data $\{x_{xi}, x_{yi}$ and x_{zi}, $i = 1, 2, \cdots; N\}$, where i is the recorded signals, to the next layer. The total training set consisted of N vibration exposures (each participant was exposed to ten field vibration exposures and seven random vibration exposures). Accordingly, the integer index for the training algorithm extended from 1 to N. The *BMI Prime* value, defined as the body mass index (*BMI*) divided by 25 (Gadzik, 2006), was an additional input to our model. This parameter reflected participant anthropometrics. Each node in layer 2 acted as a band pass filter. Seventeen band pass filters were defined based on the 1/3 octave frequency bands between 0.5-20 Hz; they were used to filter the recorded superior-inferior (Z) axis chassis acceleration data. Another two band pass filters between 0.5-20 Hz were used for the anterior-posterior (X) and medial-lateral (Y) direction chassis acceleration data. The r.m.s. values of the recorded chassis vibration data calculated in layer 3, and the corresponding *BMI Prime* values in layer 1, were used to predict the vertical seatpan r.m.s. accelerations in layer 4 by the linked NN weighting parameters.

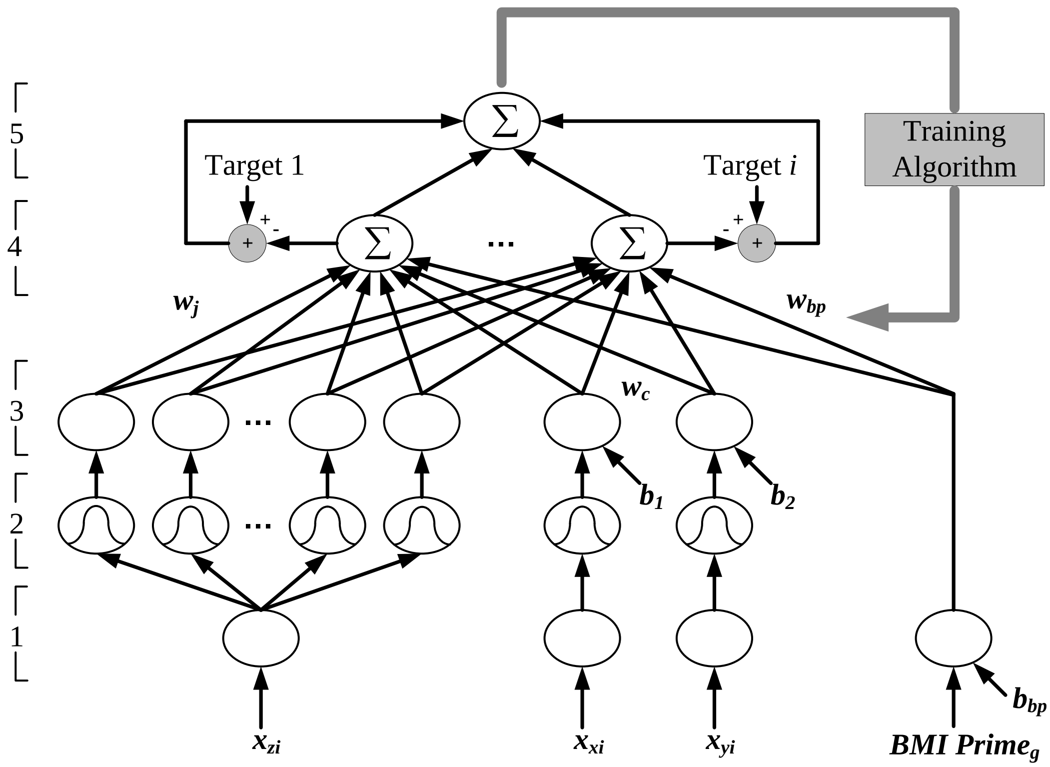


Figure 2-1. 5-layer neural network architecture with *BMI Prime* values and chassis r.m.s. accelerations in X,Y and Z directions as inputs, and the predicted seatpan r.m.s. accelerations as outputs. Weights and biases were trained by gradient method in the layer 5.

The network outputs in layer 4 were computed as the sum of incoming signals using Equation 2-1. $\mathbf{O}^{(3)}(k) = \{ O_{ji}^{(3)}(k), O_{ci}^{(3)}(k)\}$ denotes the r.m.s. magnitudes of the recorded chassis vibration data at the *kth* iteration in layer 3, and $O_i^{(4)}(k)$ denotes the forecasted output of the *i*th neuron at the *kth* iteration in layer 4 (the predicted vertical seatpan r.m.s. acceleration).

$$O_i^{(4)}(k) = \sum_1^j w_j \cdot O_{ji}^{(3)}(k) + \sum_1^c w_c \cdot (O_{ci}^{(3)}(k) + b_c) + w_{bp} \cdot (BMI\_Prime_g + b_{bp})$$
$$(i = 1, 2, \cdots N;\ j = 1, 2, \cdots 17;\ c = 1 \text{ and } 2); \qquad (2\text{-}1)$$

where $\mathbf{w} = \{w_j, w_c, w_{bp}\}$ are the weights of links from the *j*th neuron and *c*th neuron in layer 3, and the *BMI Prime* neuron in layer 1 to the *i*th neuron in layer 4 respectively; b_c

is the bias of the *c*th neuron in layer 3; and b_{bp} is the bias of *BMI Prime* neuron in layer 1; g is the number of subjects.

The NN model's optimal weights and biases were determined through system identification by matching the predicted outputs to the corresponding measured values in a processing layer 5. In our case, $y_i^{(4)}(k)$ denotes the measured (target) seatpan r.m.s. acceleration of the *i*th neuron in layer 4, $e_i^{(4)}$ is the squared error between the measured and predicted outputs, and the objective function $E^{(5)}(k)$ at the *kth* iteration was defined using Equation 2-2.

$$E^{(5)}(k) = \sum_1^i e_i^{(4)}(k) = \sum_1^i [O_i^{(4)}(k) - y_i^{(4)}(k)]^2; \qquad (2-2)$$

The objective function, minimizing $E^{(5)}(k)$, was used to adjust the weights and biases iteratively to improve the agreement between the measured and the predicted outputs. This was performed through computing the gradients of the matrix $\mathbf{P} = \{\mathbf{w}, b_c, b_{bp}\}$ by using partial derivatives (Equation 2-3).

$$\nabla_p E^{(5)}(k) = \frac{\partial E^{(5)}(k)}{\partial \mathbf{p}} = \sum_1^i \frac{\partial e_i^{(4)}(k)}{\partial \mathbf{p}} = \sum_1^i \left(\frac{\partial e_i^{(4)}(k)}{\partial O_i^{(4)}(k)} \cdot \frac{\partial O_i^{(4)}(k)}{\partial \mathbf{p}}\right); \qquad (2-3)$$

where $\nabla_p E^{(5)}$ is the gradient error with respect to the weights and biases, and **P** is the matrix combining weights and biases, which was unique for each of the five seats and represented the model of each individual seat.

The matrix **P** was updated during each training iteration based on the magnitude of the gradient error tempered by the learning rate (η_p) according to Equation 2-4.

$$\mathbf{P}(k+1) = \mathbf{P}(k) - \eta_p * \nabla_p E^{(5)}(k); \qquad (2-4)$$

where **P** (k+1) is the matrix of weights and biases at the *k+1th* iteration, **P** (k) is the matrix of weights and biases at the *kth* iteration. The learning rate η_p was selected to improve training convergence, and was set to 0.0001 in this case.

Once the optimal weights and biases were determined through training, then the model could be deployed to predict the seatpan r.m.s. accelerations for any chassis vibration pattern. Although the structure of each model was identical, the weights and biases were unique for each model, and therefore each model described the specific vibration attenuation properties of each seat.

Normally the speed of convergence during learning is predominantly affected by the size of the data set and the number of neurons in the NN structure. In this study, although there were a relatively large number of neurons in layer 2, the learning converged more quickly than the classic recurrent gradient-based algorithms (Mastorocostas and Theocharis, 2002) because there were no recurrent weighting parameters in the middle layers. Moreover, the parameter initialization in this study was much simpler than the classic neural network training approach (Timotheou, 2009); initial weights and biases were defined as 1.0 and 0.0 respectively, which greatly simplified the time-consuming problem of parameter initialization.

We implemented this NN model in Excel (Version 2007, Microsoft Corp., Redmond, WA, USA), similarly to other researchers (Aloy et al., 1997). The advantage of building our analysis on a broadly available platform is that there are fewer barriers to disseminating the seat selection algorithm.

Chapter 3

3 Optimizing seat selection for skidders in the forestry environment

3.1 Introduction

Forestry is one of the Ontario industry sectors with the highest lost time injury rates (Workplace Safety and Insurance Board of Ontario, 2013). The lower back was the leading part of the body injured in eight of the past ten years (Workplace Safety and Insurance Board of Ontario, 2013). Those data are consistent with other reports. For example, the 12 month prevalence for low-back musculoskeletal symptoms has been reported as 22.7% (Hagen et al., 1998) and the 12 month prevalence for low-back disorders has been reported as 42% (Rehn et al., 2002). Sutinen et al. (2006) reported that 38% of forestry workers were diagnosed with neck pain and low back pain. Jack et al. (2010) reported that Northern Ontario skidder drivers were exposed to large amplitude of vibration, and these high exposure levels were associated with severe health issues (e.g. low back pain). Clearly, low-back injuries related to whole-body vibration represent a significant public health problem in the forestry environment.

Seating is one of the easiest engineering controls to significantly influence vibration exposure transmitted to the heavy machine operators, and to reduce health risks (Griffin, 1978). However, some studies have revealed that suspension seats frequently amplify vibration exposures (Cation et al., 2008; Dentoni and Massacci, 2013; Donati, 2002). Various factors influence the performance of suspension systems such as inappropriate adjustment (Paddan and Griffin, 2002) or frequency-dependent properties (Gunaselvam and Van Niekerk, 2005). The purpose of this study was to implement our neural network (NN) modeling algorithm introduced in the Chapter 2, and to perform a head-to-head comparison of the vibration attenuation properties of different seats for forestry mobile machinery operation. It will enable workplaces to assess the impact of seat choices on heavy machinery operators’ vibration exposure, as well as health and safety, before purchasing the seats.

3.2 System setup

A robotic 6 degree of freedom (df) platform (R3000, Mikrolar Inc. Hampton, NH, USA; Figure 3-1) produced vibration exposures collected from field studies of heavy mobile machinery (Dickey et al., 2010), or random vibrations. The vibration attenuation properties of five different industrial seats (Amobi, Access, Caterpillar (CAT), KAB301 and KAB525; Table 3-1) were tested by mounting them to the top surface of the robotic platform. Each seat suspension was adjusted to its mid-travel position for each of the subjects. Two inertial measurement units (IMUs; MechTrack – Analog version, Mechworks Systems Inc., West Vancouver, BC, Canada), were used to record translational accelerations and rotational velocities at the center surface of the robotic platform (chassis) and the seatpan-operator interface (this IMU was embedded in a semi-rigid rubber mounting disc and placed on the seatpan). The analog data from the IMUs were sampled at 500 Hz using a 16 bit NI PXI-6143S board (National Instruments, Austin, TX, USA). Angular accelerations were calculated from the angular velocity data using finite differences. Ten subjects (seven male, three female; anthropometrics presented in Table 3-2) with no history of low-back pain were tested to develop the neural network (NN) model for the industrial seats. The NN modeling method is introduced in the Chapter 2. Given that subject anthropometrics are known to modulate their biodynamic response (ISO 5982, 2001), we incorporated *BMI Prime* as an additional input to the models. This effectively scaled the *BMI* to be close to 1.0 so that it was better conditioned such that the training process was faster than if *BMI* was used as the input in the NN scheme. Subjects wore a seatbelt, and they sat upright with their back in contact with the seat back and their feet resting on the platform surface.

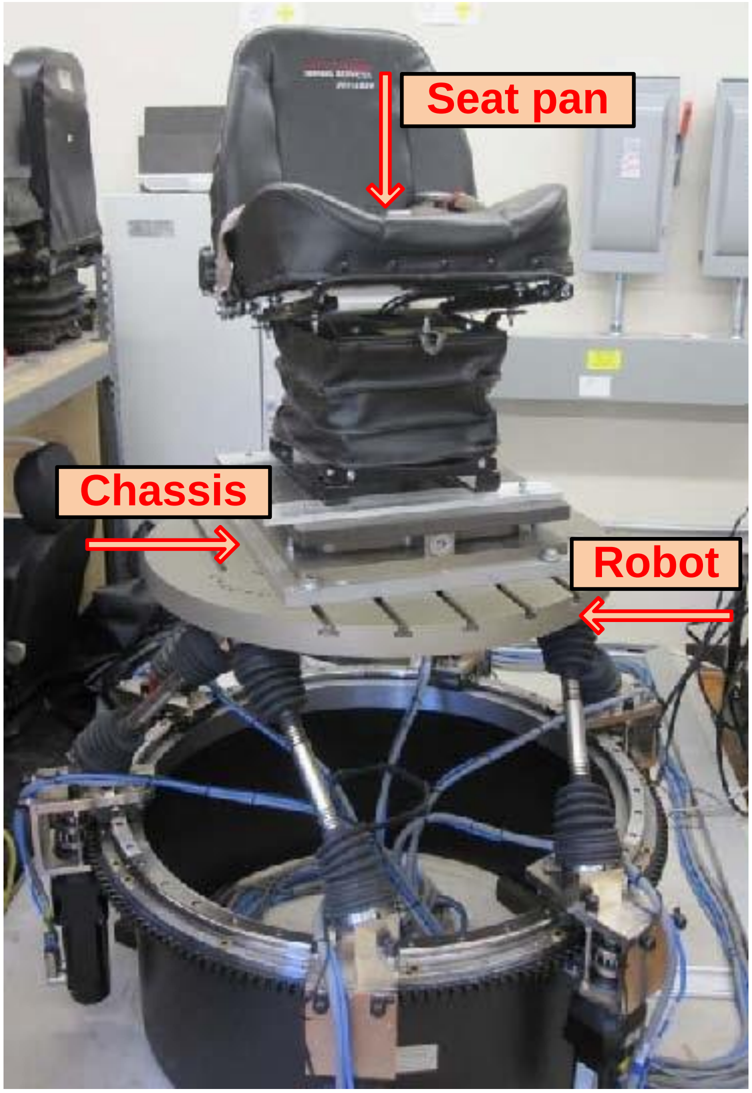


Figure 3-1. System setup showing an industrial seat mounted to the robot. The locations of the chassis and seatpan accelerometers are also shown.

Table 3-1. Details for the five industrial seats that were modeled in this study.

Industrial Seats	Manufacturers	Model
	Access mining services	Access 30019932
	Access mining services	Amobi SM2024
	Sears Manufacturing Co.	CAT EW013121
	KAB seating Ltd.	KAB 301
	KAB seating Ltd.	KAB 525

Table 3-2. Anthropometric parameters (height, mass, *BMI* and *BMI prime*) for the ten subjects. These data are presented for each of the four *BMI Prime* groups.

BMI Prime	Sex of subjects		*Mass* (kg)	*Heights* (m) Mean (SD)	*BMI* (kg/m^2) Mean (SD)	*BMI Prime* Mean (SD)
	Male	Female	Mean (SD)			
<0.74	0	1	54.5 (0.00)	1.72 (0.00)	18.42 (0.00)	0.73 (0.00)
0.74-1.0	3	1	71.0 (4.12)	1.79 (0.03)	22.08 (0.79)	0.88 (0.03)
1.0-1.2	3	0	82.3 (3.79)	1.80 (0.05)	25.41 (0.34)	1.02 (0.01)
>1.2	1	1	99.0 (4.24)	1.76 (0.13)	32.11 (3.27)	1.28 (0.13)

3.3 Vibration exposures

ISO 2631-1 standard suggests that the frequencies between 0.5 to 80 Hz impact human health. However the resonant frequencies for the human torso are between 4 and 6 Hz for the entire torso with the lower spine and pelvis, and between 10 and 14 Hz for the upper torso with forward flexion movements of the upper vertebral column respectively (Brammer, 2010). Furthermore, vertical accelerations are thought to have the highest risk of health consequences. The frequency weighting filter for vertical acceleration (W_k) greatly attenuate the signals that are less than 0.5 Hz and above 20 Hz; the amplitudes are reduced by -7.57 dB and -3.93 dB respectively (ISO 2631-1, 1997). Accordingly, we believe that the frequency range 0.5-20 Hz appropriately reflects the particular frequencies that influence human health.

Random broad-band vibration signals were used to develop each NN seat model. These broadband signals are convenient for this purpose as they contain all frequencies and therefore ensure robust models (Smith et al., 2008). We generated signals with uniform flat spectra between 0.5-20 Hz, with r.m.s. amplitudes between 0.2 and 2.0 m/s^2 on all three translational axes. In contrast to random signals, field vibration profiles consist of specific vibration spectra signatures and complicated features, such as shocks and jolts, which may lead to an incomplete assessment of the vibration exposures (Els, 2005;

Griffin, 1978) and might be poorly suited to develop the models. Our current library of occupational vibration exposures (Dickey et al., 2010) includes field measurements from routine workplace operations of specific vehicle types. The models were validated using thirty field vibration profiles representing the most common vibration characteristics of the field exposures (Dickey et al., 2010); this ensured that the models appropriately describe the target vibrations in the field. The r.m.s. and peak acceleration, crest factor (equal to peak value/r.m.s. value) and dominant frequency (DF) of each of these thirty selected field vibration exposures on the three translational axes are listed in Table 3-3. For the human subject testing, each participant was tested using seven random vibration exposures, and ten randomly selected field exposures from the set of thirty.

Table 3-3. The chassis r.m.s. and peak acceleration, crest factor and dominant frequency (DF) of each of the thirty field vibration exposures that were used to validate the NN models.

Vibration exposures	x-axis				y-axis				z-axis			
	r.m.s. m/s^2	peak m/s^2	crest factor	DF Hz	r.m.s. m/s^2	peak m/s^2	crest factor	DF Hz	r.m.s. m/s^2	peak m/s^2	crest factor	DF Hz
1	0.04	0.18	4.58	16	0.03	0.11	4.05	16	0.05	0.21	4.13	2.5
2	0.07	0.44	6.47	16	0.08	0.5	6.31	2.5	0.04	0.31	7.05	16
3	0.14	0.73	5.35	16	0.15	0.84	5.68	16	0.08	0.59	7.58	16
4	0.06	0.23	3.81	12.5	0.06	0.29	5.22	16	0.06	0.28	4.66	10
5	0.06	0.29	5.24	16	0.06	0.27	4.4	0.8	0.1	0.47	4.59	4
6	0.05	0.24	4.71	2.5	0.06	0.34	5.7	6.3	0.03	0.18	5.89	1.25
7	0.06	0.3	5.15	1.25	0.07	0.4	5.86	12.5	0.04	0.36	8.66	1.25
8	0.08	0.31	4.03	1.25	0.04	0.15	3.98	16	0.14	0.52	3.7	2.5
9	0.05	0.19	3.57	2.5	0.13	0.57	4.54	2.5	0.04	0.19	5.22	2.5
10	0.05	0.2	3.7	2.5	0.13	0.58	4.58	2.5	0.04	0.19	5.11	2.5
11	0.07	0.26	3.95	1.25	0.06	0.18	3.25	1.6	0.05	0.28	5.88	2.5
12	0.05	0.17	3.15	2	0.08	0.27	3.2	1	0.07	0.26	3.81	2
13	0.04	0.23	5.84	1.25	0.03	0.23	7.63	16	0.05	0.2	4.47	2.5
14	0.12	0.75	6.52	2.5	0.05	0.25	4.99	1.6	0.09	0.35	3.75	2.5
15	0.1	0.31	3.22	1.6	0.07	0.29	3.96	1.6	0.3	1.26	4.26	3.15
16	0.05	0.25	4.92	1.25	0.06	0.29	4.62	0.8	0.08	0.27	3.57	2
17	0.07	0.27	4.01	1.6	0.07	0.28	4.07	3.15	0.25	0.73	2.98	2
18	0.1	0.35	3.49	16	0.07	0.3	4.04	12.5	0.29	1	3.43	4
19	0.12	0.46	3.72	16	0.15	0.55	3.69	4	0.42	1.25	2.98	3.15
20	0.16	0.61	3.74	12.5	0.15	0.58	3.96	4	0.46	1.5	3.28	4
21	0.06	0.2	3.55	1.6	0.08	0.3	3.52	1.25	0.08	0.32	3.89	2
22	0.11	0.49	4.47	2	0.05	0.22	4.37	2	0.07	0.43	5.88	2.5
23	0.05	0.17	3.68	16	0.04	0.25	5.92	16	0.08	0.31	4.01	2.5
24	0.05	0.19	3.6	2.5	0.13	0.57	4.56	2.5	0.04	0.18	5.15	2.5
25	0.08	0.44	5.61	12.5	0.09	0.47	4.99	5	0.14	0.76	5.41	2.5
26	0.04	0.13	3.51	12.5	0.04	0.15	4.07	10	0.06	0.28	4.94	2.5
27	0.05	0.3	6.12	16	0.05	0.21	3.88	1.6	0.07	0.24	3.38	12.5
28	0.06	0.37	5.99	1.25	0.06	0.31	5.69	2	0.15	0.55	3.56	2
29	0.1	0.4	3.84	3.15	0.04	0.25	5.66	2	0.2	0.64	3.17	3.15
30	0.05	0.29	5.8	16	0.05	0.26	4.95	1.6	0.09	0.68	7.41	2.5

3.4 Evaluation each of five models

Each of the five seat models were evaluated by correlating the observed and predicted seatpan accelerations (Pearson product-moment correlation). Agreement was assessed using the gain and offset parameters from the line of best fit (Equation 3-1); the ideal slopes (*M*) were 1.0 and intercepts (*B*) were 0.0. The percent of measured seatpan r.m.s. acceleration variance that was explained by the model was expressed through the coefficients of determination (r^2; (McClure, 2005).

$$Y = M * X + B; \qquad (3\text{-}1)$$

3.5 Daily vibration exposure *A*(8) calculations

The equivalent exposures for a full day of vibration (8-hours) were calculated based on the predicted seatpan accelerations in the vertical direction. In specific, Daily Vibration Exposure *A*(8) values were predicted for eight representative skidder vehicles (Table 3-4 and 3-5) and each of the industrial seats using Equation 3-2 (ISO 2631-1, 1997). For each machine operation task of each specific skidder, the chassis acceleration data from the field measurements were frequency weighted in the time domain using the W_d filter for the X and Y axis data, and the W_k filter for the Z axis data, and then the appropriate axis multiplying factors for evaluating health were applied (e.g. k_x=k_y=1.4 and k_z=1.0; ISO 2631-1, 1997). The r.m.s. magnitudes of these frequency-weighted chassis translational acelerations were calculated using the 1/3 octave filters (z axis) and bandpass filters (x and y axes) mentioned in the Neural Network seat models section. Then we used these chassis weighted r.m.s. values as inputs of each NN seat model to predict the vertical seatpan weighted r.m.s. accelerations. Similarly to other studies (Eger et al., 2011b) , *A*(8) values were modeled based on the predicted weighted seatpan r.m.s. acceleration and the corresponding durations of each machine operation task; we also included three specific *BMI Prime* values (0.74, 1.00 and 1.20), equal to *BMI* values of 18.5, 25 and 30, to reflect the influence of machine operator anthropometrics. Also, similarly to Mansfield and Griffin (2000), we calculated the number of working hours to reach the upper limit (0.9 m/s^2) of the ISO 2631-1 health guidance caution zone (HGCZ) for 8-hour of exposure in order to contextualize the impact of seat selection.

$$A(8)_{hl} = \left[\frac{(\sum(a_v^2 * T_v))}{\sum T_v} \right]^{\frac{1}{2}}; \qquad (3-2)$$

where $A(8)_{hl}$ is the weighted equivalent daily r.m.s. accelerations; a_v is the weighted vibration r.m.s. accelerations for exposure duration T_v. h is the number of skidders and l is the number of seats.

Table 3-4. Summary of skidder operating conditions. Reprinted from Jack, R. J., Oliver, M., Dickey, J. P., Cation, S., Hayward, G., Lee-Shee, N., ‘Six-degree-of-freedom whole-body vibration exposure levels during routine skidder operations’, Ergonomics 53, 696-715 (2010) with permission from the Taylor & Francis Ltd, http://www.tandfonline.com.

		Skidder							
		1	2	3	4	5	6	7	8
Skidder type		Grapple	Grapple	Grapple	Grapple	Grapple	Grapple	Cable	Cable
Seat orientation (°)		0	25	15	10	10	25	0	0
Operator reported maintenance history		Greased every other day, oil changed every 500 hours	Greased every other day, oil changed every 250 hours	Greased each day, oil changed each month (every 176 h)	Greased each day, oil changed every 500 h	Greased each day, oil changed every 200 h	Greased that day, oil changed every 150-200 h	Greased once a week, oil changed each month (every 60 h)	Greased every other day, oil changed each month (every 160 h)
Operator reported tyre pressure (psi)		35	45	33.5	25	33.5	45	30	30
Terrain description	Landscape	Large hills	Large hills	Flood bed with small rolling hills	Steep rolling hills	Steep rolling hills	Steep rolling hills	Small rock outcrops on small rolling hills	Small rock outcrops on steep rolling hills
	Travel path	Rocky with loose loam soil	Rocky with loose loam soil	Sand/loam mixed soil	Gravel with sand soil	Gravel with sand soil	Gravel with sand soil	Rocky with sand/loam mix soil	Clay soil with gravel and large rocks
	Forestation	Most trees cleared	Most trees cleared	Most trees remained standing	Most trees cleared	Most trees cleared	Most trees cleared	No cleared trees	Most trees cleared

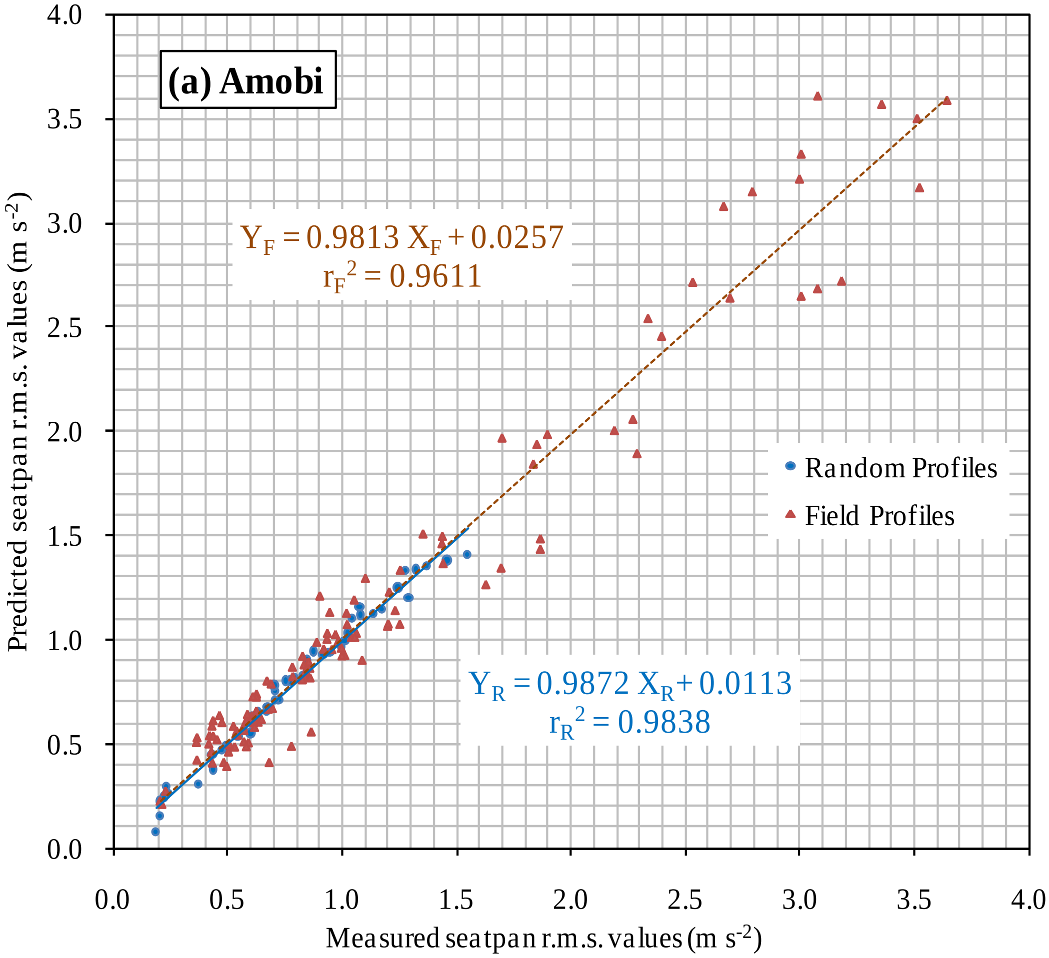
Table 3-5. Average and total data collection times for the five operating conditions monitored during field data collection for the eight skidders. Reprinted from Jack, R. J., Oliver, M., Dickey, J. P., Cation, S., Hayward, G., Lee-Shee, N., ‘Six-degree-of-freedom whole-body vibration exposure levels during routine skidder operations’, Ergonomics 53, 696-715 (2010) with permission from the Taylor & Francis Ltd, http://www.tandfonline.com.

	Operator								Total operating time (min)
	Skidder 1	Skidder 2	Skidder 3	Skidder 4	Skidder 5	Skidder 6	Skidder 7	Skidder 8	
Driving Loaded									
n	3	2	6	10	19	6	6	4	-
Average trial time (min)	1.85	0.83	1.75	0.98	1.08	3.5	5.22	4.07	-
SD (min)	0.43	0.71	1.33	0.2	0.86	1.57	2.97	2.23	-
Total operating time (min)	5.55	1.67	10.5	9.78	20.57	21	31.3	16.28	116.65
Driving Unloaded									
n	4	3	5	11	11	6	6	3	-
Average trial time (min)	3	1.22	3.29	0.96	1.22	3.49	3.37	4.54	-
SD (min)	1.05	0.94	1.64	0.29	0.8	1.56	3.58	2.94	-
Total operating time (min)	11.98	3.65	16.43	10.57	13.37	20.93	20.23	13.62	110.78
Dropping Off a Load									
n	3	2	3	8	10	5	-	3	-
Average trial time (min)	0.38	0.12	0.11	0.15	0.12	0.27	-	0.18	-
SD (min)	0.53	0.12	0.06	0.1	0.06	0.31	-	0.09	-
Total operating time (min)	1.13	0.23	0.33	2.73	1.15	1.35	-	0.55	7.48
Picking Up a Load									
n	3	2	6	9	14	5	1	3	-
Average trial time (min)	0.41	0.41	0.54	0.24	0.41	0.67	-	0.18	-
SD (min)	0.09	0.25	0.66	0.15	0.32	0.2	-	0.06	-
Total operating time (min)	1.22	0.82	3.23	2.12	5.77	3.33	0.42	0.55	17.45
Ploughing									
n	-	-	1	6	5	-	1	-	-
Average trial time (min)	-	-	-	0.66	0.83	-	-	-	-
SD (min)	-	-	-	0.27	0.28	-	-	-	-
Total operating time (min)	-	-	1.17	3.97	4.13	-	1.85	-	11.12
Total operating time (min)	19.88	6.36	31.66	29.17	44.99	46.62	53.8	31	263.48

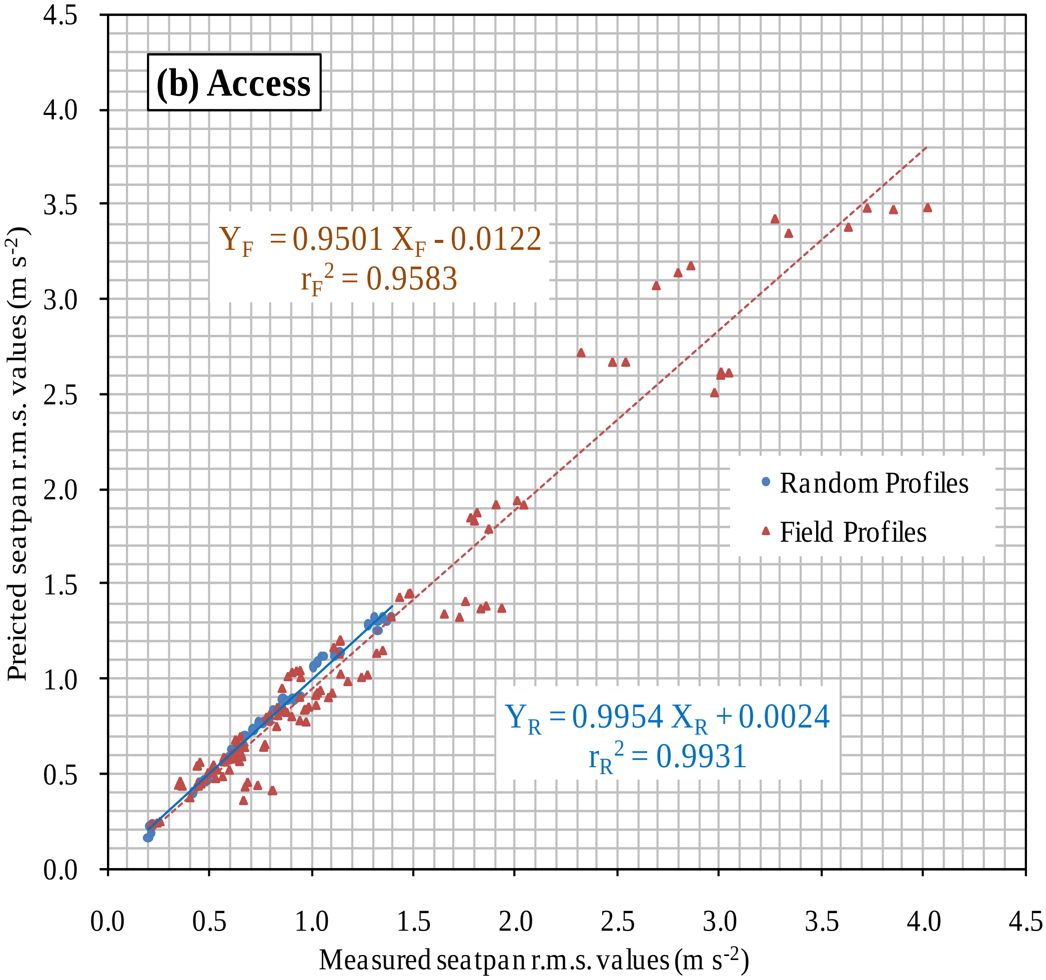
3.6 Results

3.6.1 Modeling five seats

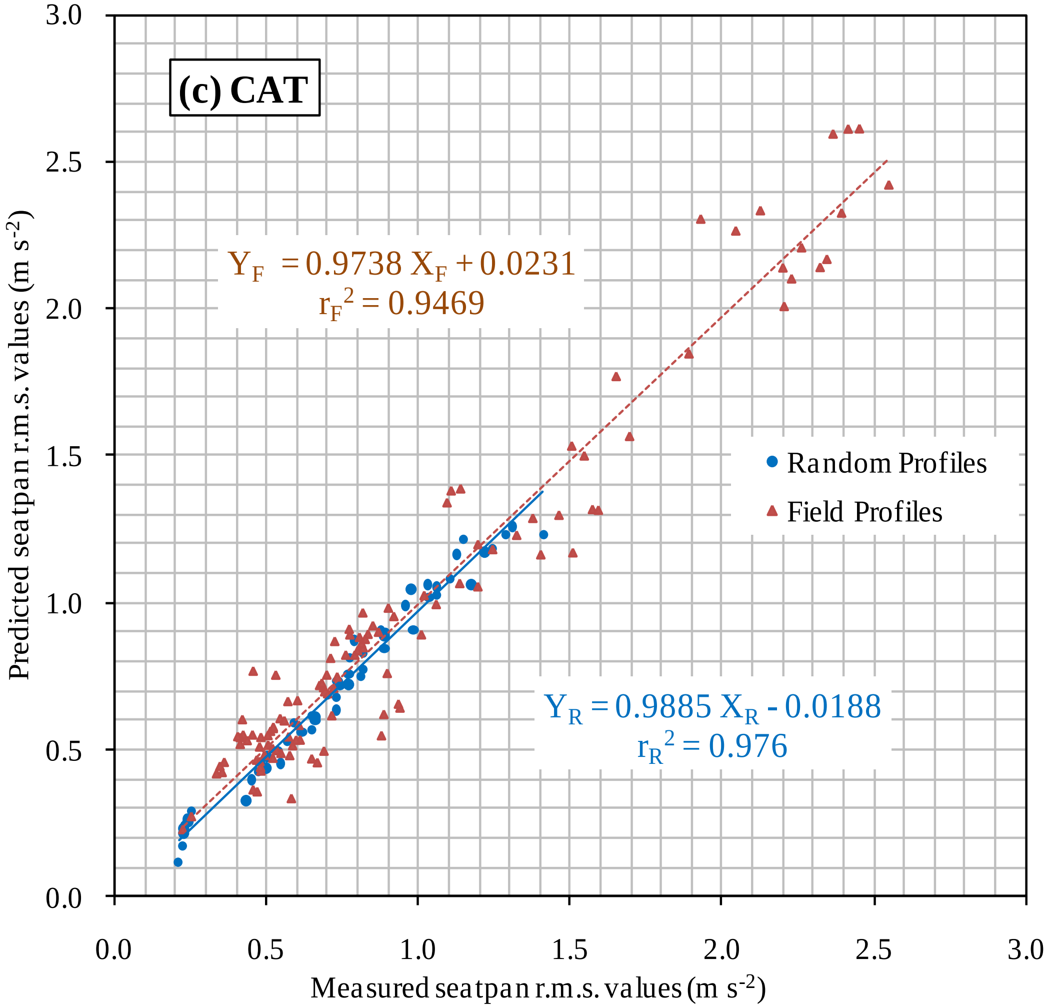
The dynamic response of five industrial seats were successfully modeled using a NN approach applied to broadband random vibration signals, and validated the models using field profiles (Figure 3-2). The seatpan r.m.s. accelerations for the random profiles ranged from approximately 0.2 to 1.5 m/s^2, and the field profiles extended up to approximately 3.5 m/s^2. Accordingly the models were developed on a smaller range of vibration magnitudes and the validation involved extrapolating to larger vibration magnitudes. This is not optimal as the field trials involved a solution space that extended beyond the range that the NN models were trained on. Although the correlations were typically smaller in the validations compared to the models development, excellent correlations for both the training and validation sets were achieved for all of the seats. The coefficients of determination (r^2) between the measured and predicted seatpan r.m.s. accelerations for the training profiles ranged between 0.97-0.99, and were slightly lower for the validation profiles (r^2 between 0.93-0.96). The slopes of linear regression equations were also close to 1.0 and the intercepts were close to zero (Figure 3-2).



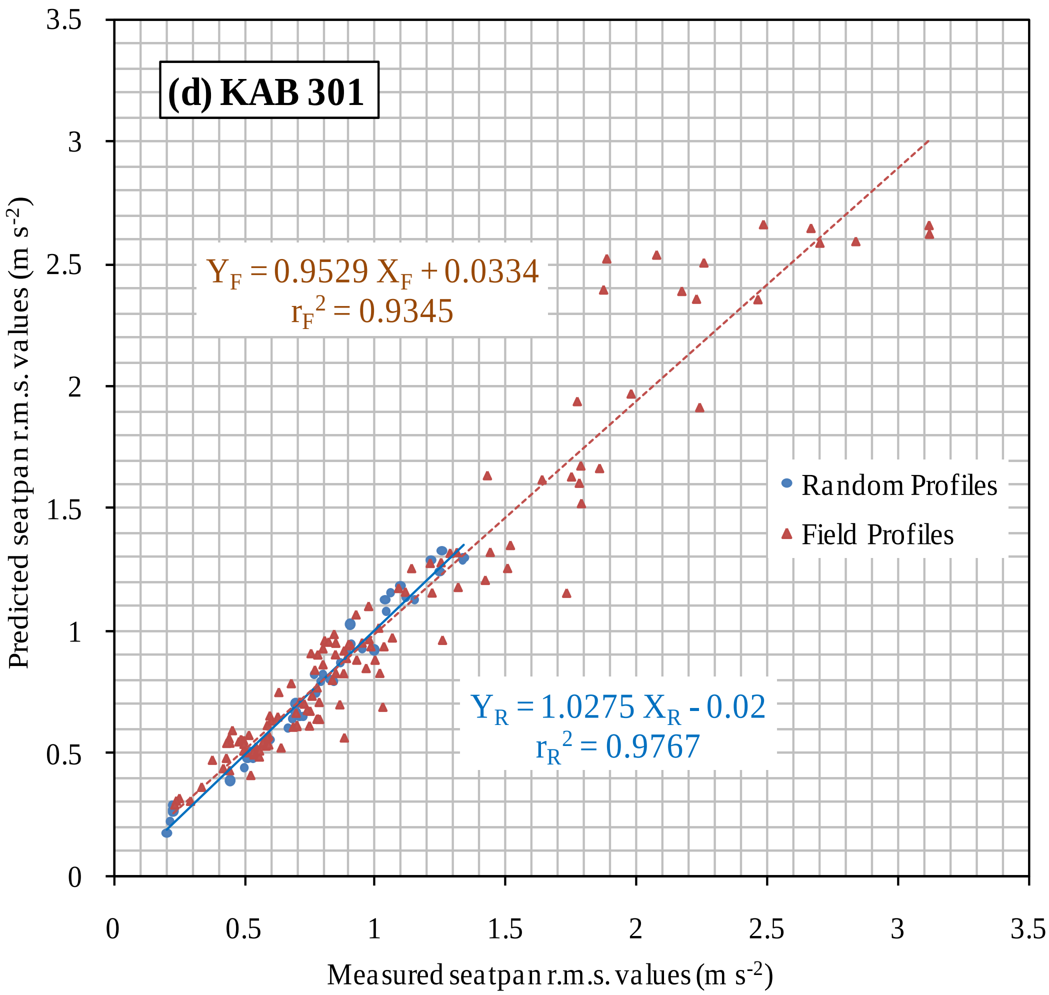
(a) Amobi
$Y_F = 0.9813\ X_F + 0.0257$
$r_F^2 = 0.9611$
$Y_R = 0.9872\ X_R + 0.0113$
$r_R^2 = 0.9838$
Random Profiles
Field Profiles
Predicted seatpan r.m.s. values (m s^{-2})
Measured seatpan r.m.s. values (m s^{-2})
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0



(b) Access
$Y_F = 0.9501\ X_F - 0.0122$
$r_F^2 = 0.9583$
$Y_R = 0.9954\ X_R + 0.0024$
$r_R^2 = 0.9931$
Random Profiles
Field Profiles
Preicted seatpan r.m.s. values (m s^{-2})
Measured seatpan r.m.s. values (m s^{-2})
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5



(c) CAT
$Y_F = 0.9738\ X_F + 0.0231$
$r_F^2 = 0.9469$
$Y_R = 0.9885\ X_R - 0.0188$
$r_R^2 = 0.976$
Random Profiles
Field Profiles
Predicted seatpan r.m.s. values (m s^{-2})
Measured seatpan r.m.s. values (m s^{-2})
0.0
0.5
1.0
1.5
2.0
2.5
3.0


(d) KAB 301
$Y_F = 0.9529\ X_F + 0.0334$
$r_F^2 = 0.9345$
$Y_R = 1.0275\ X_R - 0.02$
$r_R^2 = 0.9767$
Random Profiles
Field Profiles
Predicted seatpan r.m.s. values (m s^{-2})
Measured seatpan r.m.s. values (m s^{-2})
0
0.5
1
1.5
2
2.5
3
3.5

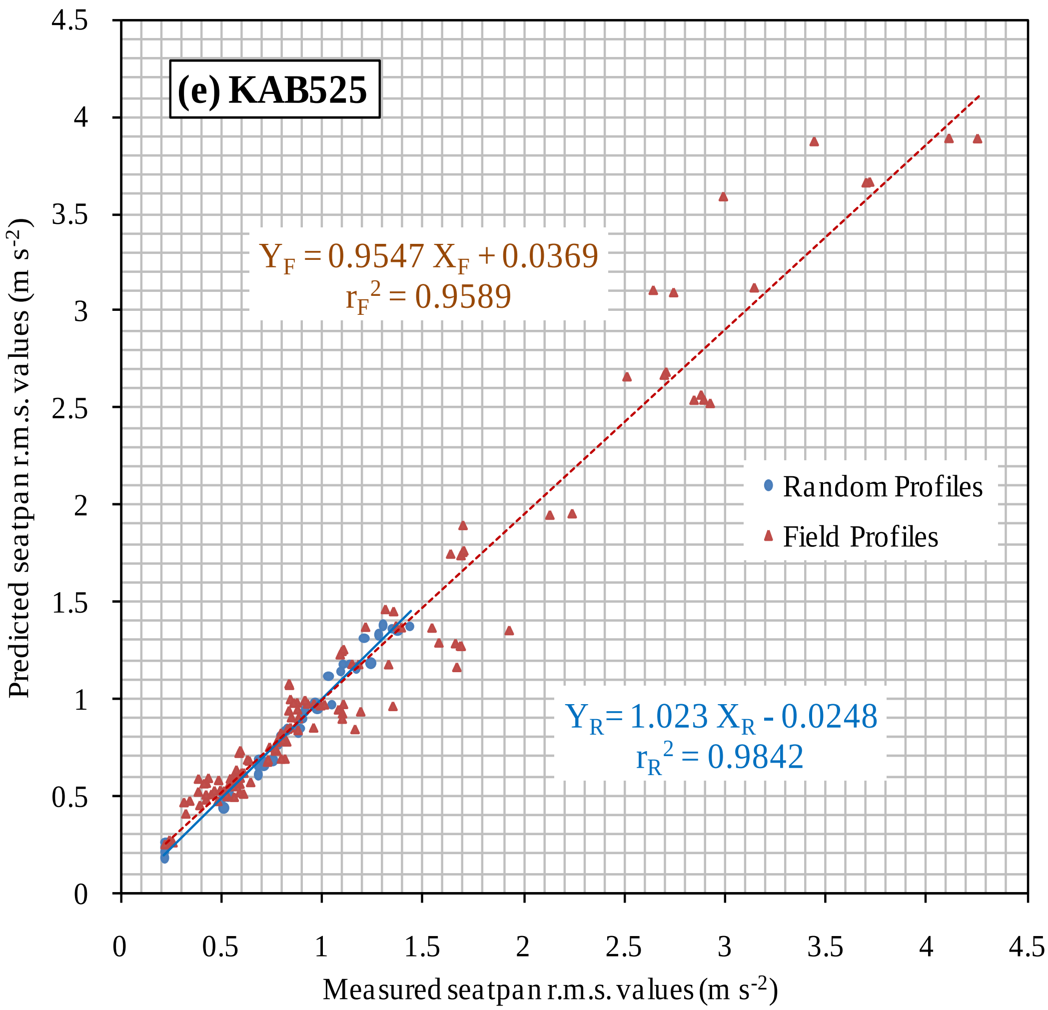


Figure 3-2. Relationship between the measured and predicted seatpan weighted r.m.s. acceleration from random profiles that were used to generate the NN models (blue circle symbols), and from field profiles that were used to validate the NN models (red triangle symbols) for five industrial seats. The regression equations and coefficients of determination are showed for the random and field trials for all seats.

3.6.2 *A*(8) results

The predicted *A*(8) accelerations varied substantially between industrial seats, and with *BMI Prime*. None of the seats were below the lower limit of the ISO 2631-1 HGCZ (0.45 m/s^2), and only one of the industrial seats attenuated 96% (23/24) of the vibration exposures of eight forestry vehicles with different *BMI Primes* below the upper limit of the ISO 2631-1 HGCZ (0.9 m/s^2; Table 3-6). The corresponding number of working hours to reach the upper limit of the HGCZ for 8-h work duration vibrations in this study ranged from a low of 2.43 hours up to a high of 22.86 hours depending on the industrial seat and the operator's *BMI Prime*. Subjects with larger *BMI Prime* values experienced smaller average daily vibration exposures *A*(8) than subjects with smaller *BMI Prime* values.

Table 3-6. *A*(8) results for five seats and three *BMI Prime* values and the working hours to reach the upper limit (0.9 m/s^2) of the ISO 2631-1 HGCZ for 8-h working duration. Bold values denote exposures that require more than 8 working hours to reach the upper limit of the ISO 2631-1 health guidance caution zone (HGCZ).

Skidders	*BMI Prime*	Access		Amobi		CAT		KAB301		KAB525	
		A(8) m/s^2	Hours	*A*(8) m/s^2	Hours	*A*(8) m/s^2	Hours	*A*(8) m/s^2	Hours	*A*(8) m/s^2	Hours
S1	0.74	0.80	**10.07**	0.99	6.67	0.68	**13.94**	0.81	**9.96**	0.87	**8.64**
	1.00	0.76	**11.16**	0.90	**8.07**	0.61	**17.43**	0.75	**11.59**	0.83	**9.48**
	1.20	0.73	**12.13**	0.83	9.48	0.55	**21.08**	0.70	**13.13**	0.80	**10.20**
S2	0.74	0.80	**10.01**	0.95	7.20	0.70	**13.32**	0.79	**10.32**	0.88	**8.45**
	1.00	0.76	**11.10**	0.86	**8.81**	0.63	**16.58**	0.73	**12.06**	0.84	**9.26**
	1.20	0.73	**12.07**	0.79	**10.45**	0.57	**19.97**	0.69	**13.71**	0.81	**9.97**
S3	0.74	0.79	**10.46**	0.98	6.73	0.81	**9.81**	0.90	7.96	0.86	**8.74**
	1.00	0.75	**11.62**	0.89	**8.17**	0.74	**11.79**	0.84	**9.12**	0.82	**9.59**
	1.20	0.72	**12.65**	0.82	**9.61**	0.69	**13.75**	0.80	**10.19**	0.79	**10.34**
S4	0.74	1.34	3.60	1.63	2.43	0.97	6.89	1.37	3.44	1.58	2.59
	1.00	1.30	3.83	1.54	2.72	0.90	**8.02**	1.32	3.75	1.54	2.72
	1.20	1.27	4.01	1.48	2.97	0.84	**9.09**	1.27	4.02	1.51	2.83
S5	0.74	1.11	5.28	1.33	3.69	0.86	**8.77**	1.13	5.11	1.30	3.84
	1.00	1.07	5.68	1.24	4.25	0.79	**10.44**	1.07	5.69	1.26	4.08
	1.20	1.04	6.03	1.17	4.77	0.73	**12.07**	1.02	6.20	1.23	4.28
S6	0.74	1.03	6.15	1.30	3.85	0.69	**13.45**	1.08	5.53	1.21	4.43
	1.00	0.99	6.67	1.21	4.46	0.62	**16.77**	1.02	6.19	1.17	4.73
	1.20	0.95	7.11	1.14	5.02	0.57	**20.23**	0.98	6.78	1.14	4.99
S7	0.74	0.87	**8.51**	0.99	6.55	0.77	**11.06**	0.84	**9.16**	0.94	7.29
	1.00	0.83	**9.35**	0.90	7.93	0.69	**13.47**	0.78	**10.60**	0.90	7.93
	1.20	0.80	**10.09**	0.83	**9.30**	0.64	**15.90**	0.74	**11.95**	0.87	**8.49**
S8	0.74	0.94	7.27	1.17	4.77	0.66	**14.85**	0.99	6.66	1.08	5.59
	1.00	0.90	7.94	1.07	5.61	0.59	**18.73**	0.93	7.54	1.04	6.02
	1.20	0.87	**8.52**	1.00	6.42	0.53	**22.86**	0.88	**8.34**	1.01	6.39

3.7 Discussion

The dynamic response of each industrial seat was successfully identified based on a NN concept model implemented in Excel; this enabled us to predict the r.m.s. magnitude of the seatpan vertical acceleration. Accelerations in three translational directions from chassis, and the corresponding subject *BMI Prime* values were used as an input to the NN model. Each of the seat models showed strong correlations between the measured and predicted seatpan r.m.s. accelerations, not only for the random (training) but also for the field (validation) profiles. The correlations for the validation sets remained strong (r^2>0.93) despite the fact that these data contained higher accelerations than the training data and therefore the validation trials involved extrapolations, which is typically not advisable (Dickey et al., 2002). Presumably this reflects that training the NN models using random signals to represent all frequency components, rather than the unique vibration signatures from field data, resulted in robust models. The strong fits in the validation data, including slopes of linear regression equations that are close to 1.0 and intercepts close to 0.0, bolster our confidence that the NN models are robust and can be applied to a broad variety of field vibration exposures.

We evaluated the health implications of these various seat choices by calculating the accelerations for *A*(8) equivalent daily exposure for 8-hour work durations. Given the chassis accelerations of eight sample skidder vehicles, none of the seats were below the lower limit of the ISO 2631-1 HGCZ. Only one of the industrial seats (CAT) limited the vast majority (23 of 24 scenarios) of vibration exposures within the HGCZ range (0.45-0.9 m/s^2), while over half of the *A*(8) values exceeded the upper limit of the HGCZ for each of the other four seats. Accordingly we predict that the CAT seat is the best choice (of the five tested seats evaluated in this study) for this particular forestry vibration environment to minimize the health risks of exposures to vibration. Moreover, we suggest that it is the only suitable choice among the five tested seats for this vibration environment as it was the only seat that reduced the vast majority of forestry vibration exposures (Dickey et al., 2010) for eight skidders and a variety of subject anthropometrics (different *BMI primes*) below the upper limit of the HGCZ. Its corresponding number of working hours to reach the upper limit of the HGCZ for 8-h work duration vibrations ranged from a low of 6.89 hours up to a high of 22.86 hours, which were much higher than other seats with respect to the same forestry vehicle and the same operator's *BMI Prime*.

The strengths of this study are the value of the predicted seatpan accelerations from the different industrial seat models and the versatility of the NN modeling approach implemented in readily available commercial software (Microsoft Excel). This simplified the training process and parameter initialization as our algorithm is more efficient than the general NN training schemes (Mastorocostas and Theocharis, 2002; Timotheou, 2009) because it greatly improved the convergence speed (because there were no recurrent weighting parameters in the middle layers) and simplified the time-consuming problem of parameter initialization. Similarly to others (Smith et al., 2008), we used random profiles to train the models; this is appropriate as these random profiles contain a wide representation of vibration frequencies. Our validation set included field measurements of vibration that were considerably larger magnitude than the random trials; the continued strong predictions of seatpan accelerations illustrates that our models are robust as they can be applied to larger magnitude vibrations, and vibrations with specific vibration spectra from field measures. Although our seat selection algorithm was based on the vertical vibration attenuation properties of the individual seats (the A(8) values were evaluated by the seatpan r.m.s. accelerations in the vertical direction), the NN models included the magnitudes of the horizontal and vertical chassis accelerations as the inputs; the magnitudes of the vertical seatpan accelerations were predicted based on the recorded chassis data on all three translational axes. This feature of the NN model reflects the known cross-axis transmissibility properties of industrial seats (Smith et al., 2008). The NN models included a measure of driver anthropometrics, *BMI prime*, and therefore identified the impact of different driver's anthropometrics on their vibration exposure. Although research studies have not revealed consistent effects of subject anthropometrics such as *BMI* and body mass (Milosavljevic et al., 2012b), our NN models yielded improved predictions when we incorporated the scaled *BMI* parameter (*BMI prime*) as an input. Interestingly, the strong predictions with our NN models were achieved without including the driver sex as an input parameter; this is consistent with a recent review of biodynamic responses that concluded that there was no large difference between male and female subjects (Rakheja et al., 2010).

In terms of limitations, the current study only predicted the vertical seatpan r.m.s. accelerations; it would be helpful to evaluate the influence of horizontal vibration exposures to operators with different industrial seats. Moreover, this study was based on a relatively small number of industrial seats, and a relatively small number of skidders for the field data; it would be helpful develop the seat models based on more random vibration exposures with a wider range of acceleration magnitudes, and to validate them on a broader range of field vibrations. The amplitudes of the random profiles for this study were constrained by performance limitations of the robotic platform. Also, increasing the number of subjects in each *BMI Prime* group will be another important factor for increasing confidence in the model. Although NN schemes suffer from problems such as difficulty determining the optimal number of neurons and network connections, overfitting, and require a large training data set (Asensio-Cuesta et al., 2010), NN schemes have been successfully used for this application.

Chapter 4

4 Optimizing seat selection for load-haul-dump (LHD) vehicles in the underground mining environment

4.1 Introduction

Load-haul-dump (LHD) vehicles are commonly used to excavate large quantities of minerals or rocks in underground mining environments. ISO 2631-1 standard (1997) presents tools to evaluate the health risk by evaluating the frequency weighted accelerations of vibration exposures. Several studies reported that operators of LHD vehicles are exposed to high magnitude WBV which often exceeds the ISO 2631-1 health guidance caution zone (HGCZ) (Aye and Heyns, 2011; Eger et al., 2006; Eger et al., 2011a; Kumar, 2004; Mandal and Srivastava, 2010; Smets et al., 2010; Van Niekerk et al., 2000; Village et al., 1989). LHDs are commonly associated with injury compensation claims (Burgess-Limerick, 2005), and one study reports that LHD operators experience LBP 4.25 times more frequently than control subjects who are not exposed to occupational WBV (Mandal and Srivastava, 2010).

Given that one particular industrial seat is the best choice (between five seats) to minimize the health risks of exposures to vibration in the forestry vibration environment (Chapter 3), the primary purpose in this study was to apply this NN approach to the LHD mining environment, and evaluate whether specific industrial seats perform well for LHDs in the underground mining environments. A second purpose was to identify the performance of these industrial seats at specific vibration frequencies by evaluating the effects of the individual frequency components on the $A(8)$ results, and reveal why the seat selection algorithm matched particular seats to specific vibration environments.

4.2 Methodology

The development of neural network (NN) models for the five industrial seats is presented in the Chapter 3. The NN models robustly described the relationship between measured and predicted seatpan r.m.s. accelerations; the coefficients of determination (r^2) ranged between 0.97-0.99 for the training profiles, and between 0.93-0.96 for the validation profiles.

Similarly to the evaluation method in the Chapter 3, we implemented each of our robust seat models to predict the daily 8-hour equivalent frequency weighted accelerations (ISO 2631-1, 1997) *A*(8), for ten LHD vehicles and three specific *BMI Prime* values (0.74, 1.00 and 1.20). These chassis acceleration data of ten LHD vehicles were collected from the mining workplace measurements (Dickey et al., 2010). We also estimated the number of working hours to reach the upper acceleration limit (0.9 m/s^2) of the ISO 2631-1 health guidance caution zone (HGCZ) for 8-hour of vibration exposures to effectively evaluate the health risk for operators and to select the most suitable seat for this mining environment.

In order to describe the frequency spectra of the vibration data, we calculated the 1/3 octaves between 0.5 and 20 Hz using the sound and vibration toolkit for LabVIEW (V10.0.1, National Instruments, Austin, TX) for each of the specific mining vehicles. Given the different vibration environment for skidders in the forestry workplace, we also performed this 1/3 octave analysis on the vibration data from eight skidders for comparison (Cation et al., 2008; Jack et al., 2010). We also performed a sensitivity analysis to gain insight into which of the input parameters most strongly influenced the output of each seat NN model. The sensitivity analysis consisted of evaluating the impact of perturbing the amplitudes of specific frequencies of the individual vehicle acceleration profiles; the acceleration magnitude in each of the 1/3 octave bands was perturbed up and down 50% towards the maximum and minimum range, and the *A*(8) acceleration magnitude was recalculated. Frequency bands that strongly influenced the output of the NN model will have a large range of *A*(8) magnitudes when their amplitude was perturbed. The *BMI Prime* was set to 1.0 for these sensitivity analyses.

4.3 Results

4.3.1 *A*(8) values and the corresponding working hours to reach the upper acceleration limit of the ISO 2631-1 HGCZ

The predicted seatpan accelerations for this group of 10 LHDs were large; of the 150 scenarios (10 LHDs, 3 operator *BMI Primes* and 5 seats) only two (two operator *BMI Primes* for one LHD) were below the lower border of the Health Guidance Caution Zone, 30 were within the Health Guidance Caution Zone, and 118 were above the Health Guidance Caution Zone (Table 4-1). On average, subjects with smaller *BMI Prime* values were predicted to experience larger average daily vibration exposures *A*(8) than subjects with larger *BMI Primes* (Table 4-1).

Table 4-1. *A*(8) results for five industrial seats with different driver anthropometrics (*BMI primes*) in the underground mining environments.

LHDs	*BMI Prime*	*A*(8)* (m/s^2)				
		Access	Amobi	CAT	KAB301	KAB525
M1	0.74	1.10	1.20	1.18	0.80	0.96
	1.00	1.06	1.11	1.10	0.74	0.92
	1.20	1.03	1.04	1.05	0.70	0.89
M2	0.74	1.04	1.15	1.21	0.80	0.92
	1.00	1.00	1.06	1.14	0.74	0.88
	1.20	0.97	0.99	1.09	0.69	0.85
M3	0.74	1.11	1.22	0.89	0.92	1.16
	1.00	1.08	1.14	0.82	0.86	1.13
	1.20	1.05	1.07	0.77	0.82	1.10
M4	0.74	0.60	0.69	0.50	0.66	0.69
	1.00	0.56	0.60	0.44	0.60	0.65
	1.20	0.53	0.53	0.39	0.56	0.62
M5	0.74	1.89	1.88	1.46	1.39	1.84
	1.00	1.85	1.79	1.39	1.33	1.81
	1.20	1.82	1.73	1.34	1.29	1.78
M6	0.74	1.54	1.58	1.39	1.15	1.43
	1.00	1.50	1.49	1.32	1.09	1.40
	1.20	1.47	1.42	1.27	1.05	1.37
M7	0.74	1.69	1.73	1.60	1.28	1.52
	1.00	1.65	1.64	1.53	1.22	1.49
	1.20	1.63	1.58	1.48	1.18	1.46
M8	0.74	1.24	1.30	1.15	0.87	1.12
	1.00	1.20	1.21	1.08	0.81	1.08
	1.20	1.16	1.14	1.03	0.77	1.05
M9	0.74	1.80	1.81	1.46	1.49	1.75
	1.00	1.76	1.73	1.39	1.43	1.71
	1.20	1.73	1.66	1.34	1.39	1.68
M10	0.74	1.56	1.63	1.58	1.45	1.47
	1.00	1.52	1.54	1.51	1.39	1.44
	1.20	1.49	1.47	1.45	1.35	1.41

* According to ISO 2631-1 the frequency weighted acceleration values corresponding to the lower and upper limits of the Health Guidance Caution Zone (for 8 hrs of exposure) are 0.45 and 0.90 m/s2 respectively.

Table 4-2. The working hours to reach the upper limit of the ISO 2631-1 health guidance caution zone (HGCZ) for 8-hour working duration.

LHDs	*BMI Prime*	Hours (h)				
		Access	Amobi	CAT	KAB301	KAB525
M1	0.74	5.31	4.52	4.69	10.04*	6.98
	1.00	5.72	5.28	5.31	11.68*	7.58
	1.20	6.07	6.01	5.89	13.23*	8.09*
M2	0.74	5.99	4.91	4.41	10.18*	7.68
	1.00	6.48	5.79	4.98	11.88*	8.38*
	1.20	6.89	6.62	5.49	13.50*	8.98*
M3	0.74	5.21	4.34	8.17*	7.67	4.78
	1.00	5.59	5.03	9.65*	8.71*	5.09
	1.20	5.92	5.67	11.07*	9.65*	5.36
M4	0.74	17.96*	13.80*	25.45*	14.90*	13.72*
	1.00	20.45*	18.08*	33.71*	17.88*	15.33*
	1.20	22.70*	22.78*	42.79*	20.80*	16.75*
M5	0.74	1.82	1.84	3.05	3.37	1.91
	1.00	1.89	2.02	3.36	3.67	1.99
	1.20	1.96	2.17	3.62	3.92	2.05
M6	0.74	2.72	2.61	3.34	4.89	3.15
	1.00	2.86	2.92	3.70	5.42	3.32
	1.20	2.98	3.21	4.01	5.88	3.47
M7	0.74	2.27	2.18	2.53	3.96	2.80
	1.00	2.37	2.40	2.75	4.33	2.94
	1.20	2.45	2.60	2.94	4.64	3.05
M8	0.74	4.25	3.83	4.87	8.58*	5.20
	1.00	4.54	4.42	5.53	9.86*	5.58
	1.20	4.78	4.96	6.13	11.05*	5.90
M9	0.74	2.00	1.97	3.03	2.92	2.13
	1.00	2.09	2.18	3.33	3.16	2.22
	1.20	2.16	2.36	3.60	3.37	2.30
M10	0.74	2.66	2.43	2.60	3.07	2.98
	1.00	2.81	2.72	2.86	3.33	3.14
	1.20	2.92	2.98	3.08	3.56	3.28

* Asterisks indicate exposures that require more than 8 working hours to exceed the upper limit of the HGCZ for five industrial seats with different driver anthropometrics (*BMI primes*) in the underground mining environment.

One LHD (M4) had lower predicted acceleration levels for all *BMI Prime* values and all seats (A(8) = 0.39-0.69 m/s^2) compared to the other LHDs; all driver and seat combinations could be tolerated for more than 8 hours (Table 4-2). In contrast, several LHDs (M5, M6, M7, M9, M10) had higher acceleration levels ($A(8)$ = 1.05-1.89 m/s^2) such that none of the driver and seat combinations could be tolerated for 8 hours (range from 1.82-5.88 hours). Specific seats in some LHDs (M1, M2, M3, M8) reduced the vibration exposure such that exposures could be tolerated for more than 8 hours while other seats in these vehicles could not be tolerated for 8 hours. The KAB301 seat reduced the vibration magnitude to levels that could be tolerated for more than eight hours more often than the other seats; 14 of the 30 vehicle and driver combinations could be tolerated for more than eight hours for the KAB301 seat compared to three each for the Access and Amobi seats, and six each for the CAT and KAB525 seats.

For the specific LHD vehicles M1, M2 and M8, the KAB301 seat was the only seat model to attenuate the occupational vibration exposures to below the upper acceleration limit of the ISO 2631-1 HGCZ (0.9 m/s^2); the KAB301 seat attenuated the vibrations approximately twice as well as the CAT seat for these specific vehicles. In contrast, for five other LHD vehicles (M5, M6, M7, M9 and M10), the KAB301 seat and CAT seat performed similarly with all $A(8)$ values larger than 0.9 m/s^2.

4.3.2 Sensitivity analysis

Given these differences in performance of the KAB301 seat between vehicles, we evaluated the frequency spectra of the vibration exposures to evaluate whether there were differences in vibration exposures between vehicles; the chassis acceleration data for the ten LHDs were evaluated in 1/3 octave proportional frequency bands between 0.5 and 20 Hz. There did not appear to be striking differences in the vibration spectra between the vehicles where the KAB301 seat performed well (M1, M2 and M8) in Figure 4-1(a) and those where the seat did not effectively attenuate the vibrations (M5, M6, M7, M9 and M10) in Figure 4-1(b). Accordingly, for comparison, we also evaluated the chassis acceleration data for eight forestry skidders from our library of industrial vibration exposures (Cation et al., 2008; Jack et al., 2010). Figure 4-2 represents the data for LHDs M1, M2 and M8 where the KAB301 seat effectively attenuated the vibrations more effectively than the CAT seat, and the data for skidders S4, S5, S6 and S8 where the CAT seat attenuated the vibrations more effectively than the KAB301 seat. These forestry vehicles had a dominant frequency of 2 Hz while the mining vehicles had a dominant frequency of 2.5 Hz.

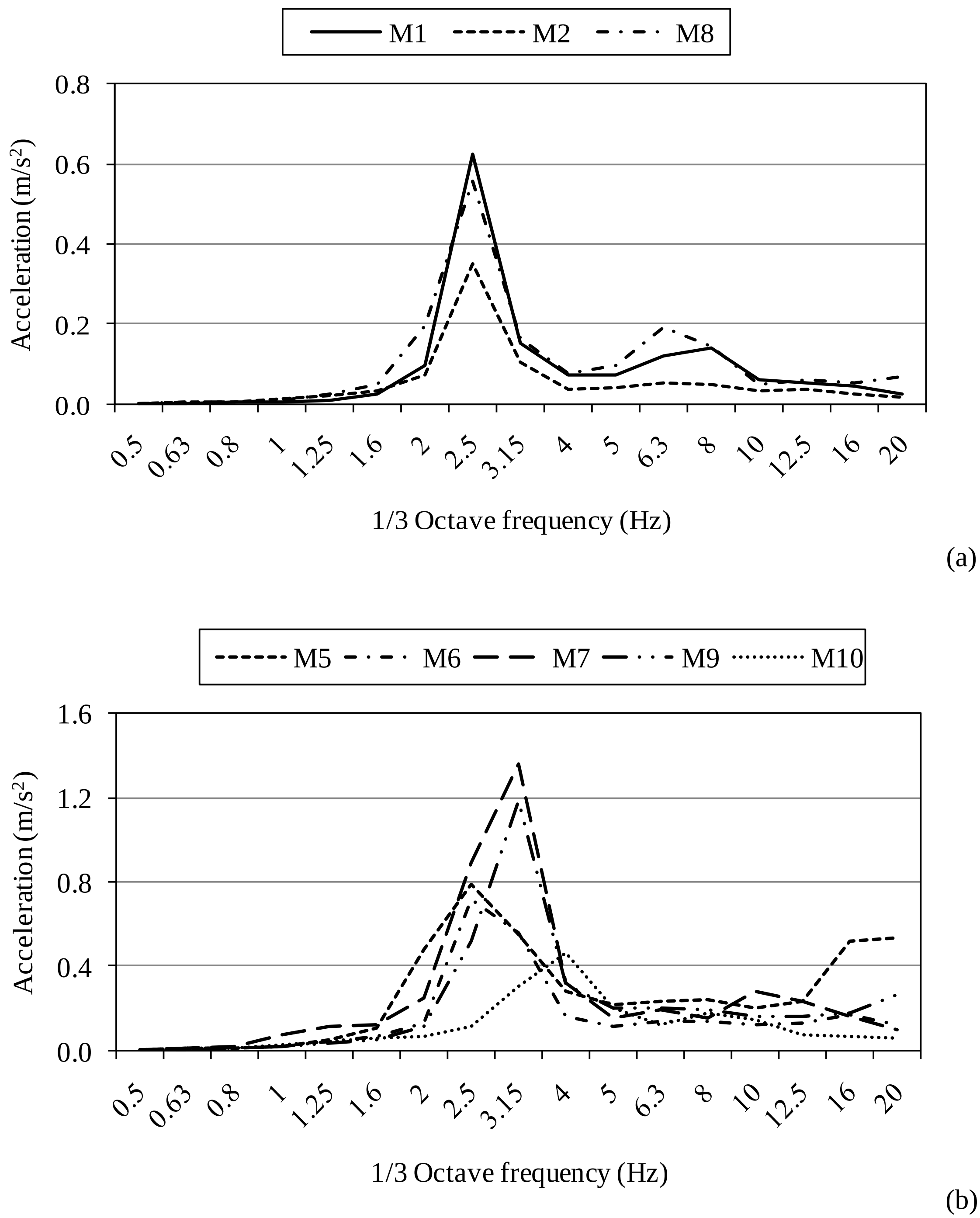


Figure 4-1. The chassis r.m.s. acceleration data of three LHDs (M1, M2 and M8) and five LHDs (M5, M6, M7, M9 and M10) at each 1/3 octave frequency band between 0.5 and 20 Hz were presented in (a) and (b) respectively. The KAB301 seat effectively attenuated the vibrations for the mining vehicles presented in (a), but not for the vehicles presented in (b).

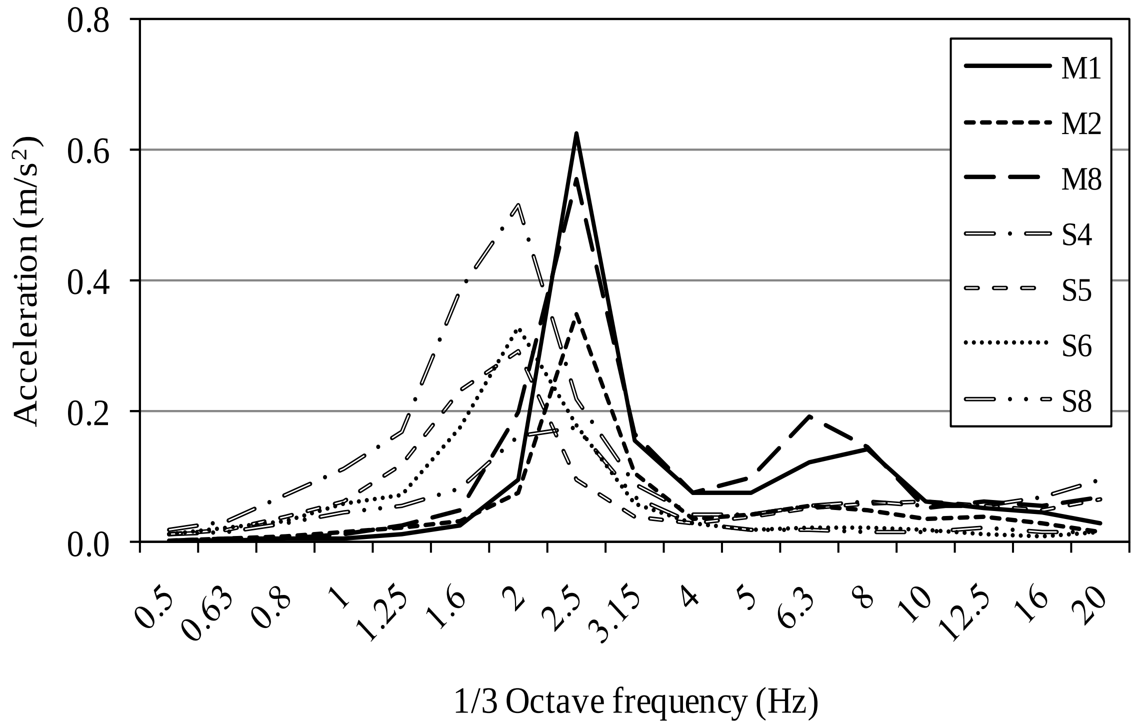


Figure 4-2. The chassis r.m.s. acceleration data of three LHDs and four skidders at each 1/3 octave frequency band between 0.5 and 20 Hz. The data for LHDs M1, M2 and M8 where the KAB301 seat performed much better than the CAT seat. The data for skidders S4, S5, S6 and S8 where the CAT seat performed much better than the KAB301 seat.

The *A*(8) results for the LHDs are presented in the Table 4-1 and the corresponding data for the skidder vehicles are presented in the Chapter 3. The predicted *A*(8) values from the sensitivity analyses (using the perturbed vibration amplitudes for each of the 1/3 octaves) for the CAT and KAB301 seats are presented in Figure 4-3. We focused on the three LHDs where the KAB301 seat effectively attenuated the vibrations (M1, M2 and M8); all three of these LHDs showed similar responses. The magnitude of the accelerations at 2.0, 2.5, 3.1 and 16.0 Hz resulted in large changes in the *A*(8) values for both industrial seats. The KAB301 seat is highly sensitive to increases in magnitude of the 2 Hz and 3.15 Hz components (26% and 22% increase in *A*(8), respectively) while the CAT seat is much less sensitive to increases in magnitude of these components (8% and 10% increase in *A*(8), respectively). However, at 2.5 Hz frequency band, the CAT seat is more sensitive to increases than the KAB301 seat.

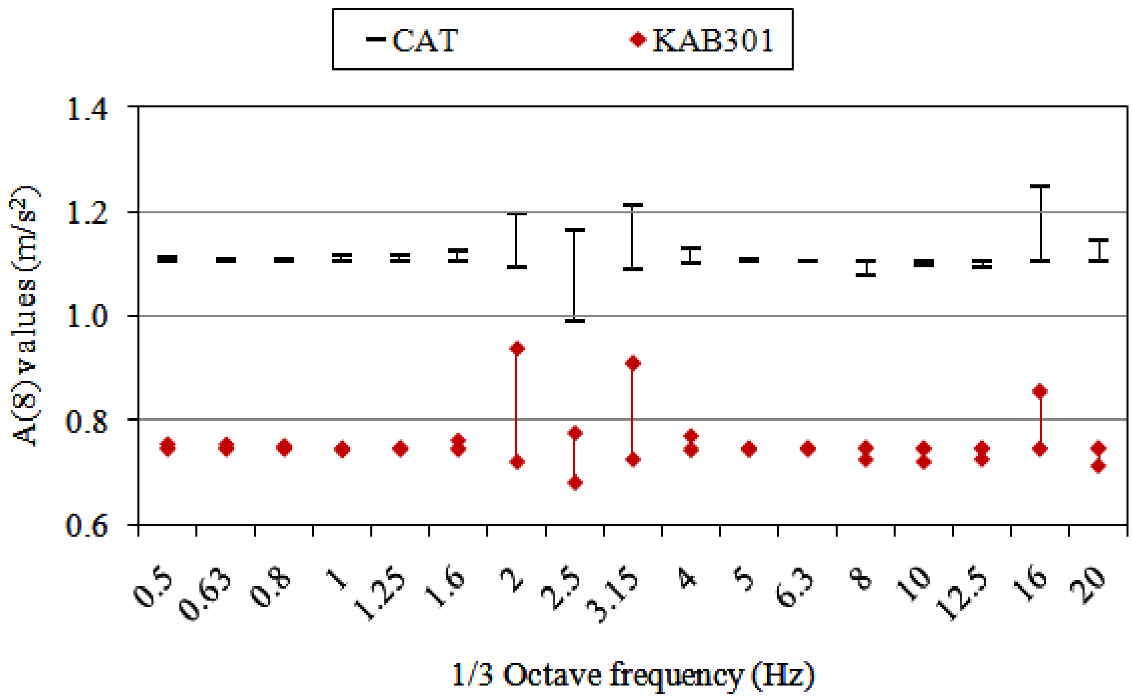


Figure 4-3. Influence of each vibration frequency band (1/3 octave frequency between 0.5 and 20 Hz) on the *A*(8) results for both CAT and KAB301 seats for one representative LHD vehicle (M1) in the mining vibration environment. The KAB301 attenuated the vibrations more effectively than the CAT seat for this vehicle. The upper and lower points at each frequency reflect the predicted seatpan *A*(8) magnitudes when the chassis acceleration at that 1/3 octave band was increased and decreased respectively.

4.4 Discussion

The operation of heavy mobile machinery leads to large vibrations in the underground mining environment (Eger et al., 2013; Kumar, 2004; Van Niekerk et al., 2000). Seat selection is a important factor for reducing driver's exposure to vibration (Gunaselvam and Van Niekerk, 2005), but it is difficult to identify optimal seats due to the complexity of the seats' performance. We developed NN models characterizing the vertical attenuation properties of five common industrial seats in the Chapter 3 and predicted their performance for LHD vehicles from our library of occupational vibration exposures (Dickey et al., 2010). We evaluated the performance of five industrial seats based on the chassis vibrations measured for each of ten specific LHD vehicles and three variations of driver anthropometrics. Overall the vibration environment for these ten vehicles was such that relatively few of the seats were effective at reducing the vibration exposure such that the workers could be exposed for 8 or more hours (32 of 150 seat, operator, vehicle combinations). Among the five tested seats, our predictions indicate that the KAB301 seat was the best choice in the mining environment; it had the lowest $A(8)$ and largest number of hours to reach the upper boarder to the HGCZ for seven of the vehicles, and was ranked second for two other vehicles, although the vibration magnitudes were similar to the best-ranked seat. All of the seats were predicted to perform well for one of the vehicles. In terms of absolute vibration magnitude, the KAB301 seat allowed approximately half of the specific operator/vehicle combinations to be operated for over 8 hours in the mining environments (14 of 30). The KAB301 seat attenuated the magnitudes of the vibration exposures for these operator/vehicle combinations below the upper limit (0.9 m/s^2) of ISO 2631-1 HGCZ, which minimized the health risks of exposures for heavy machine operators. This is similar to the vibration magnitudes reported in other mining environments; for example, Aye and Heyns (2011) reported that approximately 50% of the heavy equipment used in mining activities causes vibration exposures that exceed exposure action values. Although the vibration exposure for the remaining operator/vehicle combinations did not permit the specific operator/vehicle combinations to be operated for over 8 hours in the mining environments, the KAB301 seat performed better than the other industrial seats (except for near-ties for two vehicles, and for the vehicle where all the seats performed well). These findings are in stark contrast to a parallel study evaluating the effectiveness of these same seats for attenuating vibration exposures in forestry skidder vehicles in the Chapter 3. We observed that the CAT seat was the best choice among the five tested seats for the forestry skidders; it limited 96% of the vibrations below the upper limit of the ISO2631-1 HGCZ range. These contrasting findings affirm that seat selection algorithms is not universal - the performance and rankings of industrial seats varies between vibration environments.

Given that the magnitude of the vibration total values (a_v) are relatively similar in these two environments (Plewa et al., 2012), it appears that the performance of the seats may depend upon specific features of the vibration environment, such as the frequency spectra. The vibration spectra are different for forestry vehicles and mining vehicles; the dominant frequencies are 2 Hz for the forestry environment and 2.5 Hz for the mining environment (Figure 4-2). The sensitivity analysis (Figure 4-3) revealed that the seats had heightened sensitivity for the 2, 2.5 and 3.15 Hz frequency bands. The KAB301 seat was highly sensitive to increases in magnitude of the 2 Hz and 3.15 Hz components while the CAT seat was much less sensitive to increases in magnitude of these two frequency components. This likely explains why the CAT seat performed better with the forestry vehicles — the forestry vehicles have dominant 2 Hz vibrations, and higher 3.15 Hz vibrations than the mining vehicles (Figure 4-2); the CAT seat was much less sensitive to these frequencies than the KAB 301 seat, explaining our findings that the CAT seat is more suitable with the forestry vehicles (Chapter 3). Similarly, the KAB301 seat performs better with the mining vehicles because the dominant frequency for LHDs was 2.5 Hz, and the KAB301 seat was less sensitive to this frequency than the CAT seat. Our results are consistent with the previous report (Griffin et al., 2006) that each seat suspension system amplifies the vibration in specific frequency ranges. Seat selection must be optimized by matching the performance of specific industrial seats with the frequency spectra for the vibration environments.

In terms of limitations, this study only predicted the vertical seatpan r.m.s. accelerations; it would be helpful to evaluate the influence of horizontal vibration exposures to operators with different industrial seats. Moreover, the number of vehicles was rather limited (10 LHDs) and we analyzed a relatively small number of industrial seats. Given that the KAB301 seat appeared to be the best among these five seats in the mining environment, and that the CAT seat appeared to be the best among the five seats in the forestry environment, we focused our evaluation of the contribution of the frequency spectra to the seatpan acceleration magnitude to these two seats. It would be helpful to include more seats for this evaluation.

Chapter 5

5 Evaluation of the vibration attenuation properties of an air-inflated cushion for heavy machinery seats in multi-axis vibration environments including jolts

5.1 Introduction

Occasional extreme accelerations, such as those resulting from end stop impacts of the seat suspension, pot-holes or speed bumps have been identified as a strong risk factor for developing low back injuries (ISO 2631-5, 2004). These injuries are thought to be related to the high levels of acceleration that are transmitted to the seated occupant (Khorshid et al., 2007). A variety of approaches have been developed to try to protect workers from these extreme vibrations. For example, specialized seat suspension systems (Marcotte et al., 2010) and seat cushion systems (Chen et al., 2015; Mehta and Tewari, 2010; Van der Merwe, 2007) have been developed to attempt to reduce the vibration exposures. Seat cushions are a desirable approach since they are relatively easy to implement and have a relatively low cost.

Some studies recommend switching from foam to air cushions to improve seat comfort levels and to minimize the transmission of vibration to the operators (Chen et al., 2015; Griffin, 1990). Some air cushions have been developed with the express purpose of reducing jolt exposures (Seigler, 2002). Air cushions have also been promoted as they can evenly distribute pressure over the seatpan/buttocks interface and lower pressures under the ischial tuberosities (Huston et al., 1999). In terms of vibration attenuation, air cushions also significantly attenuate WBV compared to foam cushions on wheeled logger vehicles (Van der Merwe, 2007), trucks (Boggs and Ahmadian, 2007) and helicopters (Boggs and Ahmadian, 2007; Chen et al., 2015; Van der Merwe, 2007). Given the known health risks associated with jolt vibration exposures, and the potential for air cushions to attenuate these vibrations, further research is required to evaluate the effectiveness of air cushions when they are used with different suspension seats.

The first purpose of this study was to evaluate the performance of various the seat/cushion combinations in different vibration environments. This was accomplished using the NN modeling approach that is presented in Chapter 2 with application to the vibration exposures that are typical of heavy mobile machinery in the mining and forestry sectors. The second purpose was to evaluate the seat/cushion transmissibility with jolt vibration exposures to determine the effectiveness of the new No-Jolt™ air-inflated cushion.

5.2 Methodology

5.2.1 System setup

Two seats (Amobi SM2024, Access mining services, Quebec, Canada and KAB301, KAB seating Ltd, Vonore, Tennessee, U.S.) were selected based on their differing vibration attenuating properties in the forestry and mining vibration environments (Chapters 3 and 4). The KAB301 seat was effective at attenuating vibration for these environments, and the Amobi seat was not effective at attenuating the vibration. Accordingly the KAB301 seat represented a well tuned suspension seat while the Amobi seat represented a poorly tuned suspension seat. In addition to evaluating the performance of these seats with their original cushions, they were also evaluated with a prototype air-inflated cushion. The original seat cushions were removed and the No-Jolt™ seat air-inflated cushion (ErgoAir, Inc. Las Vegas, USA) was placed on the frame of each industrial seat (Figure 5-1). This cushion was preconditioned according to the manufacturer's instructions. First it was over-inflated, and then the valve was opened after a few minutes to let it equalize to atmospheric pressure. Then we closed the valve to make a closed system that enabled air to be shunted from the seatpan component into the seatback component when it was exposed to jolts. This cushion design is similar to other prototype cushions (Boggs and Ahmadian, 2007).

Figure 5-1. The new No-Jolt^{TM} prototype air-inflated cushion was placed on the frame of one industrial seat, which was mounted on our 6 degree of freedom (df) robotic platform.

Two 10g tri-axial accelerometers (Biometrics S2-10G-MF, NEXGEN Ergonomics, UK) were used to record accelerations at the seatpan/participant interface (embedded in a black semi-rigid rubber mounting disc and placed on the seatpan) and the center surface of the robotic platform (chassis) as recommended in ISO 2631-1 (1997). The analog data from the accelerometers were sampled at 1000 Hz using a 16 bit NI BNC-2110 board (National Instruments, Austin, TX, USA). We tested forty-one subjects (twenty-one male, twenty female (not pregnant); Table 5-1) without any history of low back pain. Their data were used to develop the NN models and evaluate the vibration exposures for the four seating conditions: the KAB301 and Amobi seats, each with their original cushions and with the No-Jolt™ seat air-inflated cushion. All seating conditions were tested in a single session for each participant. Participants were classified into four groups based on their anthropometrics. In particular, we classified them in terms of their body mass index (*BMI*), which is equal to their mass divided by their height squared. Participants' *BMI* was normalized by dividing it by 25, and is referred to as *BMI prime* (Gadzik, 2006).

Table 5-1. Anthropometric parameters of the forty-one subjects are presented for each of the four *BMI Prime* groups.

BMI Prime	Sex of subjects		*Mass* (kg)	*Height* (m)	*BMI* (kg/m^2)	*BMI Prime*
	Male	Female	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
<0.74	3	5	48.3 (3.35)	1.66 (0.07)	17.59 (0.73)	0.70 (0.03)
0.74-1.0	10	10	67.3 (12.5)	1.72 (0.12)	22.42 (1.59)	0.90 (0.06)
1.0-1.2	6	3	89.9 (11.4)	1.83 (0.07)	26.71 (1.56)	1.07 (0.06)
>1.2	2	2	108.0 (12.9)	1.74 (0.13)	35.91 (2.58)	1.44 (0.10)

5.2.2 Vibration conditions

Each participant was tested using three types of vibration signals: seven random vibration exposures, six jolt vibration exposures, and ten field exposures. The random vibrations were 3 df broadband random frequency exposures between 0.5 and 20 Hz with r.m.s. amplitudes between 0.2 and 2.0 m/s^2 on all three translational axes. The field exposures were 20 s duration 6 df signals based on a library of occupational field vibration exposures (Dickey et al., 2010); individual subjects were exposed to a subset of ten signals from the set of the thirty most common vibration characteristics of the field exposures (Dickey et al., 2010). The vibration properties of these thirty exposures are presented in the Chapter 3.

The 1 df (vertical) jolt displacement exposures were calculated by double-integrating a sinusoidal waveform that was modulated by a half sine wave (Equation 5-1) (European Project TESTOPS, 2000). A sample of sinusoidal waveform at frequency 1.0 Hz with acceleration magnitude of 1.0 m/s^2 is shown in Figure 5-2.

$$\ddot{x}(t) = A \cdot \sin(2 \cdot \pi \cdot f \cdot t) \cdot \sin(\frac{\pi \cdot f \cdot t}{4.5}) \qquad (5\text{-}1)$$

where $\ddot{x}(t)$ was the robot acceleration, f was 1.7 Hz and 2.4 Hz for the KAB301 seat and Amobi seat respectively, t ranged from 0 to $4.5/f$, and A was the acceleration magnitude.

The natural frequencies of the KAB301 and Amobi seats, with both the original and air cushions, were determined. The details are presented in Appendix A. We generated a family of jolt exposures at the seats' natural frequencies with amplitudes between 1.0 and 6.0 m/s^2. The 4.0 m/s^2 amplitude vibration at 1.7 Hz exceeded the performance envelope of the robot. Accordingly, the jolt exposures were generated with the amplitudes of 1.0, 2.0 and 3.5 m/s^2 at 1.7 Hz, and with the amplitudes of 1.0, 3.5 and 6.0 m/s^2 at 2.4 Hz.

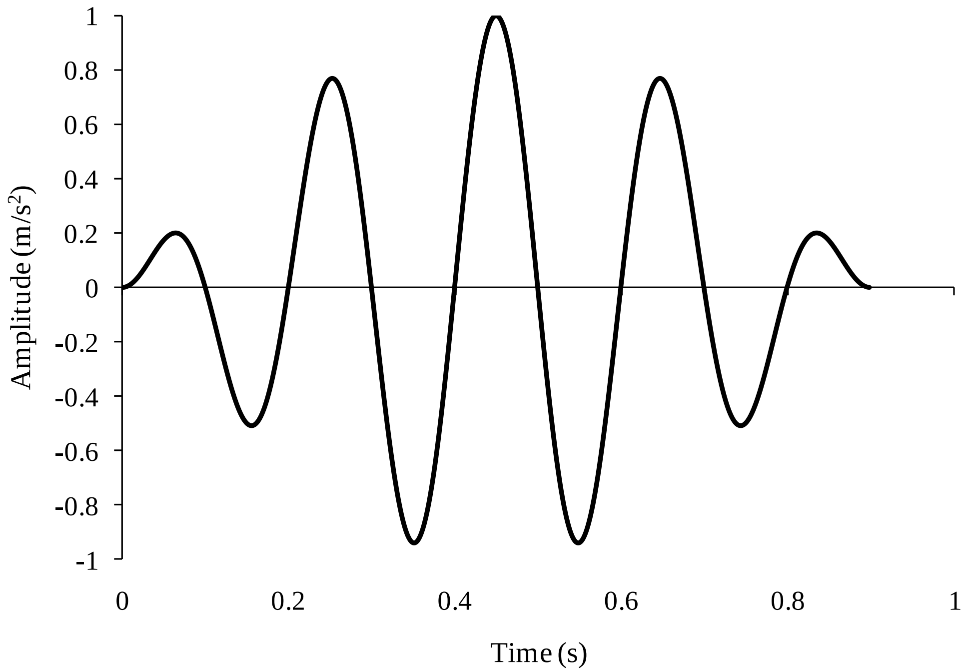


Figure 5-2. The input vibration waveform in terms of acceleration with the magnitude of 1.0 m/s^2 at frequency equal to 1.0 Hz.

5.2.3 Neural Network (NN) seat models

The architecture of our neural identification network is presented in the Chapter 2. The difference in this study is that there were forty-one participants, so the models' input translational chassis acceleration data included 697 recorded signals (forty-one participants * (ten field exposures + seven random exposures)).

The data were divided into training (to develop the NN models) and validating sets (to evaluate the NN models' performance using an independent data set). The strength of the association between the predicted and measured values was evaluated using the slopes and intercepts of the best fit lines and the coefficients of determination; this was performed for both the developing and validating data sets of each seat model.

5.2.4 Daily 8-hour Vibration Exposure *A*(8)

The daily 8-hour equivalent frequency weighted accelerations *A*(8) (ISO 2631-1, 1997) were predicted for vibration exposures based on eight skidders and ten load-haul-dump (LHDs) vehicles for the four different seating conditions and three specific driver's anthropometrics (*BMI Prime* = 0.74, 1.00 and 1.20). The details of daily *A*(8) calculation are presented in Chapter 3.

5.2.5 Analysis of jolt vibration exposures

The *VDV* was calculated according to the magnitude and duration of the vertical frequency weighted accelerations. The total dose value is given by the Equation 5-2.

$$VDV = [\int {a_w}^4(t)\ dt]^{\frac{1}{4}} \qquad (5\text{-}2)$$

where a_w (t) was the magnitude of the frequency weighted acceleration.

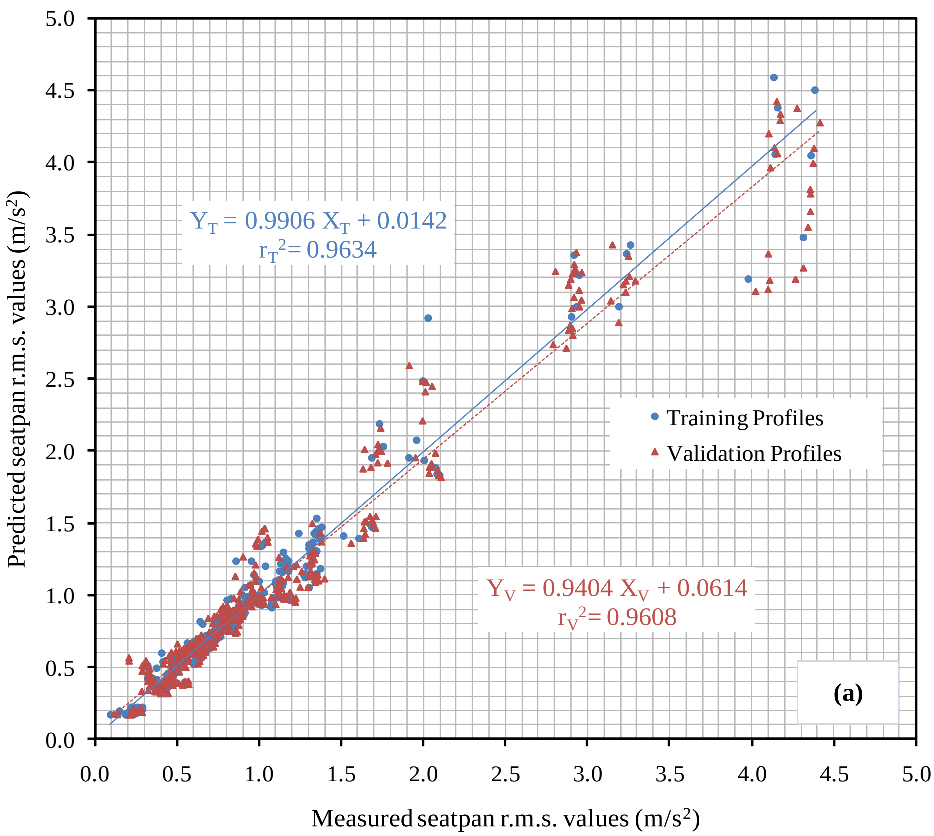
The overall performance of the four seating conditions was evaluated using the ratio between the *VDV*s at the base of the seat ($VDV_{chassis}$) and above the seat cushion ($VDV_{seat\ cushion}$; Equation 5-3).

$$VDV\ ratio = \frac{VDV_{seat\ cushion}}{VDV_{chassis}} \qquad (5\text{-}3)$$

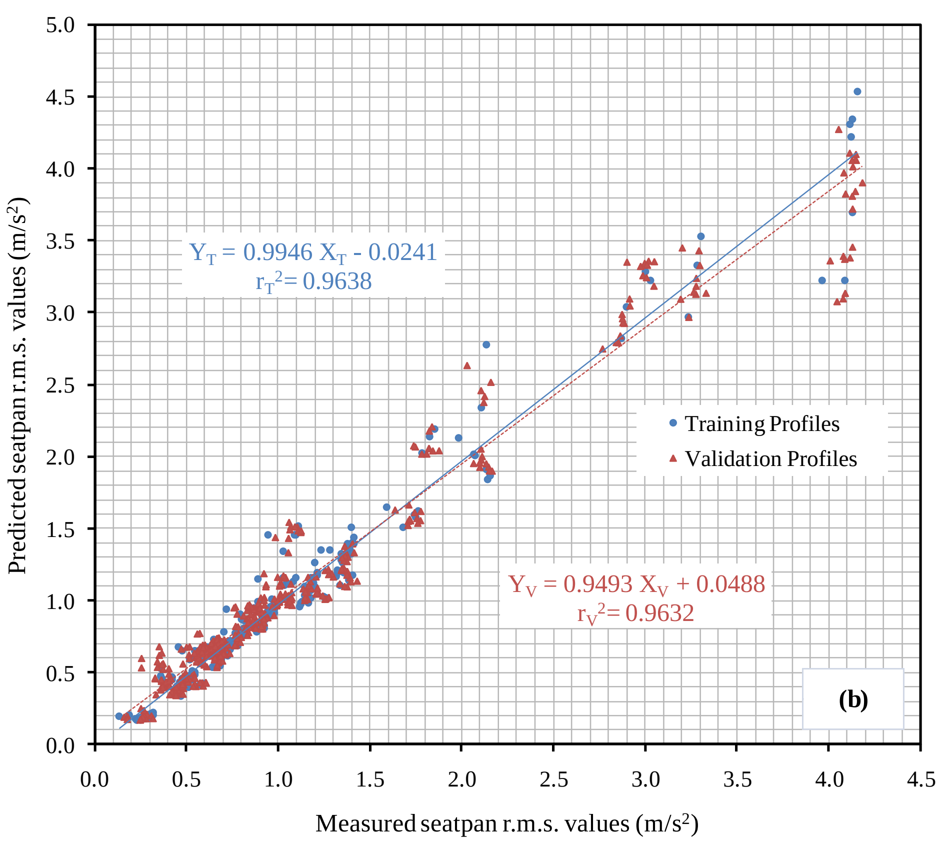
5.3 Results

5.3.1 Four NN seating condition models

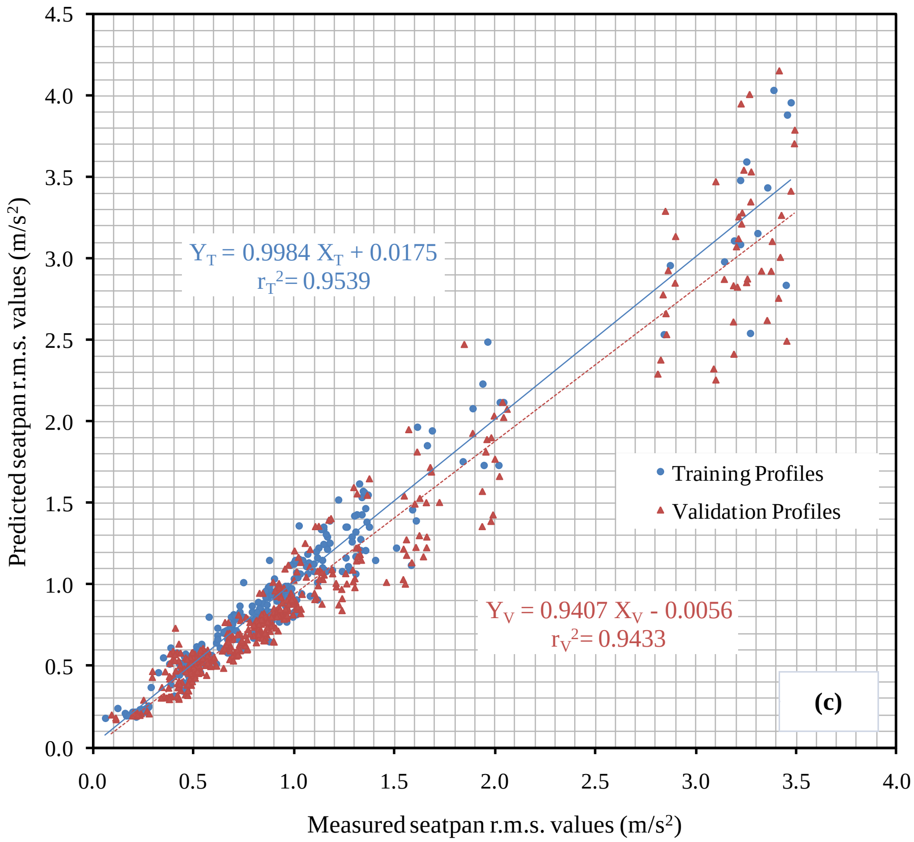
The seatpan r.m.s. accelerations ranged from approximately 0.2 to 4.5 m/s^2 for the both training and validating data sets. The vibration attenuation properties of the four seating conditions were successfully modeled using the NN intelligent mathematical algorithm (Figure 5-3). Excellent correlations were achieved for the both training and validation data sets, for all the seats. The slopes of linear regression equations ranged between 0.94 and 0.99 and the intercepts ranged between -0.02 and +0.06. The coefficients of determination (r^2) between the predicted and measured seatpan r.m.s. accelerations ranged between 0.93 and 0.96.



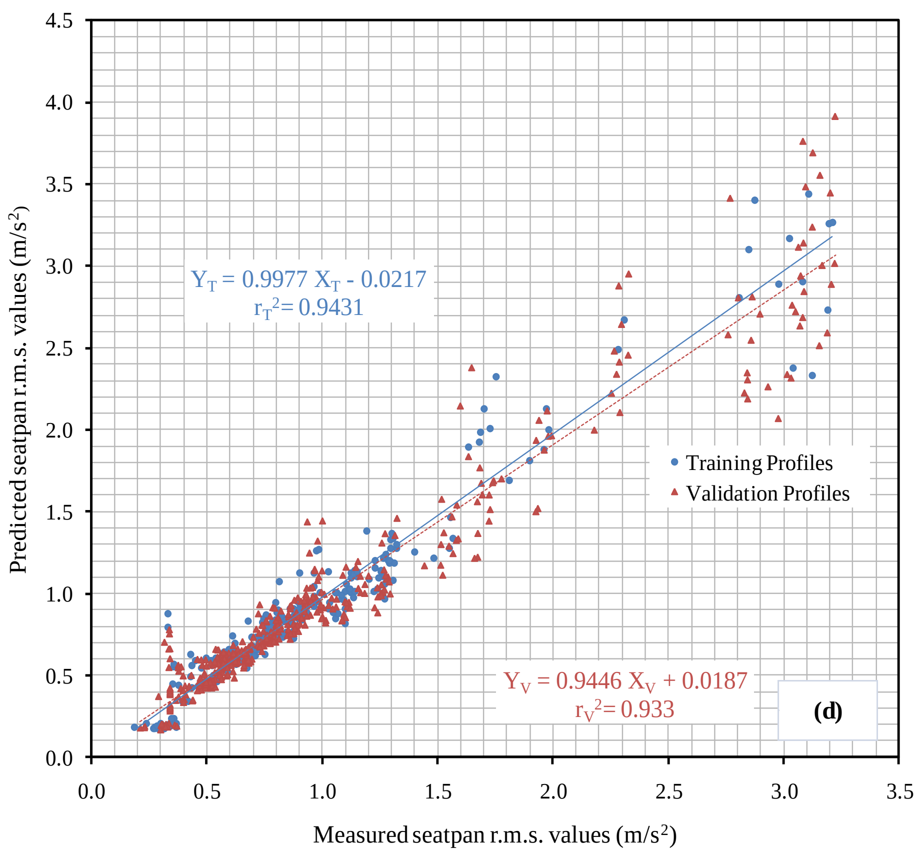
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Predicted seatpan r.m.s. values (m/s²)
Measured seatpan r.m.s. values (m/s²)
Y_T = 0.9906 X_T + 0.0142
r_T² = 0.9634
Training Profiles
Validation Profiles
Y_V = 0.9404 X_V + 0.0614
r_V² = 0.9608
(a)



5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Predicted seatpan r.m.s. values (m/s²)
Measured seatpan r.m.s. values (m/s²)
Y_T = 0.9946 X_T - 0.0241
r_T² = 0.9638
Training Profiles
Validation Profiles
Y_V = 0.9493 X_V + 0.0488
r_V² = 0.9632
(b)



$Y_T = 0.9984\ X_T + 0.0175$
$r_T^2 = 0.9539$
Training Profiles
Validation Profiles
$Y_V = 0.9407\ X_V - 0.0056$
$r_V^2 = 0.9433$
(c)
Predicted seatpan r.m.s. values (m/s²)
Measured seatpan r.m.s. values (m/s²)



$Y_T = 0.9977\ X_T - 0.0217$
$r_T^2 = 0.9431$
Training Profiles
Validation Profiles
$Y_V = 0.9446\ X_V + 0.0187$
$r_V^2 = 0.933$
(d)
Predicted seatpan r.m.s. values (m/s²)
Measured seatpan r.m.s. values (m/s²)

Figure 5-3. The correlation between the predicted and measured seatpan weighted r.m.s. acceleration. Blue circle symbols reflect the data used to develop the NN models, and the red triangle symbols reflect the data used to validate the NN models for four industrial seats. The linear regression equations and coefficients of determination are showed for all the seats. (a) the Amobi seat with its original seat cushion; (b) the Amobi seat with the air-inflated cushion; (c) the KAB301 seat with its original seat cushion; (d) the KAB301 seat with the air-inflated cushion.

5.3.2 *A*(8) results

The predicted daily 8-hour vibration exposures (*A*(8)) varied substantially between industrial seats, and with *BMI Primes*, for the both forestry and mining workplaces (Tables 5-2 and 5-3). None of the seats resulted in acceleration levels that were below the lower acceleration limit of the ISO 2631-1 HGCZ (0.45 m/s^2). The vibrations were sufficiently large that all of the four seat condition and *BMI prime* combinations were above the upper limit of the HGCZ for four of the eight skidders, and six of the ten LHDs. The remaining vehicles included some seat/BMI combinations where the vibrations were within the HGCZ.

With their original seat cushions, the KAB301 seat performed better than the Amobi seat for most scenarios from the forestry environment (21 of 24 vehicle and *BMI Prime* combinations). These differences translated into meaningful improvements in risk of injury as five of skidder vehicle and *BMI prime* combinations that exceeded the upper limit of the HGCZ in the Amobi seat were below this threshold with the KAB301 seat. In specific, 12 of the 24 combinations were below the upper limit of the HGCZ for the KAB301 seat compared with 8 of the 24 combinations for the Amobi seat. The risk reductions were even greater for the mining environment; eight of LHD vehicle and *BMI prime* combinations that exceeded the upper limit of the HGCZ in the Amobi seat were below this threshold with the KAB301 seat. In specific, 11 of the 30 LHD vehicle and *BMI Prime* combinations were below the upper acceleration limit of the HGCZ for the KAB301 seat compared with 3 of the 30 combinations for the Amobi seat.

The KAB301 seat had enhanced vibration attenuation properties with the new air-inflated cushion compared to the original cushion. Similarly to the original cushions, the attenuation effects were greater in the mining environment than forestry workplace. This was apparent in the increased number of working hours to reach the upper limit of the ISO 2631-1 HGCZ for 8-hour of vibration exposures (20% versus 5%). In contrast, the Amobi seat with air-inflated cushion slightly amplified the seatpan accelerations compared with its original cushion (decreased 7% working hours in forestry and 3% in mining).

Table 5-2. *A*(8) results and the corresponding working hours to reach the upper limit of the ISO 2631-1 health guidance caution zone for 8-hour working duration for four industrial seating conditions in the forestry environment (the KAB301 and Amobi seats, each with their original cushions and with the No-Jolt™ seat air-inflated cushion). Eight different forestry vehicles (skidders) were evaluated using three different driver anthropometrics (*BMI primes*). "Air" refers to the No-Jolt™ seat air-inflated cushion and "ori" refers to the original cushions for each seat. Bold font indicates scenarios where more than 8 hours of vibration exposures are required to exceed the upper acceleration limit of the HGCZ.

Skidders	*BMI Prime*	air Amobi		ori Amobi		air KAB		ori KAB	
		A(8) m/s^2	Hours	A(8) m/s^2	Hours	A(8) m/s^2	Hours	A(8) m/s^2	Hours
S1	0.74	0.92	7.62	0.89	**8.27**	0.79	**10.36**	0.8	**10.03**
	1.00	0.87	**8.58**	0.83	**9.44**	0.74	**11.9**	0.75	**11.56**
	1.20	0.83	**9.44**	0.78	**10.52**	0.7	**13.33**	0.71	**12.99**
S2	0.74	0.95	7.21	0.92	7.66	0.79	**10.43**	0.81	**9.89**
	1.00	0.89	**8.09**	0.86	**8.72**	0.73	**12.01**	0.75	**11.39**
	1.20	0.85	**8.89**	0.82	**9.68**	0.69	**13.47**	0.71	**12.79**
S3	0.74	0.93	7.5	0.89	**8.15**	0.92	7.62	0.94	7.33
	1.00	0.88	**8.44**	0.83	**9.3**	0.87	**8.58**	0.89	**8.27**
	1.20	0.84	**9.28**	0.79	**10.36**	0.83	**9.45**	0.84	**9.12**
S4	0.74	1.6	2.54	1.55	2.68	1.31	3.78	1.35	3.55
	1.00	1.54	2.72	1.5	2.89	1.26	4.11	1.3	3.85
	1.20	1.5	2.87	1.45	3.06	1.22	4.38	1.26	4.11
S5	0.74	1.34	3.63	1.3	3.82	1.1	5.31	1.14	5.02
	1.00	1.28	3.94	1.24	4.18	1.05	5.86	1.08	5.55
	1.20	1.24	4.2	1.2	4.49	1.01	6.34	1.04	6
S6	0.74	1.25	4.15	1.21	4.44	1.05	5.89	1.06	5.74
	1.00	1.2	4.53	1.15	4.9	1	6.54	1.01	6.39
	1.20	1.15	4.86	1.11	5.3	0.95	7.12	0.96	6.97
S7	0.74	1.05	5.89	1.02	6.25	0.83	**9.34**	0.87	**8.65**
	1.00	1	6.53	0.96	7.02	0.78	**10.66**	0.81	**9.86**
	1.20	0.96	7.1	0.92	7.7	0.74	**11.87**	0.77	**10.98**
S8	0.74	1.13	5.06	1.09	5.41	0.96	6.97	0.99	6.62
	1.00	1.08	5.58	1.04	6.03	0.91	7.82	0.93	7.43
	1.20	1.04	6.03	0.99	6.58	0.87	**8.57**	0.89	**8.16**

Table 5-3. *A*(8) results and the corresponding working hours to reach the upper limit of the ISO 2631-1 health guidance caution zone for 8-hour working duration for four industrial seating conditions in the mining environment (the KAB301 and Amobi seats, each with their original cushions and with the No-Jolt^{TM} seat air-inflated cushion). Ten different mining vehicles (LHDs) were evaluated using three different driver anthropometrics (*BMI primes*). "Air" refers to the No-Jolt^{TM} seat air-inflated cushion and "ori" refers to the original cushions for each seat. Bold font indicates scenarios where more than 8 hours of vibration exposures are required to exceed the upper acceleration limit of the HGCZ.

LHDs	*BMI Prime*	air Amobi		ori Amobi		air KAB		ori KAB	
		A(8) m/s^2	Hours	A(8) m/s^2	Hours	A(8) m/s^2	Hours	A(8) m/s^2	Hours
M1	0.74	1.17	4.71	1.15	4.89	0.82	**9.67**	0.87	**8.53**
	1.00	1.12	5.16	1.09	5.41	0.77	**11.03**	0.82	**9.7**
	1.20	1.08	5.56	1.05	5.87	0.73	**12.29**	0.78	**10.77**
M2	0.74	1.09	5.49	1.07	5.67	0.82	**9.58**	0.87	**8.58**
	1.00	1.03	6.07	1.01	6.33	0.77	**10.96**	0.81	**9.78**
	1.20	0.99	6.57	0.97	6.91	0.73	**12.23**	0.77	**10.89**
M3	0.74	1.36	3.51	1.39	3.34	1.03	6.12	1.13	5.09
	1.00	1.31	3.79	1.34	3.61	0.98	6.77	1.08	5.59
	1.20	1.27	4.02	1.3	3.85	0.94	7.34	1.04	6.03
M4	0.74	0.71	**12.71**	0.69	**13.69**	0.65	**15.32**	0.67	**14.41**
	1.00	0.66	**14.67**	0.64	**16.05**	0.6	**18.07**	0.62	**16.99**
	1.20	0.63	**16.48**	0.6	**18.26**	0.56	**20.71**	0.58	**19.44**
M5	0.74	2.16	1.39	2.14	1.42	1.36	3.52	1.52	2.81
	1.00	2.11	1.46	2.08	1.5	1.31	3.8	1.47	3.01
	1.20	2.07	1.51	2.04	1.56	1.27	4.04	1.43	3.19
M6	0.74	1.73	2.17	1.71	2.21	1.13	5.03	1.27	4.05
	1.00	1.68	2.3	1.66	2.36	1.08	5.52	1.21	4.41
	1.20	1.64	2.41	1.61	2.49	1.04	5.95	1.17	4.72
M7	0.74	1.89	1.82	1.87	1.85	1.25	4.18	1.41	3.26
	1.00	1.84	1.92	1.82	1.96	1.2	4.53	1.36	3.51
	1.20	1.8	2	1.78	2.05	1.16	4.83	1.32	3.72
M8	0.74	1.39	3.38	1.36	3.52	0.85	**8.94**	0.91	7.84
	1.00	1.33	3.65	1.3	3.83	0.8	**10.15**	0.86	**8.86**
	1.20	1.29	3.88	1.26	4.1	0.76	**11.25**	0.81	**9.79**
M9	0.74	2	1.62	1.98	1.65	1.46	3.06	1.66	2.36
	1.00	1.95	1.71	1.93	1.75	1.4	3.29	1.6	2.52
	1.20	1.91	1.78	1.88	1.83	1.36	3.49	1.56	2.66
M10	0.74	1.73	2.16	1.7	2.23	1.5	2.89	1.66	2.37
	1.00	1.68	2.3	1.65	2.39	1.44	3.11	1.6	2.53
	1.20	1.64	2.42	1.6	2.52	1.4	3.29	1.56	2.67

5.3.3 *VDV* ratios for the jolt exposures

For the jolt vibration exposures, the average *VDV* ratios of the KAB301 seat were larger for all scenarios (both female and male participants, all four *BMI Prime* groups, both original and air cushions) than the Amobi seat (the KAB301 seat at 1.7 Hz and the Amobi seat at 2.4 Hz). Female participants usually had higher *VDV* ratios than male participants for the four seating conditions. In addition, the original cushion had higher *VDV* ratios than the No-Jolt™ air-inflated cushion for the KAB301 seat in the *BMI Prime* groups 1-3, but the inverse was true for the *BMI Prime* group 4.

The KAB301 seat usually attenuated vibration better than the Amobi seat with their original cushions in the forestry and mining environments. In this study, the KAB301 seat had enhanced vibration attenuation properties when the air-inflated cushion replaced the original cushion for the jolt exposures at its natural frequency (1.7 Hz). In the *BMI Prime* groups 1-3, the *VDV* ratios were decreased between 1.0 and 6.0% for both female and male participants. However the *BMI Prime* group 4 had a 2.3% increase for female participants and 13.8% increase for male participants (Figure 5-4).

In contrast, the average *VDV* ratios were increased with the air-inflated cushion of the Amobi seat compared with its original cushion at its natural frequency (2.4 Hz) for both female and male participants and in all *BMI Prime* groups (Figure 5-5). These increases were less than 10% with the air-inflated cushion.

The *VDV* ratios of the female participants were usually higher than the male participants with the KAB301 seat. This was especially apparent in *BMI Prime* group 4; their *VDV* ratio with the air-inflated cushion was 10% higher, and it was 22.3% higher with the original cushion. However, the *VDV* ratio of the female participants was 3.4% lower than the male participants in the *BMI Prime* group 3 for the KAB301 seat with the air-inflated cushion. With the Amobi seat, there was little difference (less than 5%) in the *VDV* ratios between female and male participants for the both original and air cushions and all *BMI Prime* groups.

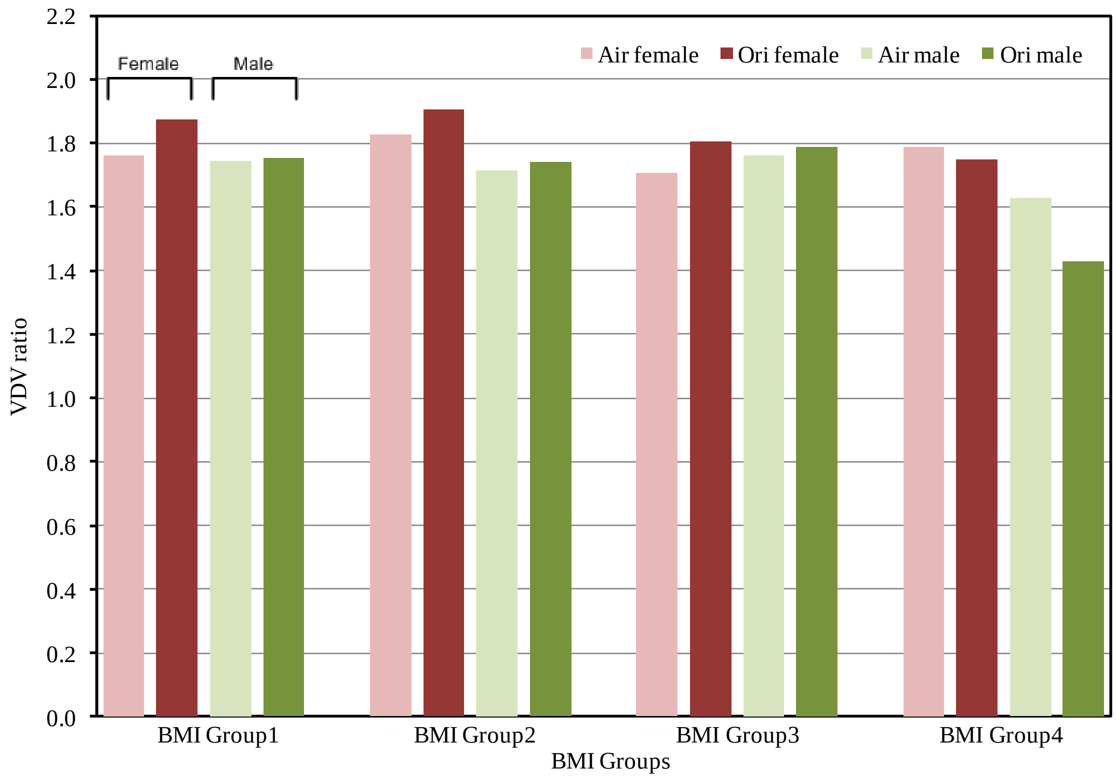


Figure 5-4. The average *VDV* ratios of the KAB301 seat with its original seat cushion and the new air-inflated cushion at frequency 1.7 Hz for both female and male participants in the four *BMI Prime* groups. “Air” refers to the No-Jolt^{TM} seat air-inflated cushion and “Ori” refers to the original cushion.

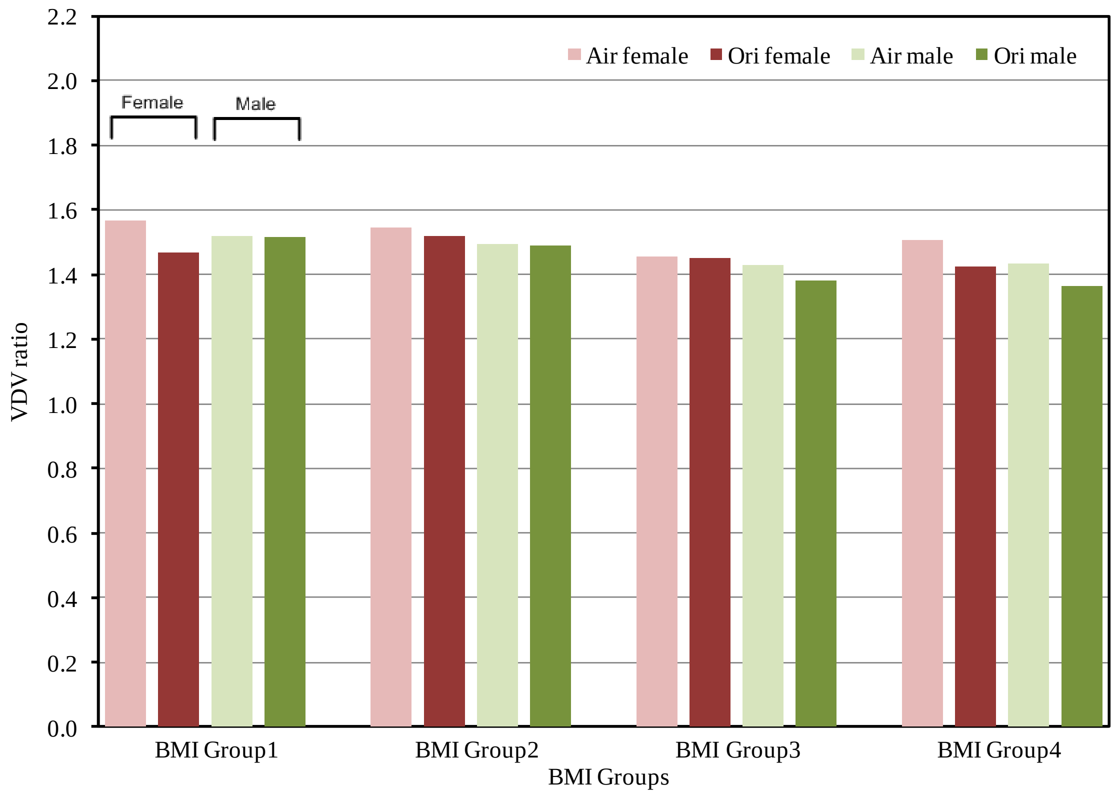


Figure 5-5. The average *VDV* ratios of the Amobi seat with its original seat cushion and the new air-inflated cushion at frequency 2.4 Hz for both female and male participants in the four *BMI Prime* groups. "Air" refers to the No-Jolt^{TM} seat air-inflated cushion and "Ori" refers to the original cushion.

5.4 Discussion

The vertical attenuation properties of four industrial seating conditions (Amobi seat with its original cushion and air-inflated cushion and KAB301 seat with its original cushion and air-inflated cushion) were identified using an intelligent NN modeling approach introduced in the Chapter 2. All of the models showed strong relationships between the predicted and measured seatpan r.m.s. accelerations as reflected by the large magnitudes of the coefficients of determination (r^2). In addition, the slopes were close to 1.0 and intercepts were close to 0.0 for both the training and validation vibration exposures. Given that the training and validation sets represented a large number of mining and forestry vehicles and a variety of vibration conditions, our NN seat models are robust and can be applied to a broad variety of field vibration exposures.

We predicted the performance of the four different seating conditions for eight skidders and ten LHDs based on the most commonly occurring chassis vibrations measured from our library of occupational vibration exposures (Dickey et al., 2010). The equivalent daily 8-hour vibration exposures, *A*(8), were used to evaluate the health implications of these seat options. Similarly to the results of Chapters 3 and 4 for these seats with the original cushions, the KAB301 seat performed better than the Amobi seat. The KAB301 seat attenuated the vibrations better than the Amobi seat. This would allow the workers to be exposed for 8 or more hours vibrations in both working environments before reaching the upper limit of the HGCZ. Moreover, the new No-Jolt^{TM} air-inflated cushion enhanced the vibration attenuation properties of the KAB301 seat for all the scenarios (the combinations of heavy machinery vehicles and driver anthropometrics). However, the new No-Jolt^{TM} air-inflated cushion did not improve the vibration attenuation properties for the Amobi seat. It seems that this new air-inflated cushion can perform well with the KAB301 seat for the occupational vibration exposures but not well for the Amobi seat.

The results of average *VDV* ratios in all *BMI Prime* groups indicate that the KAB301 seat had larger VDV ratios than the Amobi seat. This means that the seatpan vibrations will be amplified more for the KAB301 seat than the Amobi seat when they are vibrated at their natural frequencies. However, given that the KAB301 seat has a lower natural frequency than the Amobi seat (1.7 versus 2.4 Hz), and that many occupation vibration environments have larger vibrations at 2.4 than 1.7 Hz (for example, Jack et al, 2010), then perhaps it is less likely that the natural frequency of the KAB301 seat is excited compared to the Amobi seat. This may be reflected in the reduced seatpan vibration amplitudes for the KAB301 seat with the occupational vibration exposures compared to the Amobi seat. Our results affirm the sensitivity analysis in the Chapter 4, and the previous report (Griffin et al., 2006), that each seat suspension system will amplify the vibration in specific frequency ranges. It is best to pick an industrial seat that has a lower natural frequency than the vibration environment to avoid this amplification.

The new air-inflated cushion improved the attenuation properties of the KAB301 seat for jolt vibration exposures. The *VDV* ratios were decreased for both female and male participants in the *BMI Prime* groups 1-3 (from 1.0 to 6.0%). However, the air cushion amplified the vibration in the *BMI Prime* group 4 (2.3% for female participants and 13.8% for male participants). Our results are consistent previous research which observed that air cushions can only reduce vibrations for certain subjects at specific frequencies (Huston et al., 1999). Our results of the decreased *VDV* ratios are also consistent with another study (Seigler, 2002); he reported that the performance of an air-inflated cushion was 6% better than a foam cushion.

It is noteworthy that the original cushion performed better than the new air-inflated cushion for participants in the *BMI Prime* group 4 on the KAB301 seat. This group was defined as *BMI* values that were greater than 30 kg/m^2. We noticed that a large proportion of real workers in the forestry and mining environments had large *BMI*s. For example, the average *BMI* of skidder drivers was 29.6 kg/m^2 in the forestry environment, and 50% of the drivers had *BMI* values greater than 30 kg/m^2 (Jack et al., 2010). The average *BMI* values of LHD drivers in the mining sector were also large (between 25.4 and 27.9 kg/m2; Eger et al., 2011a; Grenier et al., 2009). Accordingly the KAB301 seat with the air-inflated cushion may not perform well in the forestry and mining environments because of the high proportion of workers with large *BMIs* that in those environments. It seems that there may be an opportunity for developing a special air cushion for individuals with large *BMI* values.

However, for the Amobi seat, the new air-inflated cushion made vibrations worse for jolt vibration exposures. The *VDV* ratios increased for both female and male participants and in all *BMI Prime* groups. In terms of the *VDV* ratios, it indicates that a good cushion does not compensate for a poorly tuned suspension seat. Air cushions are not always better than original foam cushions when the vibration environment includes jolt exposures.

Female participants usually had higher *VDV* ratios than male participants for the four seating conditions. These differences were small (less than 5%) for the Amobi seat in all *BMI Prime* groups. However, there were large differences for the KAB301 seat. This was especially apparent in the *BMI Prime* group 4, where the *VDV* ratios were 10% higher with the air-inflated cushion for female participants, and 22.3% higher with the original cushion. This indicates that the female workers will have higher health risks than males when the vibration environment includes jolt exposures. Although the proportion of female drivers was low in many studies (0%; Bovenzi et al., 2002; Grenier et al., 2009; Jack et al., 2010; Morgan and Mansfield, 2014) and 19 of 130 (15%) rural workers using quad bikes in New Zealand (Milosavljevic et al., 2012b), it may be increasing. Accordingly, it may be appropriate to develop a special seat/cushion for female drivers in vibration environments.

From our results, the new No-Jolt ™ air-inflated cushion is not universally suitable for all the industrial seats. It improved the vibration attenuation properties for the KAB301 seat both the forestry and mining vibration environments; however, it increased the acceleration magnitudes for the Amobi seat. Accordingly, for the two seats examined in this study, the air cushion improved the vibration attenuation properties of the seat that had good attenuation properties to start with (KAB301), and it decreased the vibration attenuation properties of the seat that had poor attenuation properties to start with (Amobi). This finding indicates that the air cushion may not be effective for remediating seats that are not performing well. It reinforces the conclusions from the previous two Chapters that seat selection is not universal – it depends on the characteristics of the vibration environments.

The strength of this study is the application of multi-axis vibration (6 df field exposures and 3 df random exposures) and jolt exposures to evaluate vibration attenuation properties for four different seating conditions. They reflect the real vibration exposures in heavy mobile machinery rather than 1 df vibration exposures as performed by other researchers (Chen et al., 2015; Huston et al., 1999; Seigler, 2002). We also evaluate these seats performance for four *BMI Prime* groups, and evenly distributed female and male participants in each group. This was important as we identified that the attenuation properties of the air-inflated cushion depended on the subject's anthropometrics and sex.

This study only predicted the vertical seatpan r.m.s. accelerations; it would be helpful to evaluate the influence of horizontal vibration exposures to operators with different industrial seats. Moreover, the magnitudes of jolt exposures were relatively small in our experiment. Accordingly we did not cause end-stop impacts, and we did not observe any discontinuity in the *VDV* responses for *VDV* values ($L_{2.5}$) equal to 2.5 $m/s^{1.75}$, as identified by other researchers that used larger magnitude vibrations (European Project TESTOPS, 2000). This is a limitation as perhaps the air-inflated cushion would perform differently with larger jolt magnitudes. All of the testing was performed with one air-inflated cushion, and we assume that its performance is representative of this model of seat cushion. Moreover, this study was based on two industrial seats – one with relatively good vibration attenuation properties, and one with relatively poor vibration attenuation properties. It would be helpful to evaluate the attenuation properties of the new No-Jolt™ air-inflated cushion on more seats. It may also be useful to evaluate different vibration environments, such as long-haul trucking, as previous research has documented that air cushions improved comfort in these environments (Huston et al., 1999). In addition, it would be helpful to recruit more subjects in each of *BMI Prime* groups to analyze the *VDV* for each of the seating conditions.

Chapter 6

6 Summary, Conclusions, Contributions and Suggestions for Future Works

6.1 Summary and Conclusions

Low back injury is a major health issue among heavy machinery operators, and matching seats to the vibration environment may reduce vibration exposure. From our results, we determined that seat selection is not universal. Due to the frequency-dependent properties of suspension seats, the performance and rank orders of industrial seats varies between vibration environments. Switching seat cushions is another approach that may reduce vibration exposures. We tested the vibration attenuation of a No-Jolt™ air-inflated cushion matched to two suspension seats, one with well tuned suspension the other with poorly tuned suspension. We observed that the air-inflated cushion only enhanced the vibration attenuation properties of the seat that had good performance in the both occupational vibration environments. Moreover, subjects' anthropometrics and sex can affect the performance of seat cushions to attenuate vibration when the vibration environment includes jolt exposures.

In order to evaluate the health risks of heavy machine operators with multi-axis vibrations, we successfully identified the vibration attenuation properties of each industrial seat based on an intelligent neural network (NN) concept model. Each of the seat models showed strong correlations between the vertical predicted and measured seatpan r.m.s. accelerations as reflected by the slopes and intercepts of the best fit lines and the coefficients of determination (r^2). Each of the developed NN models included the horizontal and vertical chassis accelerations as the input signals, which reflects the known cross-axis transmissibility properties of industrial seats. Our simplified training process and parameter initialization improved the convergence speed. The NN models also included a measure of driver anthropometrics (*BMI prime*) and sex, and therefore identified the effect of these factors on vibration exposure.

Based on our validated NN models, we evaluated the performance of five industrial seats for eight sample skidder vehicles in the forestry environment. We evaluated the vibration responses to low, medium and high driver's anthropometrics (*BMI Prime*) and sex. The equivalent daily 8-hour vibration exposures, $A(8)$, were calculated to evaluate the health implications of these seat choices. None of the seats were below the lower limit of the ISO 2631-1 health guidance caution zone (HGCZ). One industrial seat (CAT) limited 96% (23 of 24 operator/vehicle combinations) of vibration exposures within the HGCZ range. In contrast, over 50% of the $A(8)$ values exceeded the upper limit of the HGCZ for each of the other four seats. The number of working hours to reach the upper limit of the HGCZ for 8-h work duration vibrations on the CAT seat was much higher than other four seats for the corresponding skidder vehicle and operator's *BMI Prime* and sex. We predict that the CAT seat was the best choice (among the five tested seat models) for this particular forestry vibration environment to minimize the health risks of exposures to vibration.

We also implemented each of our robust seat models to predict the $A(8)$ values for ten LHD vehicles in the underground mining environment. Only 32 of 150 seat, operator and vehicle combinations effectively attenuated the vibration exposure below the lower limit of the HGCZ. The KAB301 seat was the best choice for this particular mining environment among the five tested seat models. It allowed approximately half of the specific operator/vehicle combinations to be operated for over 8 hours (14 of 30). Although the vibration exposure for the remaining operator/vehicle combinations did not attenuate the magnitudes of the vibration exposures below the upper limit of ISO 2631-1 HGCZ, the KAB301 seat performed better than the other industrial seats (except for near-ties for two vehicles, and for the vehicle where all the seats performed well). These seat rankings are in contrast our evaluation of these same seats for attenuating vibration exposures in forestry skidder vehicles. Taken together, this indicates that seat selection is not universal. The performance and rank orders of industrial seats varies between vibration environments.

We performed a sensitivity analysis to determine whether the vibration spectra between occupational environments influences the performance of the seats in the different environments. The dominant frequencies were 2 Hz for the forestry environment and 2.5 Hz for the mining environment. Moreover, the forestry vehicles had higher vibration amplitudes than the mining vehicles at 3.15 Hz. The sensitivity analysis identified that the KAB301 seat was highly sensitive to increases in magnitude for the 2 Hz and 3.15 Hz frequency bands while the CAT seat was much less sensitive to these frequencies. This likely explains why the CAT seat is more suitable with the forestry vehicles. Similarly, the KAB 301 seat performed better with the mining vehicles because the dominant frequency for LHDs was 2.5 Hz, and the KAB 301 seat was less sensitive to this frequency than the CAT seat. Our results support that each seat suspension system amplifies the vibration in specific frequency ranges. Seat selection can be optimized by matching the performance of particular industrial seats with the frequency spectra for the vibration environments.

Given the potential for air cushions to attenuate vibrations, a No-Jolt™ air-inflated cushion was selected to evaluate its vibration attenuation properties for two industrial seats in multi-axis vibration environment including jolt exposures. The KAB301 suspension with the No-Jolt™ cushion was effective at attenuating the vibration for both the forestry and mining vibration environments. This new air cushion decreased the magnitudes of vibrations on the KAB301 seatpan, and increased the working hours which the workers could be exposed for all the scenarios (driver/vehicle combinations) in the forestry and mining vibration environments. However, the new No-Jolt™ air-inflated cushion did not improve the vibration attenuation properties for the Amobi seat. Accordingly the No-Jolt™ air-inflated cushion is not a universal solution, nor can necessarily improve the performance of a poorly tuned suspension seat. This affirms the significance of seat/cushion selection for the specific vibration environments, which can minimize the health risks of multi-axis vibrations to heavy machine operators.

When the vibration environment includes jolt profiles, this new air-inflated cushion also enhanced the attenuation properties of the KAB301 seat. The *VDV* ratios were decreased for both female and male participants in the *BMI Prime* groups 1-3. However, the air cushion amplified the vibration in the *BMI Prime* group 4. In contrast, the new No-Jolt™ seat air-inflated cushion did not improve the vibration attenuation properties of the

Amobi seat. In addition, we noticed that female participants usually had higher *VDV* ratios than male participants for all seating conditions (the KAB301 and Amobi seats, each with their original cushions and with the No-Jolt™ seat air-inflated cushion). This was especially apparent in the *BMI Prime* group 4 with the KAB301 seat, where the *VDV* ratios were 10% higher with the air-inflated cushion for female participants, and 22.3% higher with the original cushion. This indicates that the female workers have higher health risks than males with the jolt exposures.

In terms of interesting findings from the jolt exposures, it was particularly noteworthy that the No-Jolt™ air-inflated cushion performed less well for the *BMI prime* group 4 – individuals with the largest *BMI*. It seems that there may be an opportunity for developing a specific air cushion for individuals with large *BMI* values. Similarly, since the original and air-inflated cushions performed relatively poorly for the female participants, there may be an opportunity for developing a specific air cushion for female drivers in vibration environments.

6.2 Contributions

We successfully identified the dynamic response of different industrial seats according to a neural network concept model. Our model used a simplified training process and parameter initialization, and achieved a fast convergence speed. Our NN model reflects the known cross-axis transmissibility properties of industrial seats based on the recorded three translational acceleration data and predicts the vertical seatpan r.m.s. accelerations. Moreover, our NN models reflect the impact of different driver’s anthropometrics (*BMI Prime* values) on the vibration exposure. We identified that seat selection is not universal by implementing our robust NN models to evaluate the health implications of various seat choices for different heavy mobile vehicles and determining that the vibration exposure differed between seats and vibration environments.

6.3 Future Works

Seat selection could also be expanded to other occupational environments. The chassis acceleration data of scrapers has been measured from the particular construction vibration environment (Dickey et al., 2010). We could evaluate the responses and health risks of heavy machine operators with multi-axis vibrations according to each of our developed NN models.

Given that the performance of the air-inflated cushion, it only decreased the magnitudes of acceleration for a well tuned suspension seat. Accordingly, it would be helpful to evaluate the vibration attenuation properties of the air-inflated cushion with more industrial seats in different vibration environments.

Anecdotally we noticed that some participants were concerned about sliding laterally on the air-inflated cushion. So it would be interesting to evaluate the influence of lateral vibration exposures with different industrial seats. We could implement our NN modeling architecture to predict acceleration and assess the vibration impacts in the horizontal directions.

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Appendices

Appendix A: Natural frequencies for both seats

The natural frequency of each seat was determined by evaluating the magnitude of the seatpan acceleration for sinusoidal accelerations between 1.25 and 3.15 Hz at each 1/3 octave frequency band, and between 1.6 and 2.5 Hz at 0.1 Hz intervals, when the seats were loaded with a 72 kg mass (sand bags). The vibration attenuation/amplification properties of each seat were determined using the Seat Effective Amplitude Transmissibility (S.E.A.T.; Equation A-1). S.E.A.T. values less than 1.0 indicate vibration attenuation whereas values over 1.0 represent amplification of the vibration. Similarly to other researchers (Choi and Han, 2007), the natural frequency was identified as that frequency with the largest magnitude of S.E.A.T.

$$S.E.A.T. = \frac{r.m.s.\ acceleration_{sp}}{r.m.s.\ acceleration_{ch}} \qquad \text{(A-1)}$$

where $Acceleration_{sp}$ is the unweighted r.m.s. acceleration measured on the seatpan and $Acceleration_{ch}$ is the unweighted r.m.s. acceleration measured on the chassis. In cases where the S.E.A.T. values were large for a range of frequencies, then a specific frequency that was high in both the original cushion and the air cushion was selected as the natural frequency.

The following Figures show the S.E.A.T. performances of the KAB301 seat and the Amobi seat with their original and air-inflated cushions at different acceleration magnitudes for the frequency range between 1.25 and 3.15 Hz.

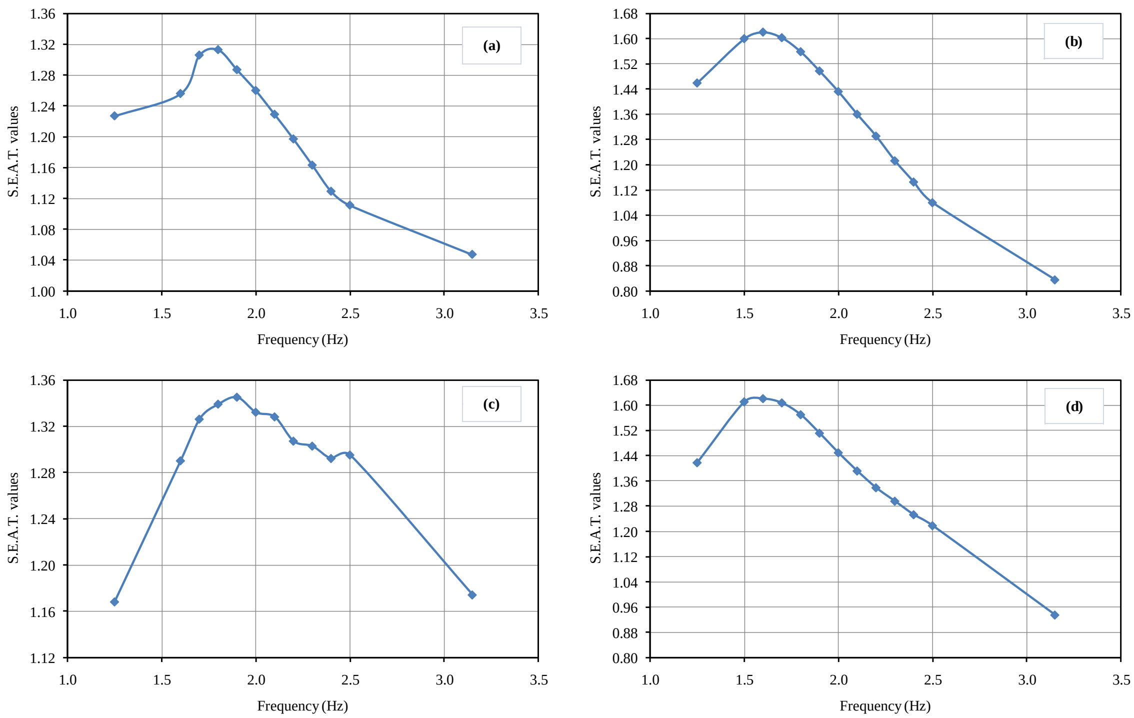

Figure A-1. The S.E.A.T. performance of the KAB301 seat with its original (a and c) and air-inflated (b and d) cushions with the magnitudes of acceleration 1.0 m/s^2 and 1.5 m/s^2 respectively for the frequency range between 1.25 and 3.15 Hz.

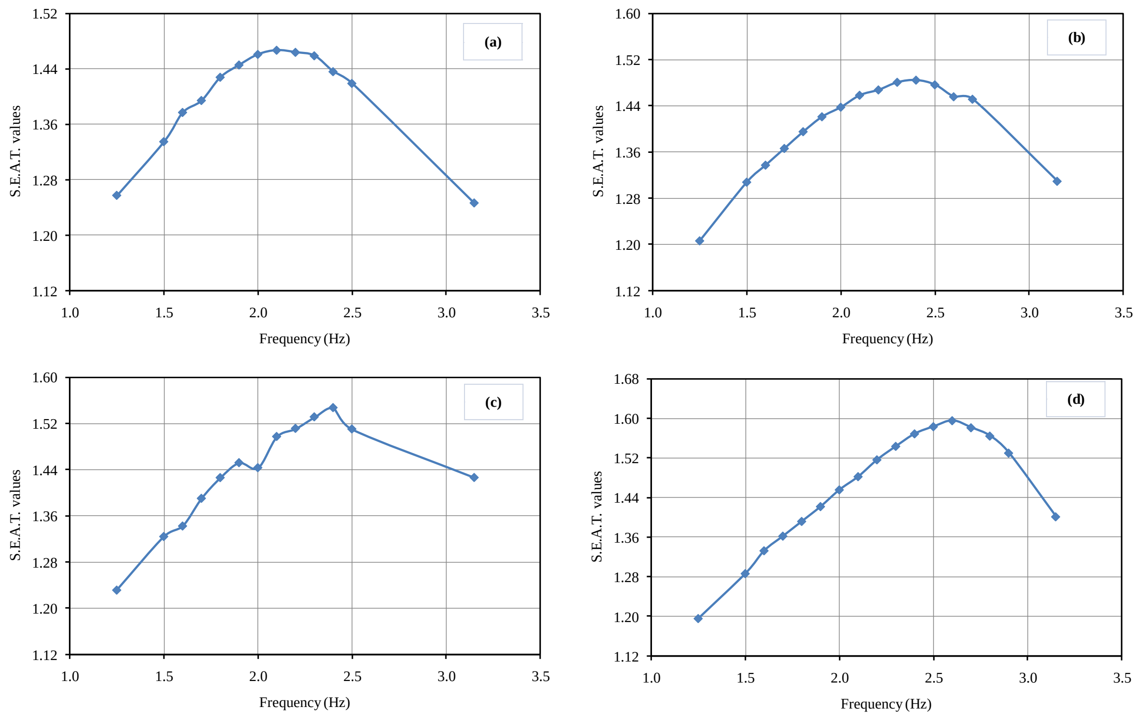

Figure A-2. The S.E.A.T. performance of the Amobi seat with its original (a and c) and air-inflated (b and d) cushions with the magnitudes of acceleration 1.0 m/s^2 and 1.5 m/s^2 respectively for the frequency range between 1.25 and 3.15 Hz.

Appendix B: Ethics approval

Use of Human Participants - Ethics Approval Notice

Research Western

Principal Investigator: Dr. Jim Dickey
Review Number: 15178E
Review Level: Delegated
Approved Local Adult Participants: 280
Approved Local Minor Participants: 0
Protocol Title: Assessment of the effectiveness of heavy machinery seats for multi-axis vibration environments
Department & Institution: Kinesiology, University of Western Ontario
Sponsor: Workplace Safety and Insurance Board

Ethics Approval Date: February 21, 2012 **Expiry Date:** December 31, 2012
Documents Reviewed & Approved & Documents Received for Information:

Document Name	Comments	Version Date
Revised Study End Date	The study end date has been extended to December 31, 2012 to allow for project completion.	

This is to notify you that The University of Western Ontario Research Ethics Board for Health Sciences Research Involving Human Subjects (HSREB) which is organized and operates according to the Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans and the Health Canada/ICH Good Clinical Practice Practices: Consolidated Guidelines; and the applicable laws and regulations of Ontario has reviewed and granted approval to the above referenced revision(s) or amendment(s) on the approval date noted above. The membership of this REB also complies with the membership requirements for REB's as defined in Division 5 of the Food and Drug Regulations.

The ethics approval for this study shall remain valid until the expiry date noted above assuming timely and acceptable responses to the HSREB's periodic requests for surveillance and monitoring information. If you require an updated approval notice prior to that time you must request it using the UWO Updated Approval Request Form.

Members of the HSREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussion related to, nor vote on, such studies when they are presented to the HSREB.

The Chair of the HSREB is Dr. Joseph Gilbert. The UWO HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Ethics Officer to Contact for Further Information

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This is an official document. Please retain the original in your files.

The University *of* Western Ontario
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Western Research

Research Ethics

Western University Health Science Research Ethics Board
HSREB Full Board Initial Approval Notice

Principal Investigator: Dr. Jim Dickey
Department & Institution: Health Sciences\Kinesiology, Western University

HSREB File Number: 106228
Study Title: Assessment of the effectiveness of heavy machinery seats for multi-axis vibration environments including jolts
Sponsor: Natural Sciences and Engineering Research Council

HSREB Initial Approval Date: March 02, 2015
HSREB Expiry Date: March 02, 2016

Documents Approved and/or Received for Information:

Document Name	Comments	Version Date
Instruments	Screening Questionnaire	2014/12/28
Western University Protocol		2015/02/12
Letter of Information & Consent		2015/02/12
Recruitment Items	Poster	2015/02/12

The Western University Health Science Research Ethics Board (HSREB) has reviewed and approved the above named study, as of the HSREB Initial Approval Date noted above.

HSREB approval for this study remains valid until the HSREB Expiry Date noted above, conditional to timely submission and acceptance of HSREB Continuing Ethics Review. If an Updated Approval Notice is required prior to the HSREB Expiry Date, the Principal Investigator is responsible for completing and submitting an HSREB Updated Approval Form in a timely fashion.

The Western University HSREB operates in compliance with the Tri-Council Policy Statement Ethical Conduct for Research Involving Humans (TCPS2), the International Conference on Harmonization of Technical Requirements for Registration of Pharmaceuticals for Human Use Guideline for Good Clinical Practice (ICH E6 R1), the Ontario Personal Health Information Protection Act (PHIPA, 2004), Part 4 of the Natural Health Product Regulations, Health Canada Medical Device Regulations and Part C, Division 5, of the Food and Drug Regulations of Health Canada.

Members of the HSREB who are named as Investigators in research studies do not participate in discussions related to, nor vote on such studies when they are presented to the REB.

The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

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Curriculum Vitae

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	The University of Western Ontario London, Ontario, Canada 2011-2015 Ph.D.
Related Work Experience	2006-2007, Teaching Assistant, Lakehead University 2007-2008, Research Assistant, Lakehead University 2011-2015, Teaching Assistant, The University of Western Ontario

Publications:

- **Xiaoxu Ji**, Tammy R. Eger and James P. Dickey. *Optimizing seat selection for LHDs in the underground mining environment*. The Journal of The Southern African Institute of Mining and Metallurgy. (in process).
- **Xiaoxu Ji**, Tammy R. Eger and James P. Dickey. *Development of a seat selection algorithm to match industrial seats with specific mining vibration exposures*. Association of Canadian Ergonomists (ACE)**,** 45th Annual Conference, (2015).
- **Xiaoxu Ji**, Tammy R. Eger and James P. Dickey. *An Algorithm for Optimal Seat Selection for Heavy Mobile Machinery in Different Industrial Vibration Environments*. 25th Canadian Congress of Applied Mechanics, (2015).
- **Xiaoxu Ji**, Tammy R. Eger and James P. Dickey. *Development of a seat selection algorithm to match industrial seats with specific forestry vibration exposures*. International Journal of Forest Engineering, 26 (2015) 48-59.
- James P. Dickey, Tammy R. Eger, Ryan J. Frayne, Giselle P. Delgado and **Xiaoxu Ji**. *Research Using Virtual Reality: Mobile Machinery Safety in the 21st Century*. Minerals, 3 (2013) 145-164.
- **Xiaoxu Ji** and W. Wang. *A Neural Fuzzy System for Vibration Control in Flexible Structures*. Journal of Intelligent Control and Automation, 2 (2011) 57-68.