4-7-2020 1:00 PM

Comparison of Whole-body Vibration Attenuation Properties Between Active and Passive Suspension Seats

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A thesis submitted in partial fulfillment of the requirements for the Master of Science degree in Kinesiology

Abstract

Professional drivers are at a high risk of WBV injury as they are exposed to vibration constantly throughout a working day. Recently, a company has attempted to mitigate the risk by developing an active suspension seat aimed at reducing WBV exposure for long haul truck drivers. The purpose of this thesis was to compare the new active suspension technology to the current industry standard passive suspension seat. Seats were tested with stochastic vibration exposures and exposures simulating Canadian long-haul trucks. Seats were evaluated by A(8) daily vibration exposure and peak transmissibility metrics. The results determined that the active suspension is significantly more effective in the attenuating z-axis vibration at the frequencies that are most impactful on human health. However, both seats A(8) daily vibration exposures were below the ISO 2631-1 HCGZ caution limit. This suggests that there is no difference in health risks between seats.

Keywords

Whole body vibration, long-haul trucking, active suspension seat, frequency response, Canadian roads, Bose ride®, low back pain, A(8)

Summary for Lay Audience

Whole body vibration (WBV) is a term describing any vibration that is transmitted to the human body from supporting surfaces. The average individual can be exposed to WBV regularly throughout their day such as when driving a car. Chronic WBV exposure has been linked to negative health effects such as digestive disorders, sciatica, prostate cancer, low back pain, and musculoskeletal disorders. Professional drivers are exposed to WBV throughout their workday and because of this have documented higher occurrences of low back pain compared to professionals that are exposed to less WBV.

One solution for limiting WBV for professional drivers has been the implementation of suspension seats. Every long-haul truck has a suspension seat equipped in order to attenuate (reduce) the vibration exposure for the operator. It is common for these suspension seats to have dampers in the form of an air spring. These types of seats are called passive seats. Recently, there has been a development of a new suspension seat technology regarded as being more effective at reducing WBV exposure. This active seat suspension technology includes an actuator that works with an air spring to reduce vibration. The purpose of this research was to compare active and passive suspension seats in order to determine what technology is more effective at reducing WBV. We tested these seats with stochastic vibration exposures and vibration exposures that simulated long-haul trucks on Canadian roads. We determined that the active suspension seat was better at reducing the vibration in the z-axis (vertical axis) compared to the older style passive suspension seat. When we stimulated a Canadian truck driver’s full work day exposure level of WBV, both seats attenuated the exposures to the point where health risks were reduced. Therefore, although the active suspension seat was better at reducing WBV. Ultimately, the current industry standard seat is sufficient for attenuating vibration on Canadian roads.

Acknowledgments

Most importantly I would like to thank my supervisor Jim Dickey for mentoring me for the past three years. He’s been a great sounding board for more than just scientific inquires. I hope to one day fill the shoes of such a great scientist and an even better man.

I’d like to thank Shea Tough for the unrelenting support and love I get from her daily. Thank you for everything.

I’d like to thank my parents for supporting me no matter where I am on my adventure.

To all my lab mates, thank you for the enjoyable memories and all the best in the future.

Table of Contents

List of Tables

List of Figures

List of Appendices

Introduction

1.1 Whole Body vibration

Whole body vibration (WBV) refers to vibrations that are transferred to the human body via supporting surfaces. The International Organization for Standardization (ISO) have published standards that describe procedures for collecting, analyzing and interpreting vibration data from human participants in seated, standing, and recumbent postures[1]. When seated, vibration can be transmitted to the body via the feet, buttocks, back, and hands. Frequency, magnitude, and duration are the main characteristics of WBV. WBV exposure between 0.1 Hz and 0.5 Hz may cause motion sickness whereas 0.5 to 80 Hz has effects on health, comfort, and perception[1]. The most impactful range on human health is between 5 and 9 Hz[1]. Discomfort and health risks increase with vibration magnitude. Magnitudes of WBV above 0.8 m/s^2 r.m.s. will likely result in discomfort, and exposure above 2.0 m/s^2 could result in extreme discomfort[1]. Longer duration exposures with low magnitudes can be equally as impactful as shorter duration exposures with high magnitude[1].

The effects of whole body vibration include decreased comfort, interference with activities, impaired health, perception of low-magnitude vibration, and motion sickness[2]. These effects can be experienced simultaneously. This thesis focuses on the risks of health effects associated with WBV. These health effects include sciatica[2,3], digestive disorders[2], genitourinary problems[2], hearing damage[2], low back pain[3,4], decreases in visual acuity[5], and musculoskeletal disorders[3]. One study determined that workers exposed to WBV were at higher risk of developing prostate cancer (1.44 odds ratio)[6]. A review of the literature suggested that workers exposed to WBV had a higher incidence (2.3 combined odds ratio) of low back pain disorders compared to non-exposed controls[7]. As well, driving seems to pose a health risk. For example, professional drivers exposed to WBV had a higher incidence of low back pain compared to non-exposed controls in a profession that spent the majority of the work day seated (odds ratio = 1.41-2.08

depending on the vibration dose)[8]. In addition, a longitudinal study conducted on professional drivers that had no prevalence of low back painLBP in the previous 12 months at baseline observed 38.6% cumulative prevalence of LBP in the following year[4].

Whole body vibration affects trunk proprioception. For example, muscle response latency is increased following perturbation when participants were exposed to 3.0 Hz WBV while seated compared to participants that were not exposed to vibration[9]. WBV exposure increases errors in participants ability to sense and reproduce lumbar posture compared to non-exposed controls. These findings suggest that individuals exposed to WBV could be at a greater risk of injury when reacting to sudden unexpected perturbations. In contrast, one study found that seated vibration led to increased flexibility and reduced lower lumbar lordosis following a vibration exposure[10]. These incongruous findings may because this study evaluated vibration exposures at 18 Hz which is outside of the more impactful range on human health of 5 to 9 Hz as determined by the standard ISO 2631-1[1]. These contrasting findings suggest that the effects of WBV on trunk proprioception can change based on exposure frequency[9,10].

Although there are a variety of health effects associated with excessive whole-body vibration exposure, this thesis is chiefly concerned with LBP. The seated human body's resonant frequency occurs somewhere between 4 to 8 Hz depending on posture, location of measurement, vibration direction, and back rest presence[11–13]. The mechanism of WBV related LBP is still not clear; however, there has been speculation. One study suggested that low back injuries will arise from bending deformations of the spine[12]. Another hypothesized that dynamic compressive loading of the intervertebral joint leads to micro fractures at the end plate and dynamic shear, bending, or rotational loading of the intervertebral joint leads to breakdown of the annular lamellae resulting in disc degeneration[14].

1.1.1 Driving related WBV

An observational study observed a dose-response pattern between driving related low back pain and WBV in professional drivers after adjusting for other contributing factors (e.g. lifting, bending, previous job with heavy loading)[15]. Low back pain has also been found to develop in healthy drivers that are exposed to WBV[4]. A meta-analysis evaluating twenty-seven different articles found that there is an increased risk of low back pain and sciatica with exposure to WBV compared to non-exposed groups (2.17 pooled odds ratio)[3].

1.1.2 Truck drivers as at risk individuals

Long haul truck drivers are at an increased risk for diabetes[16], obesity[16–19], myocardial infarction[20], musculoskeletal disorders[3,21], and psychological distress from occupational stressors[22] compared to the U.S. adult working population. The transportation and material moving industry is the only occupational group that is among the top five for all risk factors observed (obesity, lack of leisure time or physical activity, and short sleep)[18]. In addition, a survey of truck drivers observed that 73.8% of men and 80.5% of women had less than 30 minutes of physical activity for five days in the previous week[17]. Additionally, 28.4% of men and 25.2% of women had zero days with 30 mins of physical activity in the previous week[17]. Another survey observed that 71% of long haul truck drivers were driving despite fatigue, bad weather, or heavy traffic because they needed to deliver or pick up a load[23]. These points suggest that truck drivers are a vulnerable to a variety of health risks.

Previous work reported that truck drivers had the third highest median days away from work due to musculoskeletal disorders[21]. Exposure to WBV may be a potential reason for this. Long haul truck drivers are at high risk for WBV injury as they work long hours and spend most of the work day seated and being exposed to WBV[22].

1.2 Evaluation of WBV (ISO 2631-1)

Health effects of WBV are not only amplitude dependent but also frequency dependent[1]. ISO 2631-1 outlines the frequency weighting required evaluated health effects of WBV[1]. This standard describes that 5-9 Hz frequencies are most impactful on human health. The standard describes different methods for evaluating vibration exposures as well as, how to interpret health effects of WBV exposure.

1.2.1 Direction of measurement

WBV is typically measured along three linear axes; sagittal (*x*), lateral (*y*), and vertical (*z*). Figure 1.1 presents these axes. There is also rotational vibration that occurs around these linear axes; roll (rotating about the x-axis), pitch (rotating about the y-axis), and yaw (rotating about the z-axis).

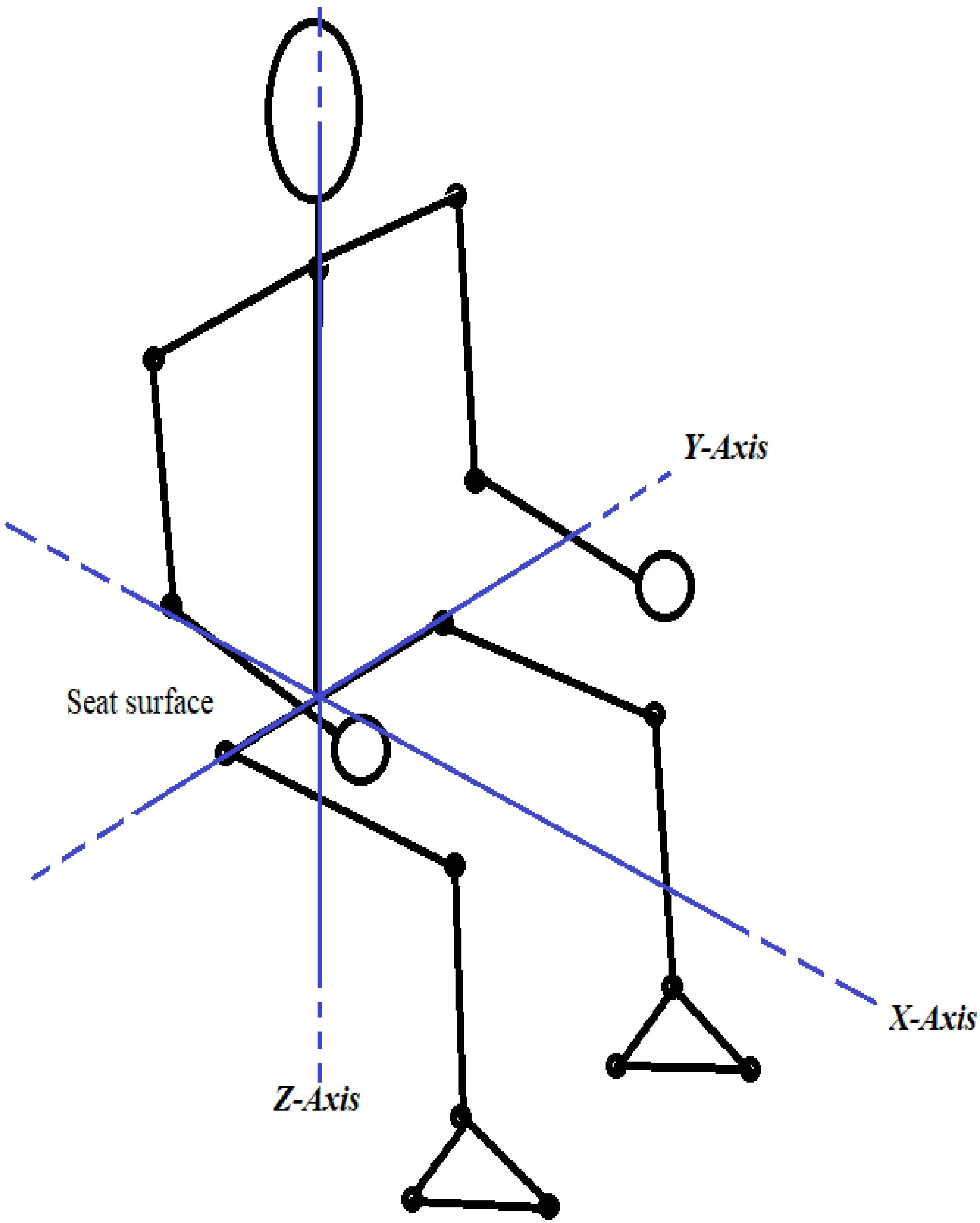

Figure 1.1: Convention describing the axes for seated person.

The effects of vibration on health, comfort, perception and motion sickness are frequency dependent[1]. There are two main frequency weightings for health outcomes, W_k for the z-axis and W_d for the x and y-axis (Figure 1.2). Frequency weightings are used to filter WBV to place less emphasis on vibrations with less harmful health outcomes. Vibration exposures are multiplied by the weighting factor at the given frequency.

As an example, an unweighted vibration exposure made up of only 1 and 10 Hz exposure

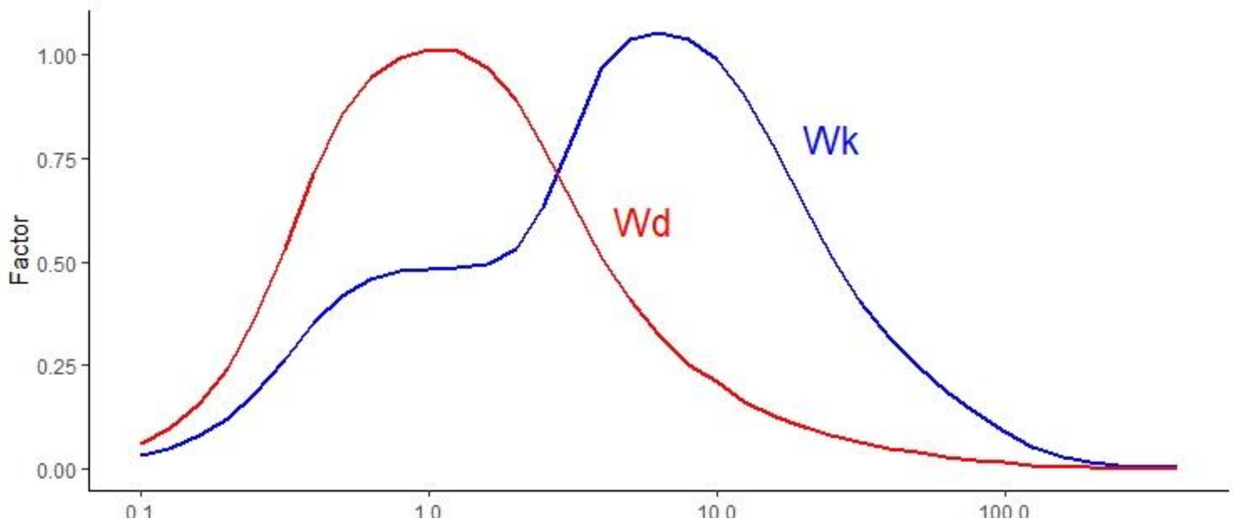

Figure 1.2: Frequency weighting curves for vertical W_k, lateral and sagittal W_d.

frequency will equally emphasize the 1 and 10 Hz components. When this exposure is weighted with the Wk factor, the 1 Hz exposure will be multiplied by a factor of approximately 0.5 and the 10 Hz exposure will be multiplied by a factor of approximately 1. This places more emphasis on the 10 Hz component compared to the 1 Hz component.

1.2.3 Evaluation of Vibration

Vibration is commonly evaluated using the root mean square (r.m.s.) of the acceleration in meters per second squared (m/s^2). Vibration is a movement that oscillates about a fixed point and will have a mean of zero. Therefore, the r.m.s. of the vibration exposure provides non zero value to quantify the vibration. For evaluating the health risk of vibration exposures, the measured vibrations are modulated by the frequency weightings as described in section 1.2.2 and are referred to as weighted vibrations. The weighted vibration exposure is calculated according to Equation 1.1,

$$a_w = \left[\frac{1}{T}\int_0^T a_w^2\,(t)dt\right]^{\frac{1}{2}} \qquad (1.1)$$

where $a_w(t)$ is the weighted acceleration as a function of time in m/s^2, and T is the duration of the measurement in seconds.

Transmissibility is a measure of how much vibration goes through a medium. Transmissibility indicates whether the vibration is attenuated or amplified by the medium. If transmissibility is greater than 1.0 then the vibration is being amplified by the medium, and if the vibration is less than 1.0 then the vibration is being attenuated. The power spectral density (PSD) and cross spectral density (CSD) are two different methods used to calculate transmissibility[24]. The PSD method is susceptible to noise and does not provided accurate measures if the system is nonlinear. It is recommended that CSD methods are used to avoid these inaccuracies[24].

Coherence reflects the power transfer between the input and output signals, reflecting the fraction of the output signal power that is produced by the input signal at each frequency[25]. Coherence has a maximum value of 1.0 and is reduced by nonlinearities in the signal such as noise or interference. Small vibration energy also decreases the coherence.

A worker's daily vibration exposure accumulates while driving different vehicles, performing different tasks within the vehicle, and driving on different roads[24]. There is more than one way to calculate WBV exposure. VDV_{total} and a_w are the two main methods for evaluating daily vibration exposures. VDV_{total} places emphasis on shocks more than a_w methods. The crest factor, the ratio of the peak acceleration to the r.m.s. acceleration,[1] is used to suggest which method is used for evaluation of daily vibration exposure. If the crest factor is above 9 then VDV_{total} should be used to evaluate daily exposures. If the crest factor is below 9 then a_w should be used.

1.2.4 Health caution guidance zone

The ISO 2631-1 health caution guidance zone (HCGZ) lower and upper boundaries are 0.45 and 0.9 m/s^2 r.m.s. for a_w normalized to an eight hour work day[26]. The ISO standard states that health risks have not been documented or observed for exposures below the lower boundary of the HCGZ[1]. Exposures above the upper limit are likely to result in negative health effects[1]. The ISO 2631-1 standard suggests "caution with respect to potential health risks" for exposures in the HCGZ[1].

1.3 European Union Directive 2002/44/EC

The European Union (EU) directive 2002/44/EC is a under the larger umbrella of the 89/381/ECC directive for the safety and health of workers at work[27]. Directive 2002/44/EC outlines exposure and action limits for whole body vibration that is different from ISO 2631-1 HCGZ. The EU directive has a daily exposure action value of 0.5 m/s^2 and a daily exposure limit of 1.15 m/s^2 [1,28].However, the 2002/44/EC references the ISO 2631-1 for methods related to assessment of whole body vibration, and it applies the same weightings and locations for measurement for vibration exposure[28].

1.4 Reduction of WBV

The best action for the reducing driving related whole body vibration is the elimination of the source of vibration[2]. Numerous interventions have been used to reduce WBV. Such interventions can include construction of new roads, however, such interventions are expensive and usually not feasible[2]. Reducing driving speed has also been an effective method for reducing WBV[29]. The next option is reducing vibration from the source using isolation methods[2]. Isolation interventions include implementing or improving cab and seat suspension[30]. Active cab suspensions have been implemented with successfully reduced WBV for telescopic handlers[31]. However, few intervention studies have evaluated real world applications for cab suspensions[30]. The most studied design intervention has been the implementation and optimization of suspension seats[30].

Suspension seats are equipped with linkage(s) and dampener(s) in effort to absorb some of the shock that the user is exposed to. Suspension seats should be tuned to the relevant vibration environment meaning that seats should be designed to attenuate the vibration at dominant frequencies of their specific environment[2].

1.4.1 Anthropometric factors and WBV

There is disagreement over whether body mass index (BMI), height, or weight is the best predictor of WBV exposure. Previous work showed that driver weight did not influence WBV exposure; however, sample size for this experiment was small and unequal[32]. In contrast, a previous study used BMI over body mass as it more accurately predicted WBV attenuation properties of suspension seats[33]. In addition, another study demonstrated that BMI was a more robust variable for predicting WBV exposure than height and body mass separately[34]. In conclusion, there is evidence to suggest that BMI is a better predictor of WBV exposure than body weight.

1.4.2 Passive suspension seats

Passive suspension seats are defined by having one or multiple passive dampener(s) to reduce the impacts of shocks and vibration. Passive dampeners can include, but are not limited to, steel springs, hydraulic dampeners, and air bags. A large body of work has evaluated passive suspension seats in various vehicles and vibration environments, and has illustrated that passive suspension seats can attenuate WBV exposure at some frequencies[32,35–42].

1.4.3 Active suspension seats

Active suspension seats have actuators and controllers coupled with passive dampeners to improve vibration attenuation characteristics. An active suspension seat model describes a seat controller receiving feedback from the actuator and then adjusts the force of the actuator[43]. Recently, a commercially available active suspension seat has been developed (Bose Ride®, Bose Corporation, Massachusetts, USA) for the long-haul trucking environment. The performance of this active seat has been evaluated in field studies in buses[44] and long-haul trucks[44–46]. Active suspension seats have greater z-axis WBV attenuation than their passive counterparts [44–47]. However, these studies did not perform a multi axis frequency response analysis of the active suspension seat[44–47]. A multi axis frequency response analysis would provide insight into which vibration environment the active seat is tuned for.

If vibration exposure is below the ISO action limit, then the improved performance in vibration attenuation may not translate to reductions in risk of WBV injury. Active suspension seats are more expensive than their passive suspension counterparts making them less appealing to companies looking for WBV attenuation solutions. Accordingly, there is a need to evaluate the performance characteristics of active and passive suspension seats, including evaluating whether participants' BMI influences the seat performance.

2 Purpose Statement and Hypothesis

2.1 Purpose Statement

This study has two purposes. First, to quantify the WBV attenuation characteristics of active and passive suspension seats across varying amplitudes and a range of frequencies. Second, to evaluate the efficacy of commercially available active and passive suspension seats as interventions for reducing the health risks caused by WBV for long haul truck drivers on Canadian roads.

2.2 Hypotheses

1) The active suspension seat will decrease WBV transmissibility more effectively than the passive suspension seat.

2) The vibration exposures simulating Canadian long-haul trucks will be below HCGZ and EU directive when using either the passive or active suspension seat, and preference of one seat as an intervention will not be given.

3 Methods

3.1 Participants

This study was approved by the Western University Health Sciences Research Ethics Board (HSREB Protocol 106228). Twenty-five participants volunteered to partake in this study. All participants provided informed consent before completing any aspect of this study. Exclusion criteria included not being involved in an automobile accident in the previous five years, having a history of low back pain, having discomfort in sitting, or not being able to communicate clearly in English. Participants were compensated 20 dollars for their time. Participant height and weight were self-reported for calculating body mass index (BMI). Formula for calculating BMI is presented in Appendix A.

3.2 Long-Haul Truck Vibration Exposure Library

The laboratory vibration exposures in this thesis are based on a set of previously collected long-haul truck vibration data. The details of the field vibration data collection and data processing are outlined below for completeness. However, the collection of field exposures is only relevant insofar as they were used to create field profiles used to test suspension seats in the laboratory.

A library of field exposures was created based on WBV exposures collected from twenty-five long-haul trucks prior to commencement of this thesis. The make and model of trucks are presented in Table 3.1. Vibration records from the chassis (below the seat) and seat pad for these long-haul trucks were collected for the duration of the drivers' work day. As per the ISO 2631-1[1] standard, a triaxial accelerometer (S2A-16G-MF, NexGen Ergonomics, Pointe Claire, QC, CA) was mounted in a rubber seat pad to the top of the truck operator's seat, and a second triaxial accelerometer (same model) was mounted to the floor of the truck's cab beneath the driver's seat. Raw acceleration data were recorded at 500 Hz using an eight channel datalogger (DataLOG II P3X8, Biometrics, Gwent, UK). Data were collected for the duration of the drivers shift.

Table 3.1: Truck make/model, year, Trailer, Load (Kg), and Seat model and model year for 25 trucks used to create vibration library. Information that was not made available is indicated with N/A.

Truck	Make/Model	Year	Trailer	Load (Kg)	Seat Type and Date
1	Volvo	N/A	N/A	N/A	N/A
2	Volvo	N/A	N/A	N/A	N/A
3	Volvo	N/A	N/A	N/A	N/A
4	Volvo	N/A	N/A	N/A	N/A
5	Volvo	N/A	N/A	N/A	N/A
6	Volvo D12 Day Cab	N/A	N/A	N/A	Bose Ride®
7	Volvo D12 Small Bunk	2012	Flat bed trailer	9000	Man Seat - 2016
8	Freightliner Cascadia Day Cab	2016	Great dane	11000	Man Seat - 2016
9	Volvo D13	2011	Gravel trailer	54000	Man seat - 2011
10	Mack Pinnacle	2015	Super B	57000	Man seat - 2016
11	Volvo - D13	2015	Tandem turn pike 253	N/A	Man seat - 2015
12	Volvo D15 Day	2013	Step deck	N/A	Man. Seat - 2012
13	Volvo D15 Day	2013	Step deck	N/A	Man. Seat - 2013
14	Volvo D13 Day Cab	2014	Super 8	60000	Man. Seat - 2014
15	Kenworth T800	1999	Flatbed	N/A	Seats Inc. - 1999
16	Volvo D13 Day Cab	2010	Tri-axle HiBay	16000	National - 2016
17	Volvo D13 Day Cab	2010	Tri-axle HiBay	22000	National - 2016
18	Volvo D13 Day Cab	2013	Triden step deck	N/A	Man seat - 2013
19	Freightliner Cascadia	2014	Two van trailers	N/A	Bose Ride® - 2014
20	Peterbilt 379 LongNose	2012	Wilson Livestock	36000	Legacy - 2002
21	Freightliner Cascadia	2016	Wilson Livestock	45000	Man. Seat - 2016
22	Western Star 4964F	1994	Step deck	20000	National - 1996
23	Kenworth T800	2004	Wilson Livestock	45000	Legacy LoSilver - 2015
24	Kenworth T800	2004	Wilson Livestock	N/A	Legacy LoSilver - 2016
25	Peterbilt 579	2015	Dry Van - Trailer tail	18000	Std Air ride - 2015

Geographical position, speed, and time stamps of the long-haul trucks in Manitoba were recorded at 1 Hz using a GPS tracker (Model DG-100; GlobalSat, Chino, CA, USA). This data were stored as KLM files which were loaded into Google Earth, and visually examined to determine the type of road (road types were: highway, rural, urban, jobsite, and provincial road) that the trucks were travelling on. The GPS time stamps were cross referenced with vibration data to identify segments of the vibration data corresponding to the specific road segments. These road segments were then subdivided into 20 second sub-segments, a duration that is appropriate for reliably measuring human responses to vibration exposures in laboratory testing[48]. The 20 second segments were grouped by road type and then divided further by ranking the vibration magnitude on each axis into tertiles. Profiles were grouped by the magnitude of the vibration in each axis (XYZ), similarly to previous research[49]. For example, a vibration profile with high vibration (exposures in the third tertile) on all axes was described as 333 while a vibration profile with low (exposures in the first tertile) vibration on the x- and y- axes, and moderate (exposures in the second tertile) on the z-axis, would be described as 112. The frequencies of occurrence for all ranks of profiles for each road type were calculated. . Segments were excluded from selection if truck speed was lower than 5 km/h to ensure that trucks were in motion and drivers were present in seats, similarly to other research[45]. One 20 second segment was selected randomly for each of the six most common ranks within each of the five road types, yielding a set of 30 representative segments that would be used for the field profiles in the laboratory testing.

The 30 segments were vetted to ensure that they were free of artifacts by screening for raw mean acceleration above 1 m/s^2 over the 20 seconds and a peak acceleration over 20 m/s^2, similarly to previous research[45]. The segment accelerations were bandpass filtered between 0.5 and 20 Hz with a second order Butterworth filter using a custom LabVIEW program (v2012, National Instruments; Austin, TX, USA). The acceleration data were down sampled from 500 to 200 Hz using a custom LabVIEW program to comply with the motion platform requirements. Acceleration data were then double integrated using Simpson’s Rule, scaled to millimeters, and formatted with a header and footer to produce paths for input to the motion platform.

3.3 Laboratory Testing Procedures

Participants sat on suspension seats that were mounted to the top surface of a 6df motion platform (R3000, Mikrolar Inc. Hampton, NH, USA) (Figure 3.1). Each seat's suspension was set to the maximum seat height that the participant's feet rested flat on the top of the motion platform. Participants were instructed to sit upright with their back in contact with the seat back, arms resting either in their lap or on the arm rests of the seat, and to keep their feet in contact with the top of the motion platform. Participants could adjust the arm rests and back-rest angle to their liking provided participants remained in a seated posture.

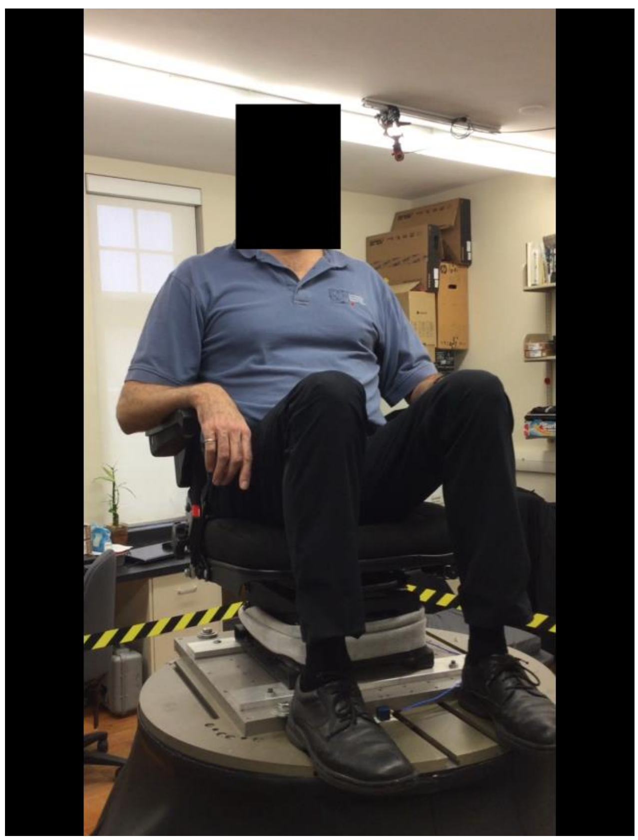

Figure 3.1: Example of laboratory experimental set up with seat mounted atop 6df motion platform and participant sitting on seat.

An active suspension seat (Bose Ride®, Bose Corporation, Massachusetts, USA) and a passive suspension seat (Legacy Silver, Seats Incorporated, Wisconsin, USA) were tested. Both seats are designed to perform in a long-haul trucking vibration environment and are similar to the seats used in the field testing. Both seats were not modified from factory specification and were run-in according to recommendations for seat testing[50]. Both seats' air suspension systems were filled by an air compressor (CL0502710, Powermate LLC, Long Grove, IL.) at 120 psi. The Bose Ride® seat was powered with a 12 V power supply (RSP-1000-15, MEAN WELL, New Taipei City, Taiwan).

Per the ISO 2631-1 standard[1], one triaxial accelerometer (S2A-16G-MF, NexGen Ergonomics, Pointe Claire, QC, CA) was placed in a rubber pad on the seat cushion and a second matching accelerometer was placed atop the 6df motion platform, in front of the seat and in line with the seat pan accelerometer. Both accelerometers were secured via double sided tape to avoid shifting during trials. The data were recorded from the accelerometers at 1000 Hz with a 16-bit analog-to-digital converter (USB 6225, National Instruments, Plano, TX) using a custom LabVIEW program (version 2010, National Instruments, Plano, TX). Participants were exposed to ten field exposure paths and three stochastic vibration paths. The field exposure paths were randomly selected from the 30 paths generated for testing. The three stochastic vibration paths were 60 s long and contained a uniform frequency content between 0.5 and 20 Hz, with r.m.s. accelerations of 0.2, 1.0, and 1.5 m/s^2 respectively. All three of the stochastic vibration trials were triaxial and had the same vibration magnitude on all axes.

All experimental measures were collected in a single session for each participant. The experimental sessions were approximately 45 minutes long with both seats being tested in the same session. All field exposures were tested first followed by all the stochastic exposures for the first seat. Seats were then swapped as the participant waited in the laboratory, this provided a break from vibration exposure. All stochastic exposures were tested followed by all the field exposures for the second seat. Seat order alternated for each participant with all even numbered participants completing testing for the Bose

Ride® seat first followed by the Legacy seat. Odd numbered participants completed testing for the Legacy seat first followed by the Bose Ride® seat.

3.4 Analysis

The platform and seat pan accelerations were processed using a custom LabVIEW program (version 2010, National Instruments, Plano, TX). In specific, the bias was removed from each channel and then the signals were low-pass filtered at 80 Hz using a Butterworth second-order filter. The filtered signals were then calibrated to yield accelerations in meters per second squared. The initial and final one second was removed from each file to remove filter artifacts. Accordingly, the field vibration exposures were 18 seconds long, and the stochastic vibration exposures were 58 seconds long.

3.4.1 Transfer Function Calculations

Frequency response transfer functions (transmissibility and phase) were calculated with a custom written LabVIEW program using the Sound and Vibration Toolkit[51]. First, the power spectral density of each signal was calculated using Welch's method with 50% overlapping 4 second windows (resolution 0.25 Hz) for the frequency range 0.5 – 20 Hz, according to Equation 3.1.

$$PSD\ (f) = \lim_{T\to\infty} \frac{E|X_T(f)|^2}{T} \qquad (3.1)$$

Where $E|X_T(f)|$ is the expected value of the Fourier transform of truncated data and T is the record length in seconds.

Cross spectral density (CSD) and transmissibility was calculated along the x-, y-, and z-axes according to the CSD function (Equation 3.2) and the CSD transfer function (Equation 3.3). This parameter compares the amount of vibration at two locations (platform and seat pan) and expresses the amplitude and phase differences at each frequency[24].

$$CSD\ function\ (f) = \lim_{T\to\infty} E\,\frac{\{X_T(f)Y_T(f)\}}{T} \tag{3.2}$$

Where $X_T(f)$ and $Y_T(f)$ are Fourier transforms of the input and output signals respectively,T is the record length in seconds, and E is the expected value of the function.

$$CSD\ transfer\ function\ (f) = \frac{CSD_{input\ output}(f)}{PSD_{input}(f)} \tag{3.3}$$

These measures inherently assume that the frequency content of the two signals is similar, which can be directly assessed using the signal coherence. Coherence, a measure of the correlation between the input and output signals, was calculated according to Equation 3.4.

$$coherence\ function\ (f)^2 = \frac{\left|CSD_{input\ output}(f)\right|^2}{PSD_{input}(f)\times PSD_{output}(f)} \tag{3.4}$$

A value of 1 indicates that the two signals have identical frequency content. In practice, the coherence is less than 1 due to nonlinearities which develop due as the vibration is transmitted, as well as noise in the signals. If the coherence value is below 0.5 then caution should be applied when interpreting transfer function findings[45].

3.4.2 A(8) calculations

Daily vibration exposure was calculated as outlined in ISO-2631-1. R.M.S. Acceleration (A_w) at the floor and seat pan were calculated using Equation 3.5

$$A_w = \left[\frac{1}{T}\int_0^T A_w^2\,(t)dt\right]^{\frac{1}{2}} \tag{3.5}$$

where $A_w(t)$ is the weighted acceleration as a function of time in m/s^2 and T is the duration of the measurement, in seconds.

The health effects of vibration were calculated using the A(8) parameter, as described in ISO 2631-1. To evaluate the efficacy of the seats using the field exposures, A_w seat pan accelerations were normalized to an 8-hour work day. This approach calculated theoretical vibration exposures based on 8-hour workdays composed of different tasks with their corresponding vibration exposure. This is a similar approached that was used previously on load-haul-dump vehicles[29]. Two variants of exposure were calculated based on the proportion of highway and rural/provincial road (PR) driving. These variants are referred to as the highway bias and the rural/PR bias. The highway biased A(8) calculations had the majority of the theoretical exposure provided from highway exposures. Likewise, the rural/PR exposures had the majority of exposure time coming from rural and provincial roads. The breakdown of time spent on each rank of road for the theoretical exposure is presented in Table 4.4, 4.5, or 4.6. Further, daily vibration exposures were also grouped by BMI to identify differences in vibration exposures between BMI groups in addition to seat groups. BMI was selected rather than body mass since BMI was a more robust variable for predicting WBV exposure than height and body mass separately[34]. Time of zero minutes and A_w value of “N/A” in the second theoretical exposures is used when there is no independent observation of frequency weighted acceleration for all BMI groups. For example, if there were participants from the normal and overweight groups that completed the urban trial ranked 222 but there was no participant from the obese group that completed that trial then urban trial ranked 222 was not used in the calculation of A(8).

3.5 Statistical analysis

Nine histograms of peak transmissibility at 5, 7, and 9 Hz on all three axes for 0.2, 1.0, and 1.5 m/s^2 r.m.s. excitation amplitude (three axes × three accelerations) from stochastic exposure trials were created to visually evaluate normality. This analysis determined that the vibrations at 5, 7 and 9 Hz along the X and Y axes histograms followed a normal distribution. The z-axis plots had a right skew and a left tail suggesting the data were not normally distributed. A square root transformation was performed to normalize the z-axis data. This transformation was selected because the variances between groups were most equal following this transformation compared to a natural log or a log base 10 transformations. Peak transmissibility data at exposure frequencies of 5, 7 and 9 Hz were extracted for the analysis. These frequencies span the range of most impactful frequencies on human health for z-axis exposure[1].

Peak transmissibility magnitude data were used in 9 three-way repeated measures ANOVAs (BMI x seat x frequency) with BMI as a between group factor and with seat and frequency being within group factors. The analyses for the x- and y-axis used unweighted peak transmissibility magnitude data. The analysis of z-axis used unweighted square-root transformed peak transmissibility magnitude data. If an interaction was statistically reliable, then a group F score was calculated to determine if simple effects were statistically reliable. If an F score investigating simple effects was statistically reliable, then contrast tests were conducted to determine where differences within groups lay. Tukey honest significant difference (Tukey HSD) tests were used to evaluate main effects. A Bonferroni-Holm correction was used with an alpha level of 0.05. This resulted in a critical alpha value of 0.016 for initial repeated measures ANOVAs, 0.0015 for z-axis post hoc analysis concerned with excitation amplitudes of 0.2 and 1.0 m/s^2 R.M.S., 0.001 for z-axis post hoc analysis with an excitation amplitude of 1.5 m/s^2 R.M.S. The critical alpha value for the x-and y-axis post hoc analysis with 0.2 m/s^2 R.M.S. was 0.008. No *a priori* tests were planned. All statistical calculations and tests were performed with R (version 4.0.0, R Core Team, Vienna, Austria).

4 Results

4.1 Participants

Participant BMI ranged from 22 to 39 kg/m^2. The normal BMI group had 8 participants while the obese and overweight groups had 7 participants per group. Group mean and standard deviation was 22.6 ± 0.52 kg/m^2, 28.0 ± 1.6 kg/m^2, and 32.8 ± 3.5 kg/m^2 for normal, overweight, and obese groups respectively.

4.2 Frequency response to stochastic vibration exposures

Coherence for both seats at all excitation amplitudes and all axes is presented in Appendix B.

4.2.1 Z-axis

Z-axis median , 25^{th} percentile, and 75^{th} percentile transmissibility at the dominant frequency for Bose Ride® and Legacy seats is presented in Table 4.1.The Bose Ride® seat had a dominant frequency of 0.5 Hz on the z-axis across all excitation amplitudes. The dominant frequency range for the Legacy seat was 1.75 to 3.75 Hz on the z-axis. The Bose Ride® seat had lower 25^{th} percentile, median, and 75^{th} percentile transmissibility on the z-axis compared to the Legacy seat across all excitation amplitudes at each seat's respective dominant frequency. At 0.2 m/s^2 r.m.s. the Legacy seat had over double the 25^{th}, median, and 75 percentile transmissibility compared to the Bose Ride® seat with the Legacy seat's 75^{th} percentile transmissibilities exceeding a magnitude of 3.0. The Bose Ride® seat had more consistent transmissibility performance. It had interquartile ranges between 0.04 and 0.06 while the Legacy seat's interquartile ranges were between 0.06 and 0.36.

Table 4.1: Z-axis median, 25th percentile, and 75th percentile transmissibility at respective dominant frequencies for each excitation amplitude and seat.

Excitation amplitude	**0.2 m/s²**		**1.0 m/s²**		**1.5 m/s²**	
Seat	Bose	Legacy	Bose	Legacy	Bose	Legacy
Dominant Frequency	0.50	3.75	0.50	1.75	0.50	2.00
25th Percentile	1.16	2.71	1.25	1.48	1.20	1.36
Median Transmissibility	1.18	2.89	1.27	1.51	1.22	1.46
75th Percentile	1.22	3.07	1.29	1.54	1.26	1.49

The Z-Axis Transmissibility across the tested frequency range is presented in Figures 4.1, 4.2, and 4.3 for 0.2, 1.0, and 1.5 m/s^2 r.m.s. excitation amplitudes respectively. The transmissibility pattern was similar at all the excitation amplitudes for the Bose Ride® seat. The transmissibility was greater than 1.0 for frequencies below 1 Hz and the transmissibility decreased until 2.5 Hz where it demonstrated a small plateau and then decreased to almost zero beyond 5 Hz. The interquartile range was small across all excitation amplitudes for the Bose Ride® seat. Transmissibility of the Legacy seat increased from 0.5 Hz till the dominant frequency (between 1.75 and 3.75 Hz) and then decreased until approximately 10 Hz where it reached a plateau close to 0.1. Beyond 10 Hz, the interquartile range was small for the Legacy seat.

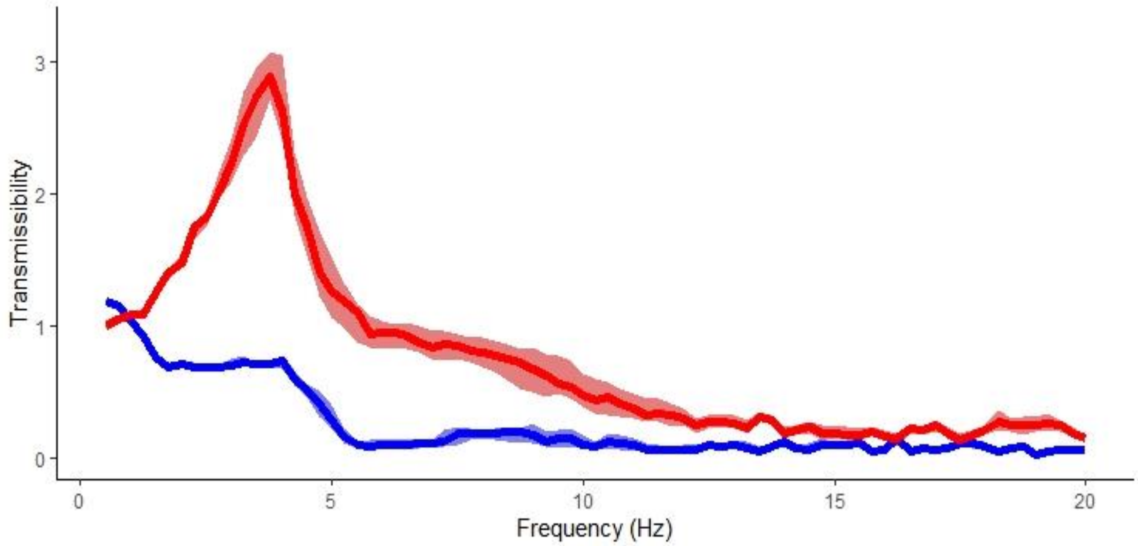

Figure 4.1: Z-axis transmissibility of Bose Ride® (blue trace) and Legacy (red trace) seats excited at 0.2 m/s^s r.m.s. Solid lines represent the median value while the shaded area represents the 25th and 75th percentile.

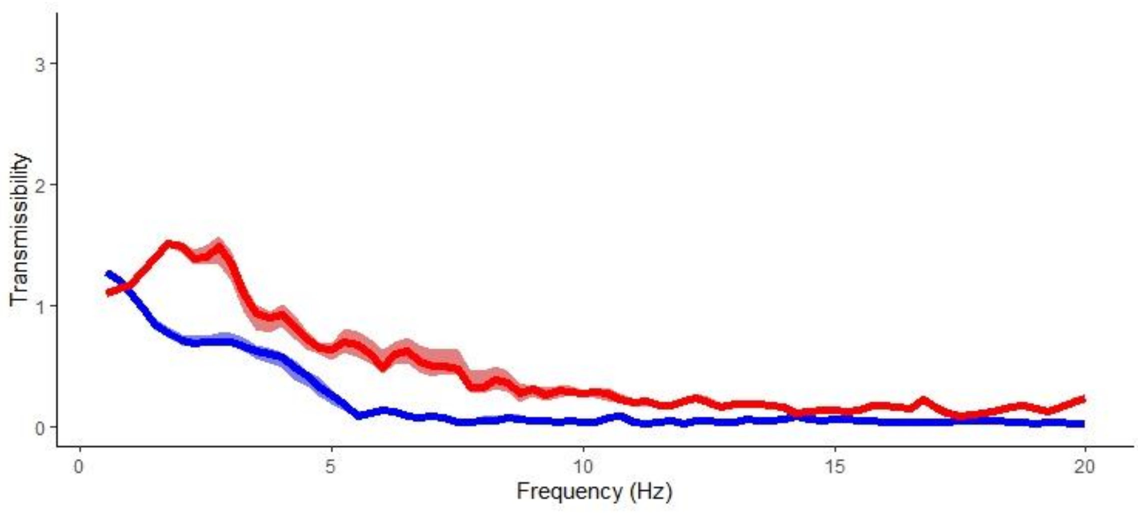

Figure 4.2: Z-axis transmissibility of Bose Ride® (blue trace) and Legacy (red trace) seats excited at 1.0 m/s^s r.m.s. Solid lines represent the median value while the shaded area represents the 25th and 75th percentile.

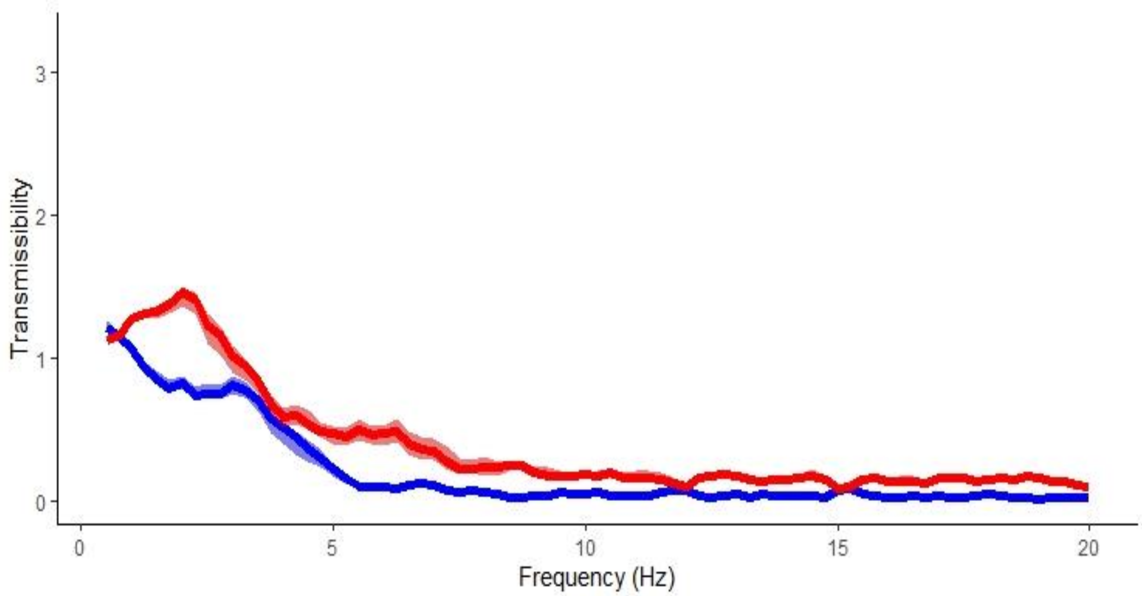

Figure 4.3: Z-axis transmissibility of Bose Ride® (blue trace) and Legacy (red trace) seats excited at 1.5 m/s^s r.m.s. Solid lines represent the median value while the shaded area represents the 25th and 75th percentile.

4.2.2 Y-axis

Y-axis median, 25th percentile, and 75th percentile transmissibility at the dominant frequency for Bose Ride® and Legacy seats is presented in Table 4.2.The Bose Ride® seat had the largest dominant frequency range on the y-axis (6.5 Hz) with dominant frequencies of 8.00 and 7.75 Hz when excited at 1.0 and 1.5 m/s^2 r.m.s. The Legacy seat had a dominant frequency range of 17.25 to 18.75 Hz. All observed 25th, median , and 75 percentile transmissibilities at the dominant frequency for the Legacy seat were approximately 2 at 0.2 m/s^2 r.m.s. The Legacy seat had larger interquartile ranges compared to the Bose Ride® seat across all excitation amplitudes at each seats' respective dominant frequency. The Bose Ride® seat had lower 25th, median, and 75th percentile transmissibility than the Legacy seat at each of the excitation amplitudes.

Table 4.2: Y-axis median, 25th percentile, and 75th percentile transmissibility at respective dominant frequencies for each excitation amplitude and seat.

Excitation amplitude	**0.2 m/s²**		**1.0 m/s²**		**1.5 m/s²**	
Seat	Bose	Legacy	Bose	Legacy	Bose	Legacy
Dominant Frequency	1.50	18.75	8.00	18.25	7.75	17.25
25th Percentile	1.22	1.90	1.12	2.02	1.19	2.13
Median Transmissibility	1.29	2.22	1.35	2.27	1.35	2.37
75th Percentile	1.33	2.40	1.48	2.46	1.55	2.55

The median y-axis transmissibilities across the tested frequency range are presented in Figures 4.4, 4.5, and 4.6 for 0.2, 1.0, and 1.5 m/s^2 r.m.s. excitation amplitude respectively. The Legacy seat appears to have two resonant frequencies – one at approximately 2 Hz and another between 17 and 19 Hz. The Bose Ride® seat has an initial resonance at 2 Hz and a second resonance between 7 and 9 Hz.

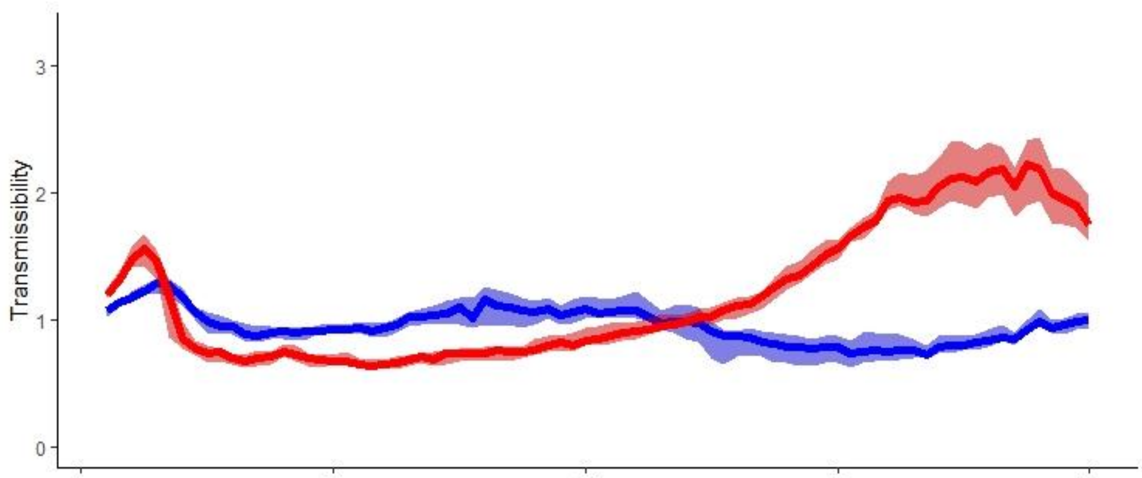

Figure 4.4: Y-axis transmissibility of Bose Ride® (blue trace) and Legacy (red trace) seats excited at 0.2 m/s^s r.m.s. Solid lines represent the median value while the shaded area represents the 25th and 75th percentile.

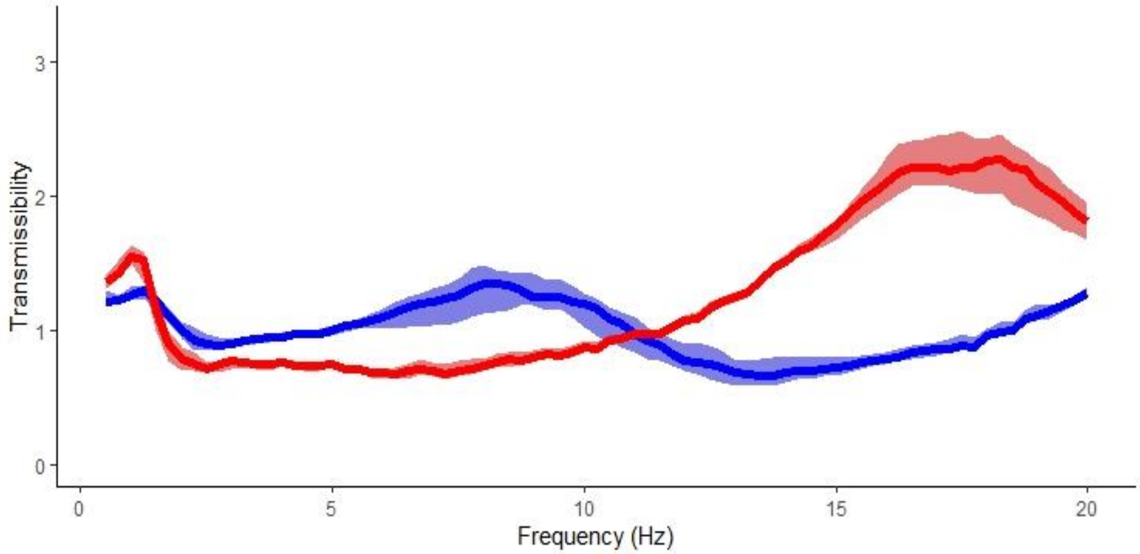

Figure 4.5: Y-axis transmissibility of Bose Ride® (blue trace) and Legacy (red trace) seats excited at 1.0 m/s^s r.m.s. Solid lines represent the median value while the shaded area represents the 25th and 75th percentile.

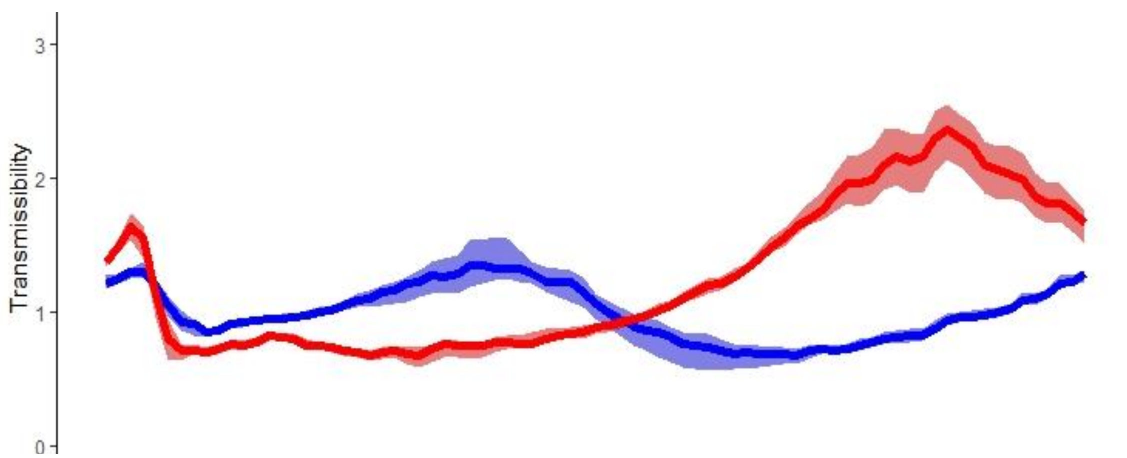

Figure 4.6:Y-axis transmissibility of Bose Ride® (blue trace) and Legacy (red trace) seats excited at 1.5 m/s^s r.m.s. Solid lines represent the median value while the shaded area represents the 25th and 75th percentile.

4.2.3 X-Axis

X-axis median , 25th percentile, and 75th percentile transmissibility at the dominant frequency for Bose Ride® and Legacy seats are presented in Table 4.2. The Bose Ride® and Legacy seats had the same dominant frequency (1.25 Hz) for 1.0 and 1.5 m/s^2 r.m.s. excitation amplitudes. The Legacy seat had lower peak median transmissibility at 1.0 and 1.5 m/s^2 r.m.s. excitation amplitudes compared to the Bose Ride® seat. The Bose Ride® seat had lower peak median transmissibility at 0.2 m/s^2 r.m.s. excitation amplitude. The Bose Ride® seat's median transmissibility at the dominant frequency increased with excitation amplitude.

Table 4.3: X-axis median, 25th percentile, and 75th percentile transmissibility at respective dominant frequencies for each excitation amplitude and seat.

Excitation amplitude	**0.2 m/s^2**		**1.0 m/s^2**		**1.5 m/s^2**	
Seat	Bose	Legacy	Bose	Legacy	Bose	Legacy
Dominant Frequency	2.50	2.00	1.25	1.25	1.25	1.25
25th Percentile	1.08	1.29	1.53	1.22	1.63	1.55
Median Transmissibility	1.18	1.42	1.66	1.25	1.75	1.60
75th Percentile	1.26	1.55	1.72	1.33	1.85	1.67

X-Axis Transmissibility across the tested frequency range is presented in Figures 4.7, 4.8, and 4.9 for 0.2, 1.0, and 1.5 m/s^2 r.m.s. excitation amplitude respectively. The transmissibility pattern was similar at all excitation amplitudes – the transmissibility was greater than 1.0 for frequencies less than approximately 3 Hz, and the transmissibility was approximately 0.5 for frequencies between 3 and 20 Hz. Interquartile range decreased above 10 Hz form both seats at 1.0 and 1.5 m/s^2 r.m.s.

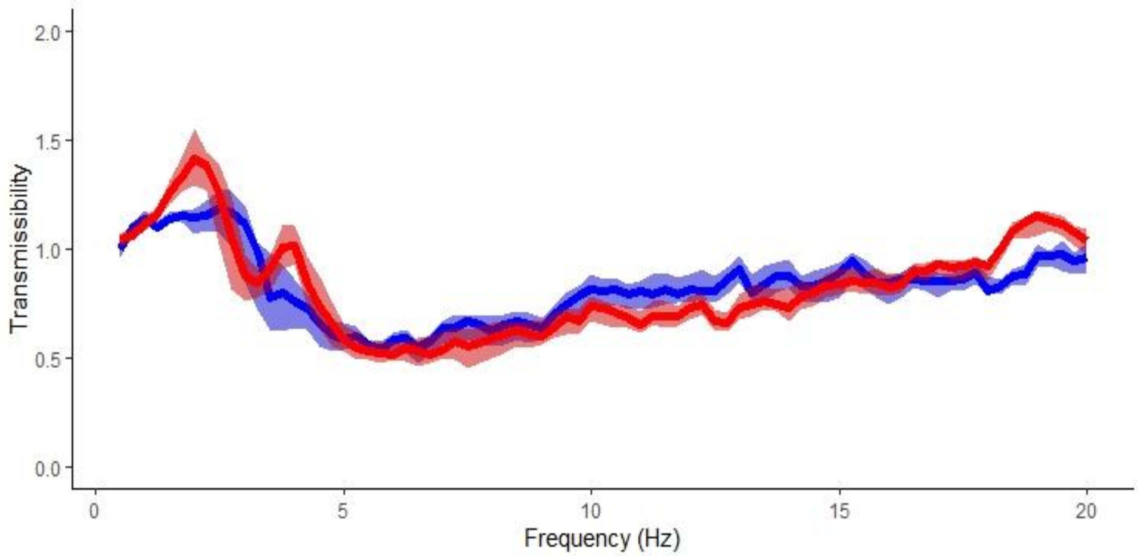

Figure 4.7: X-axis transmissibility of Bose Ride® (blue trace) and Legacy (red trace) seats excited at 0.2 m/s^s r.m.s. Solid lines represent the median value while the shaded area represents the 25th and 75th percentile.

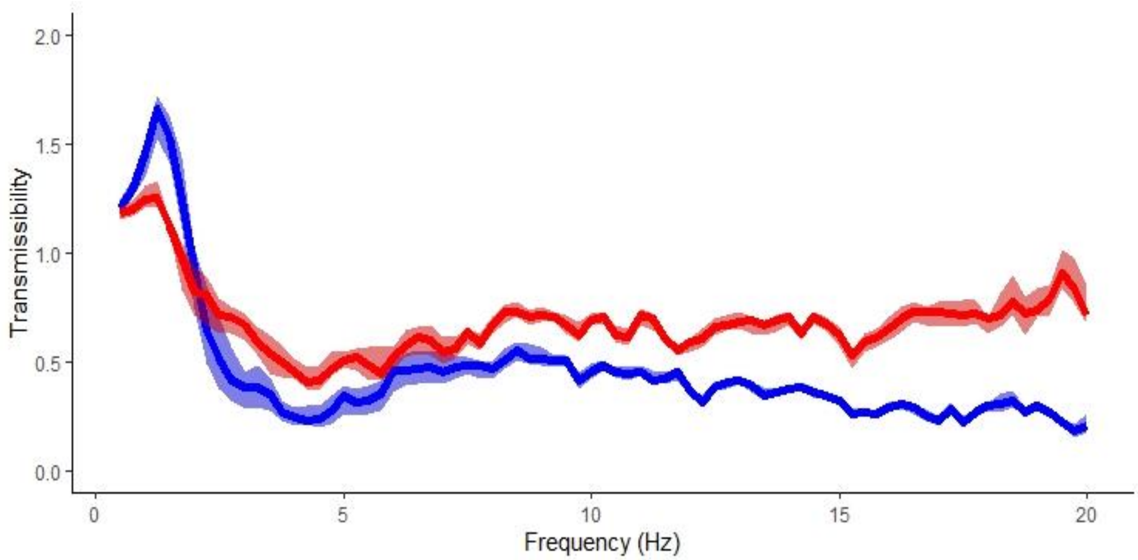

Figure 4.8: X-axis transmissibility of Bose Ride® (blue trace) and Legacy (red trace) seats excited at 1.0 m/s^s r.m.s. Solid lines represent the median value while the shaded area represents the 25th and 75th percentile.

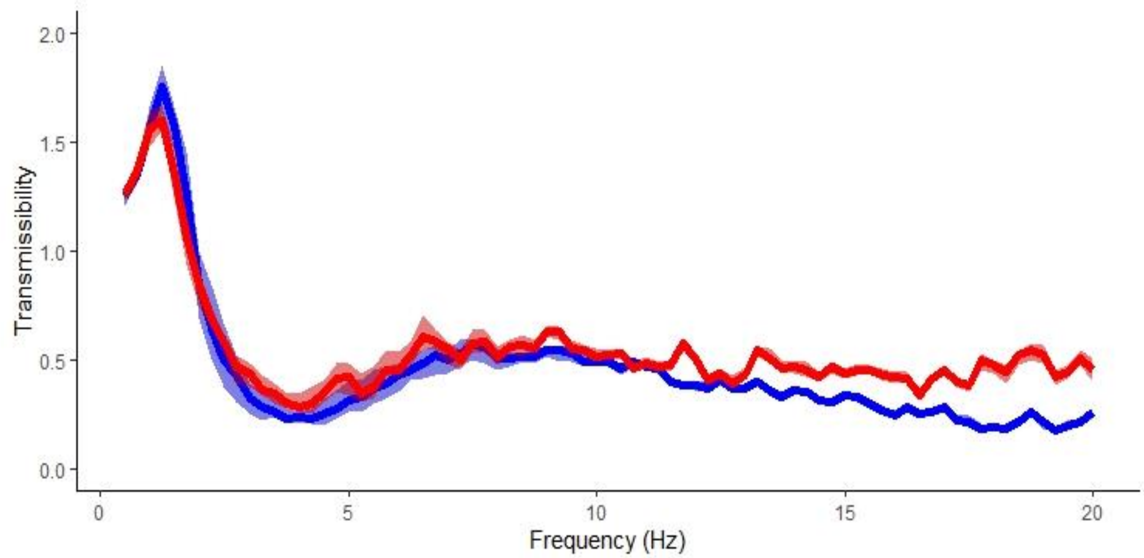

Figure 4.9: X-axis transmissibility of Bose Ride® (blue trace) and Legacy (red trace) seats excited at 1.5 m/s^{s} r.m.s. Solid lines represent the median value while the shaded area represents the 25th and 75th percentile.

4.3 Peak Transmissibility at 5, 7, and 9 Hz

4.3.1 Z-Axis

4.3.1.1 0.2 m/s^2 r.m.s. Vibration Amplitude

There was no statistically reliable three-way interaction between seat model, exposure frequency, and BMI group ($p = 0.177$). The two-way interactions between BMI and seat model and between BMI and frequency, were not statistically reliable either (BMI-seat, $p = 0.142$; BMI-frequency, $p = 0.280$). The two-way interaction between seat model and frequency was statistically reliable ($p < 0.001$). The main effects of seat model and frequency were statistically reliable (seat, $p < 0.001$; frequency, $p < 0.001$). These main effects were not evaluated as seat and frequency were involved in a reliable interaction. Finally, the main effect of BMI was not statistically reliable ($p = 0.021$).

Following the statistically reliable seat-frequency interaction, a test of simple effects of seat within specific levels of frequency and frequency within specific levels of seat was conducted. The group F score comparing levels of frequency for the Bose Ride® and Legacy seats were statistically reliable ($p < 0.001$). Contrast tests for the Bose Ride® seat between 5-7 Hz and 5-9 Hz were statistically reliable ($p < 0.001$) with the contrast test between 7-9 Hz was not reliable ($p = 0.015$). The peak transmissibility at 5 Hz was higher than at 7 and 9 Hz for the Legacy seat. Peak transmissibility was lower at 9 Hz compared to 7 Hz. All these contrasts were statistically reliable ($p < 0.001$).

The Bose Ride® seat had a lower peak transmissibility than the Legacy seat across all frequencies. These differences were statistically reliable ($p < 0.001$). Mean and standard deviation of transmissibility for both seats at 5, 7, and 9 Hz is presented in Figure 4.10. The Bose Ride® seat had its lowest transmissibility at 7 Hz compared to the Legacy seat which had its lowest transmissibility at 9 Hz.

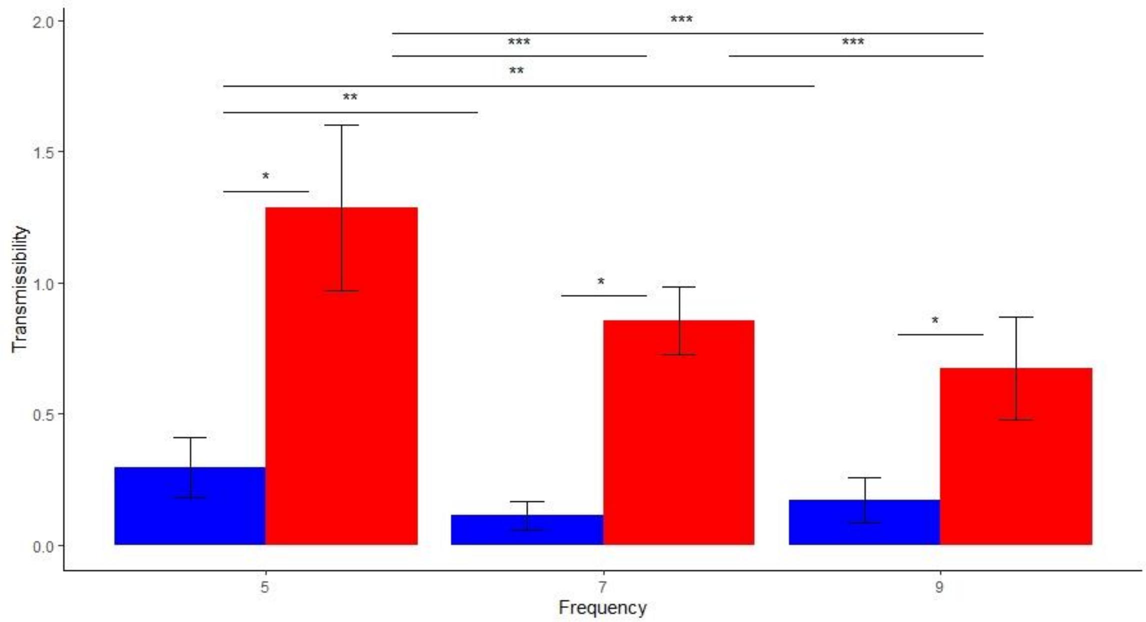

Figure 4.10: Mean transmissibility for Bose Ride® (blue) and Legacy (red) seats at 5, 7, and 9 Hz with vibration magnitude of 0.2 m/s^2 R.M.S. Error bars are ± standard deviation. * denotes statistically reliable difference between seats. ** denotes statistically reliable difference between frequencies for the Bose Ride® seat. * denotes statistically reliable difference between frequencies for the Legacy seat.**

4.3.1.2 1.0 m/s^2 r.m.s. Vibration Amplitude

The three-way interaction between seat, frequency, and BMI was not statistically reliable at 1.0 m/s^2 r.m.s. ($p = 0.551$). The two-way seat-frequency interaction was statistically reliable ($p<0.001$). Two-way interactions of seat-BMI and frequency-BMI were not statistically reliable seat-BMI, $p = 0.340$; frequency-BMI, $p = 0.080$). The main effects of seat and frequency were statistically reliable ($p < 0.001$) however no tests of main effects were performed as both factors were included in a statistically reliable interaction. The main effect of BMI was not statistically reliable ($p=0.075$).

A test of simple effects of seat within specific levels of frequency and frequency within specific levels of seat was conducted. The group F score comparing peak transmissibility between frequencies within Legacy and Bose Ride® seat trials was statistically reliable ($p < 0.001$). All contrast tests performed were statistically reliable ($p < 0.001$). Peak transmissibility decreased as frequency increased for both seats as presented in figure 4.11.

Calculation of group F score for comparison of seats within frequency was not necessary as only two seats were tested. Contrast tests between the Bose Ride® and Legacy seat were statistically reliable across all frequencies tested ($p < 0.001$) . The Bose Ride® had lower peak transmissibility than the legacy seat in all frequencies tested as seen in figure 4.11.

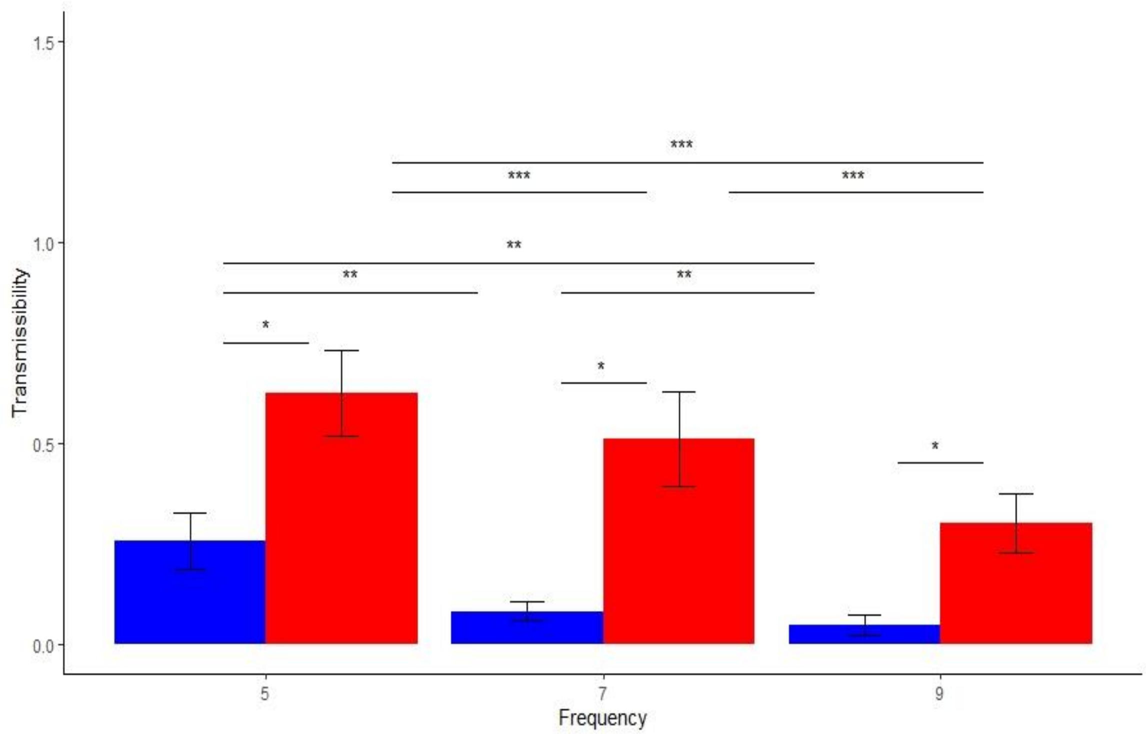

Figure 4.11: Mean Z-axis transmissibility for Bose Ride® (blue) and Legacy (red) seats at 5, 7, and 9 Hz with vibration magnitude of 1.0 m/s^2 R.M.S. Error bars are ± standard deviation. * denotes statistically reliable difference between seats. ** denotes statistically reliable difference between frequencies for the Bose Ride® seat. * denotes statistically reliable difference between frequencies for the Legacy seat.**

4.3.1.3 1.5 m/s^2 r.m.s. Vibration Amplitude

There weas no statistically reliable three-way interactions at 1.5 m/s^2 r.m.s. excitation amplitude for the z-axis ($p = 0.304$). The BMI-frequency interaction was statistically reliable ($p = 0.00456$) while the seat-frequency and seat-BMI interactions were not statistically reliable. (seat-BMI p=0.494; seat-frequency, $p = 0.070$;) . The main effects of seat and frequency were statistically reliable (seat, $p = < 0.001$; frequency, $p < 0.001$) however only the main effect of seat was evaluated as the frequency factor was included in in a statically reliable interaction. The post hoc Tukey HSD test was statistically reliable ($p < 0.001$). Bose Ride® seat had lower transmissibility compared to the Legacy seat when averaged over frequency and BMI (Figure 4.12) The main effect of BMI was not statistically reliable ($p = 0.0390$) as p value was not below alpha level of 0.16.

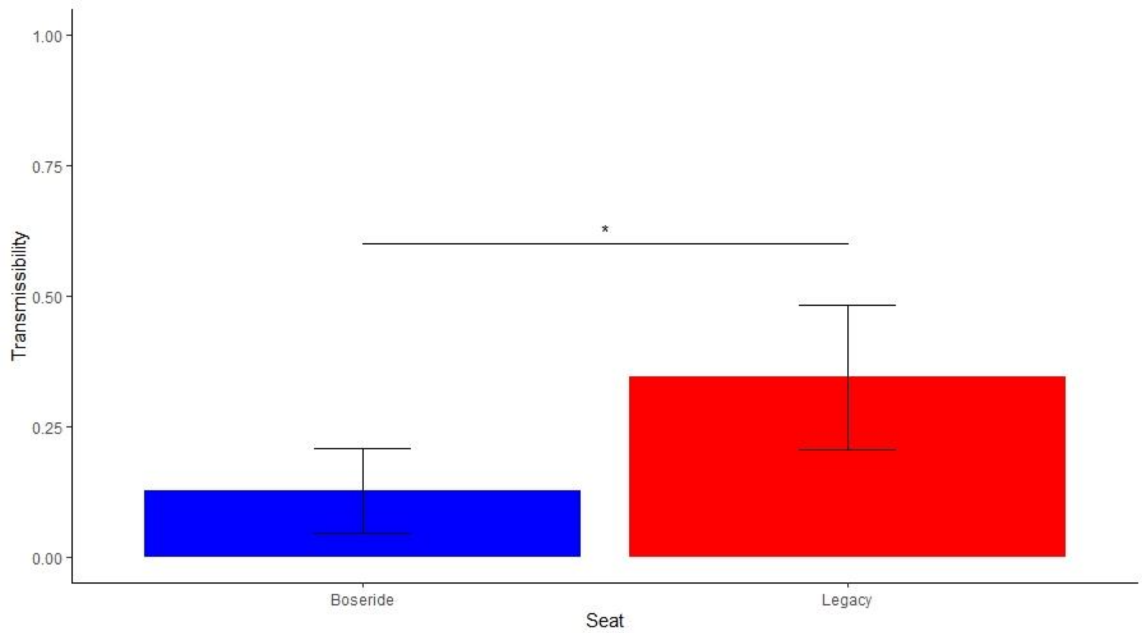

Figure 4.12: Mean peak Z-axis transmissibility for Bose Ride® (blue) and Legacy (red) seats at with vibration magnitude of 1.5 m/s^2 R.M.S. Error bars are ± standard deviation. * denotes statistically reliable difference between seats.

All within BMI group F scores were statistically reliable ($p < 0.001$). Following this, only the comparisons between 5 and 9 Hz were reliable within BMI groups ($p < 0.001$). The contrasts tests between 5-7 Hz (normal, p = 0.006; overweight, p = 0.095; obese, p = 0.018) and 7-9 Hz (normal, p = 0.006; overweight, p = 0.002; obese, p = 0.02) were not statistically reliable as p values were not below adjusted alpha level of 0.001.Peak transmissibility decreased as frequency increased as seen in figure 4.13.

All within frequency group F scores were not statistically reliable (5 Hz, p = 0.099; 7 Hz, p = 0.52; 9 Hz, p = 0.74). Because of this result, no follow up contrast tests were performed between BMI groups within tested frequencies.

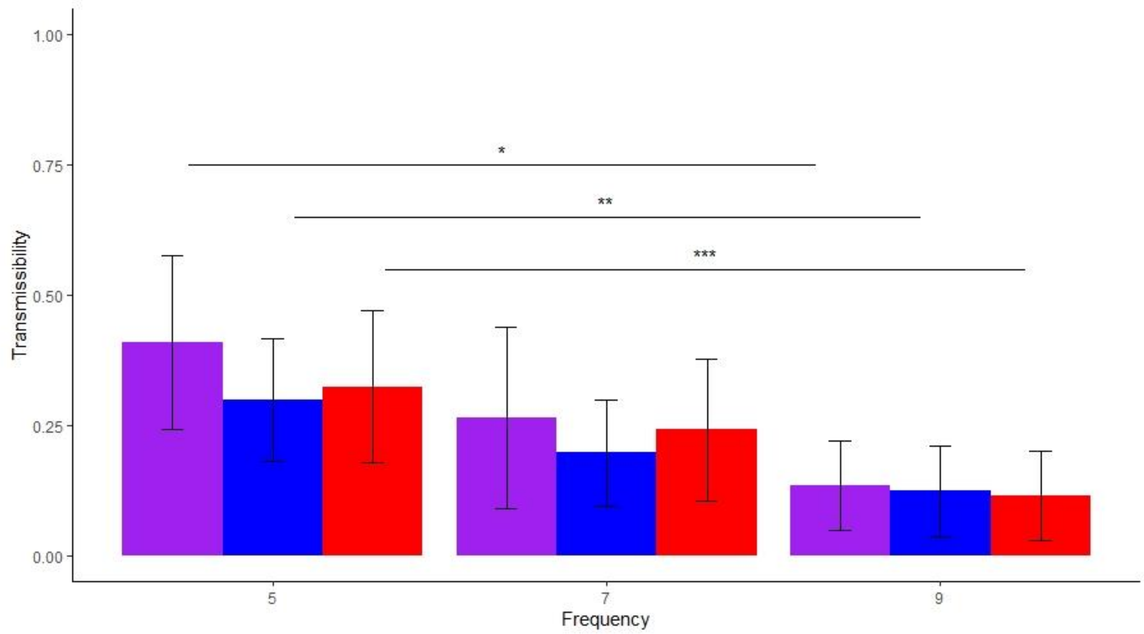

Figure 4.13: Mean peak Z-axis transmissibility for normal (purple) obese (blue), and overweight (red) BMI groups with vibration magnitude of 1.5 m/s^2 R.M.S. Error bars are ± standard deviation. * denotes statistically reliable difference between frequencies within the normal BMI group. ** denotes statistically reliable difference between frequencies within the obese BMI group. * denotes statistically reliable difference between frequencies within the overweight BMI group.**

4.3.2 X-Axis

4.3.2.1 0.2 m/s^2 r.m.s. Vibration Amplitude

There were no statistically reliable three-way interactions (seat-BMI-frequency, p = 0.27), two-way interactions (BMI-frequency, p = 0.95; seat-frequency, p = 0.46; seat-BMI, p = 0.046). Main effects of BMI (p = 0.41), and frequency (p = 0.71).The main effect of seat was statistically reliable (p = 0.0099). However, the follow up Tukey HSD test was not statistically reliable (p = 0.21). Mean peak transmissibility of Bose Ride® and Legacy seats are well within group error as seen in Figure 4.14.

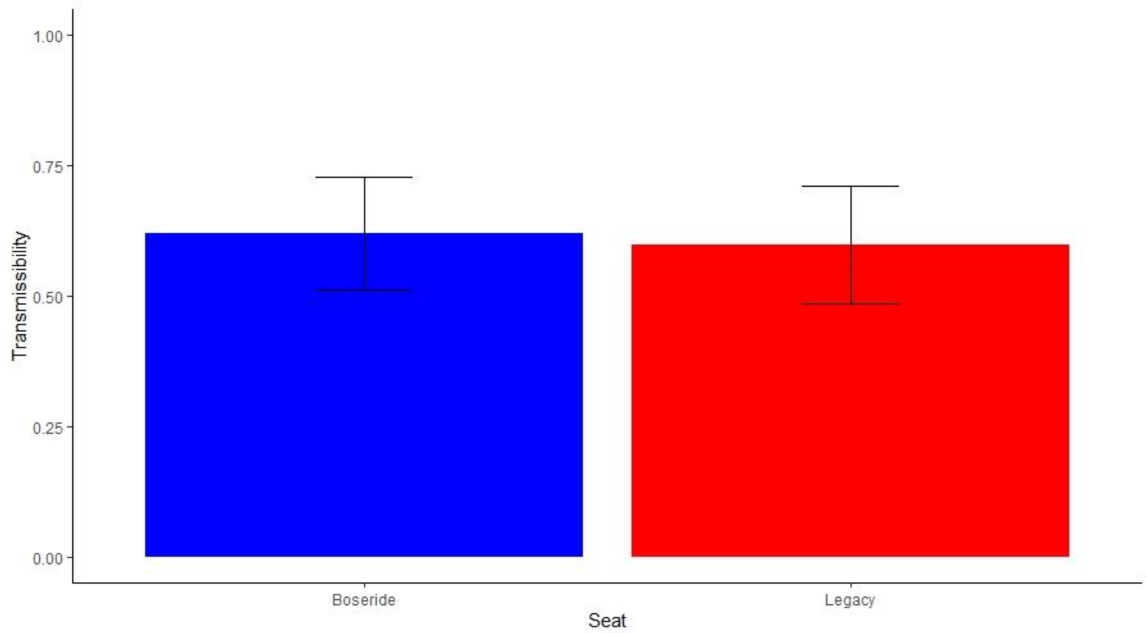

Figure 4.14: Mean peak x-axis transmissibility for Bose Ride® (blue) and Legacy (red) seats at with vibration magnitude of 0.2 m/s^2 R.M.S. Error bars are ± standard deviation.

4.3.2.2 1.0 m/s^2 r.m.s. Vibration Amplitude

There are no statistically reliable three-way interactions(seat-BMI-frequency, p = 0.15), two-way interactions (BMI-frequency, p = 0.20; seat-frequency, p = 0.85; seat-BMI, p = 0.40), or main effects (BMI, p = 0.45; frequency, p = 0.20; seat, p = 0.38) on the x-axis with 1.0m/s^2 r.m.s. The mean ± sd peak transmissibility for all BMI groups was 0.60 ± 0.27 (sample mean ± sample variance).

4.3.2.3 1.5 m/s^2 r.m.s. Vibration Amplitude

There are no statistically reliable three-way interaction (seat-BMI-frequency, p = 0.37), two-way interactions (BMI-frequency, p = 0.32; seat-frequency, p = 0.92; seat-BMI, p = 0.50), or main effects (BMI, p = 0.53; frequency, p = 0.043; seat, p = 0.73) on the x-axis with 1.5m/s^2 r.m.s. Peak transmissibility for all groups was 0.60 ± 0.38 (sample mean ± sample variance).

4.3.3 Y-Axis

4.3.3.1 0.2 m/s^2 r.m.s. Vibration Amplitude

The two- and three- way interactions for the transmissibility at 0.2 m/s^s r.m.s. excitation amplitude on the y-axis were not statistically reliable (seat-BMI-frequency, $p = 0.029$; BMI-frequency, $p = 0.68$; seat-frequency, $p = 0.098$; seat-BMI, $p = 0.98$). The main effect of seat was statistically reliable (seat, $p = < 0.001$) while the main effects of BMI and frequency were not statistically reliable (frequency, $p = 0.092$; BMI, $p = 0.99$)).

The Post hoc Tukey HSD test between seats was statistically reliable ($p < 0.001$) with the Bose Ride® seat having higher peak transmissibility than the Legacy seat. These differences can be observed in Figure 4.15

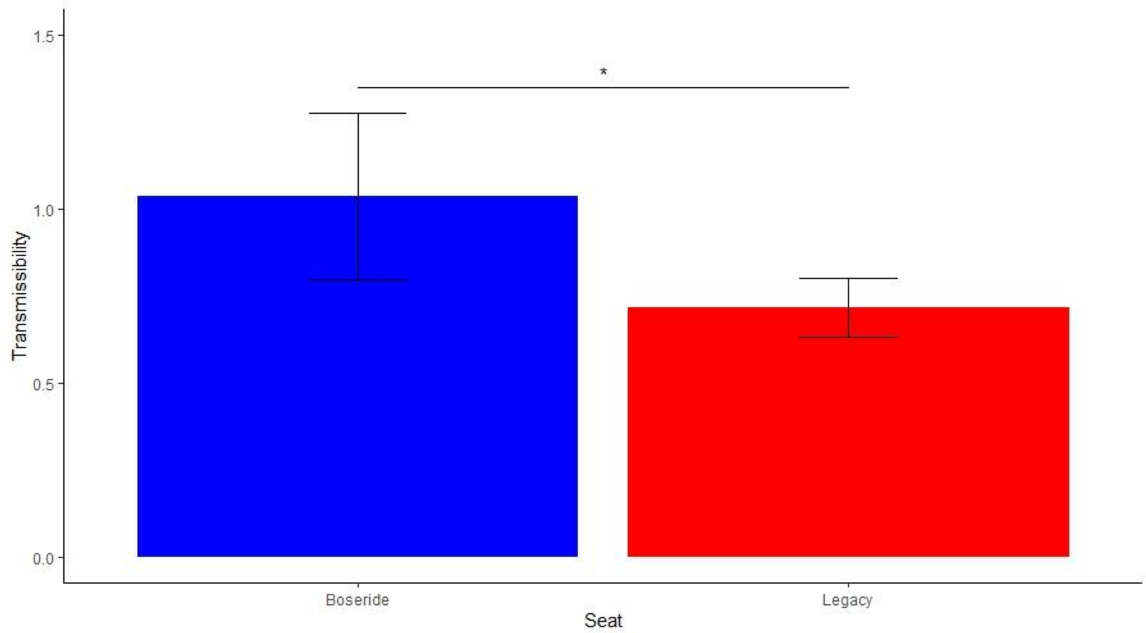

Figure 4.15: Mean peak y-axis transmissibility for Bose Ride® (blue) and Legacy (red) seats at with vibration magnitude of 0.2 m/s^2 R.M.S.. Error bars are ± standard deviation. * denotes statistically reliable difference between seats.

4.3.3.2 1.0 m/s^2 r.m.s. Vibration Amplitude

There were no statistically reliable two- or three-way interactions for the transmissibility at 1.0 m/s^2 r.m.s. excitation amplitude (seat-BMI-frequency, p = 0.25; seat-BMI, p = 0.55; seat-frequency, p = 0.95; BMI-frequency, p = 0.20). The main effects of BMI, seat, and frequency were not statistically reliable (BMI, p= 0.54; frequency, p = 0.97; seat, p = 0.57).

4.3.3.3 1.5 m/s^2 r.m.s. Vibration Amplitude

The two- and three-way interactions were not statistically reliable (seat-BMI-frequency, p = 0.32; seat-BMI, p = 0.55; seat-frequency, p = 0.73; BMI-frequency, p = 0.43). There were not statistically reliable main effects (BMI, p = 0.54; seat, p = 0.72; frequency, p = 0.82).

4.4 Daily vibration exposure

Predicted A(8) frequency weighted daily vibration exposure values at the participant/seat interface for field exposures with highway bias and rural/provincial road bias are presented in Figure 4.11 and Figure 4.12 respectively. The time and dominant axis weighted accelerations used to calculate A(8) daily vibration exposure are presented in Table 4.4, 4.5. and 4.6 for normal, obese, and overweight BMI groups respectively. No theoretical exposure for any group with a highway or rural bias exceeded the ISO 2631-1 HGCZ action limit or the EU 2002/44/EC directive's action value. The Bose Ride® seat had lower predicted daily vibration exposure than the Legacy seat across all comparisons. Groups responded similarly between exposure biases with the Bose Ride® A(8) exposure at approximately 0.3 m/s^2 r.m.s., and the Legacy seat at approximately 0.4 m/s^2 r.m.s., for all BMI groups.

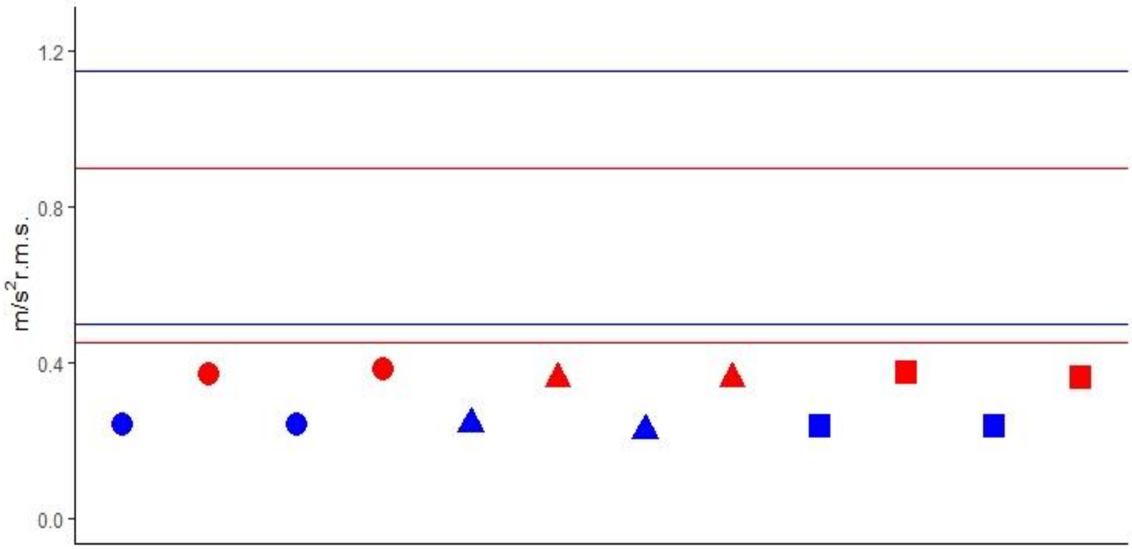

Figure 4.16: Predicted Daily vibration exposure normalized to 8 hours with highway bias for truck operators with different BMIs for both the Bose Ride® (blue) and Legacy (red) seats. Circles represent normal BMI, triangles represent obese BMI and squares represent overweight BMI. Blue horizontal lines represent the upper and lower limits of the EU directive action limits and the red lines represent the upper and lower limits of the ISO 2631-1 Health Guidance Caution Zone.

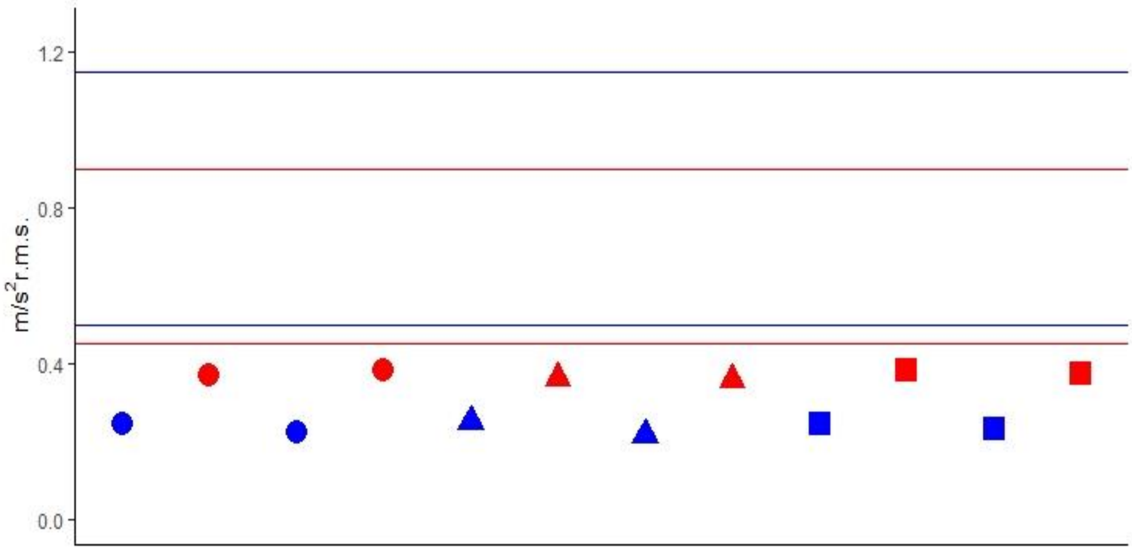

Figure 4.17: Predicted Daily vibration exposure normalized to 8 hours with rural/provincial road bias for truck operators with different BMIs for both the Bose Ride® (blue) and Legacy(red) seats. Circles represent normal BMI, triangles represent obese BMI and squares represent overweight BMI. Blue horizontal lines represent the upper and lower limits of the EU directive action limits and the red lines represent the upper and lower limits of the ISO 2631-1 Health Guidance Caution Zone.

Table 4.4 Weighted r.m.s. accelerations for predicted Bose Ride® and Legacy seat vibration exposures, theoretical exposure (TE) time for rural and highway bias, and vibration ranking for daily vibration exposures used to calculate A(8) for theoretical drivers (TD) with normal BMI.

		Hi-Way Bias		Rural Bias		TD1		TD2	
Road type	Rank	Time TE1 (Min)	Time TE2 (Min)	Time TE1 (Min)	Time TE2 (Min)	Bose	Legacy	Bose	Legacy
Highway	333	47	47	6.67	6.67	0.3423	0.3947	0.3422	0.4691
Highway	323	47	47	6.67	6.67	0.2086	0.3342	0.2112	0.3675
Highway	312	47	47	6.67	6.67	0.2057	0.3678	0.2053	0.2985
Highway	121	47	47	6.67	6.67	0.2386	0.4048	0.2255	0.4403
Highway	232	47	47	6.67	6.67	0.2808	0.4510	0.3088	0.4494
Highway	233	47	47	6.67	6.67	0.3191	0.5405	0.3321	0.4944
Urban	332	6.67	0	5	0	0.2663	0.3660	0.2774	0.3647
Urban	222	6.67	0	5	0	0.1641	0.2916	0.1721	0.2595
Urban	233	6.67	20	5	15	0.3423	0.4454	0.2903	0.5261
Urban	212	6.67	20	5	15	0.1682	0.2950	0.1795	0.3100
Urban	333	6.67	0	5	0	0.2769	0.4436	0.2706	0.5758
Urban	323	6.67	0	5	0	0.1727	0.3887	N/A	N/A
Rural	232	3.33	5	15	22.5	0.2606	0.3146	0.2482	0.3477
Rural	333	3.33	0	15	0	0.4658	0.5459	0.5073	0.7140
Rural	323	3.33	5	15	22.5	0.2201	0.3241	0.1898	0.3623
Rural	212	3.33	5	15	22.5	0.1352	0.2447	0.1409	0.2629
Rural	222	3.33	5	15	22.5	0.2402	0.3521	0.2479	0.3424
Rural	111	3.33	0	15	0	0.1682	0.1863	0.1588	0.1858
Provincial	233	6.67	0	35	0	0.2767	0.5151	0.2751	0.5270
Provincial	333	6.67	0	35	0	0.3660	0.4510	N/A	N/A
Provincial	211	6.67	0	35	0	0.2289	0.3958	N/A	N/A
Provincial	312	6.67	13.33	35	70	0.3039	0.5097	0.3024	0.5266
Provincial	212	6.67	13.33	35	70	0.2269	0.3811	0.2176	0.4667
Provincial	323	6.67	13.33	35	70	0.2891	0.4337	0.2671	0.4321
Jobsite	323	1.33	0	3.33	0	0.0733	0.0995	0.0704	0.0885
Jobsite	223	1.33	0	3.33	0	0.0420	0.0570	0.0306	0.0485
Jobsite	222	1.33	2.67	3.33	6.67	0.0305	0.0422	0.0319	0.0422
Jobsite	332	1.33	2.67	3.33	6.67	0.1136	0.1209	0.1160	0.1169
Jobsite	333	1.33	2.67	3.33	6.67	0.2802	0.2923	0.2636	0.2797
Jobsite	322	1.33	0	3.33	0	0.0536	0.0659	0.0531	0.0574
Off		90	90	90	90	0.0000	0.0000	0.0000	0.0000
Total		480	480	480	480				

Table 4.5: Weighted r.m.s. accelerations for predicted Bose Ride® and Legacy seat vibration exposures, theoretical exposure (TE) time for rural and highway bias, and vibration ranking for daily vibration exposures used to calculate A(8) for theoretical drivers (TD) with obese BMI.

		Hi-Way Bias		Rural Bias		TD1		TD2	
Road type	Rank	Time TE1 (Min)	Time TE2 (Min)	Time TE1 (Min)	Time TE2 (Min)	Bose	Legacy	Bose	Legacy
Highway	333	47	47	6.67	6.67	0.3443	0.4167	0.3160	0.3664
Highway	323	47	47	6.67	6.67	0.2148	0.3194	0.2150	0.3162
Highway	312	47	47	6.67	6.67	0.2018	0.3375	0.2006	0.3233
Highway	121	47	47	6.67	6.67	0.2380	0.3757	0.2482	0.3755
Highway	232	47	47	6.67	6.67	0.2845	0.4329	0.2583	0.4387
Highway	233	47	47	6.67	6.67	0.3264	0.5134	0.2818	0.5517
Urban	332	6.67	0	5	0	0.2801	0.3521	0.2875	0.3529
Urban	222	6.67	0	5	0	0.1752	0.2741	0.1592	0.3127
Urban	233	6.67	20	5	15	0.3234	0.4211	0.2721	0.4086
Urban	212	6.67	20	5	15	0.1873	0.2948	0.1794	0.3086
Urban	333	6.67	0	5	0	0.2507	0.4593	N/A	N/A
Urban	323	6.67	0	5	0	0.1731	0.3528	0.1668	0.3522
Rural	232	3.33	5	15	22.5	0.2739	0.3264	0.2497	0.3562
Rural	333	3.33	0	15	0	0.4710	0.5717	0.5030	0.6023
Rural	323	3.33	5	15	22.5	0.1721	0.3695	0.1622	0.3321
Rural	212	3.33	5	15	22.5	0.1406	0.2620	0.1339	0.2348
Rural	222	3.33	5	15	22.5	0.2744	0.3282	0.2452	0.3640
Rural	111	3.33	0	15	0	0.1761	0.1875	N/A	N/A
Provincial	233	6.67	0	35	0	0.2658	0.4658	0.2705	0.4565
Provincial	333	6.67	0	35	0	0.3873	0.4690	0.3663	0.4587
Provincial	211	6.67	0	35	0	0.2216	0.3863	0.1910	0.4148
Provincial	312	6.67	13.33	35	70	0.2989	0.4938	0.2817	0.4770
Provincial	212	6.67	13.33	35	70	0.2465	0.4019	0.2228	0.4124
Provincial	323	6.67	13.33	35	70	0.3123	0.4088	0.2660	0.4330
Jobsite	323	1.33	0	3.33	0	0.0727	0.0887	0.0685	0.0816
Jobsite	223	1.33	0	3.33	0	0.0274	0.0278	0.0295	0.0416
Jobsite	222	1.33	2.67	3.33	6.67	0.0279	0.0456	0.0417	0.0541
Jobsite	332	1.33	2.67	3.33	6.67	0.1189	0.1320	0.1176	0.1300
Jobsite	333	1.33	2.67	3.33	6.67	0.3134	0.3376	0.3278	0.3758
Jobsite	322	1.33	0	3.33	0	0.0515	0.0725	N/A	N/A
Off		90	90	90	90	0.0000	0.0000	0.0000	0.0000
Total		480	480	480	480				

Table 4.6: Weighted r.m.s. accelerations for predicted Bose Ride® and Legacy seat vibration exposures, theoretical exposure (TE) time for rural and highway bias, and vibration ranking for daily vibration exposures used to calculate A(8) for theoretical drivers (TD) with overweight BMI.

		Hi-Way Bias		Rural Bias		TD1		TD2	
Road type	Rank	Time TE1 (Min)	Time TE2 (Min)	Time TE1 (Min)	Time TE2 (Min)	Bose	Legacy	Bose	Legacy
Highway	333	47	47	6.67	6.67	Bose	Legacy	Bose	Legacy
Highway	323	47	47	6.67	6.67	0.3391	0.4330	0.3471	0.4120
Highway	312	47	47	6.67	6.67	0.2040	0.3454	0.1977	0.3101
Highway	121	47	47	6.67	6.67	0.1954	0.3458	0.1988	0.2929
Highway	232	47	47	6.67	6.67	0.2171	0.3958	0.2283	0.3604
Highway	233	47	47	6.67	6.67	0.2916	0.4576	0.2796	0.4106
Urban	332	6.67	0	5	0	0.3155	0.5233	0.3155	0.5503
Urban	222	6.67	0	5	0	0.2729	0.3656	N/A	N/A
Urban	233	6.67	20	5	15	0.1462	0.2987	N/A	N/A
Urban	212	6.67	20	5	15	0.2753	0.4508	0.3020	0.4558
Urban	333	6.67	0	5	0	0.1803	0.3147	0.1778	0.3083
Urban	323	6.67	0	5	0	0.2962	0.4548	0.2563	0.4692
Rural	232	3.33	5	15	22.5	0.1689	0.3902	0.1963	0.3808
Rural	333	3.33	0	15	0	0.2710	0.3249	0.2602	0.3361
Rural	323	3.33	5	15	22.5	0.4978	0.5174	N/A	N/A
Rural	212	3.33	5	15	22.5	0.1699	0.3639	0.1697	0.3977
Rural	222	3.33	5	15	22.5	0.1425	0.2721	0.1437	0.2492
Rural	111	3.33	0	15	0	0.2750	0.3251	0.2548	0.3310
Provincial	233	6.67	0	35	0	0.1693	0.1873	0.1705	0.1881
Provincial	333	6.67	0	35	0	0.2605	0.4943	N/A	N/A
Provincial	211	6.67	0	35	0	0.3920	0.4823	0.3707	0.4707
Provincial	312	6.67	13.33	35	70	0.2152	0.4093	0.2209	0.4384
Provincial	212	6.67	13.33	35	70	0.2962	0.5276	0.2947	0.5176
Provincial	323	6.67	13.33	35	70	0.2328	0.4367	0.2247	0.4163
Jobsite	323	1.33	0	3.33	0	0.2885	0.4822	0.3084	0.4600
Jobsite	223	1.33	0	3.33	0	0.0745	0.0831	N/A	N/A
Jobsite	222	1.33	2.67	3.33	6.67	0.0356	0.0655	N/A	N/A
Jobsite	332	1.33	2.67	3.33	6.67	0.0346	0.0288	0.0577	0.0446
Jobsite	333	1.33	2.67	3.33	6.67	0.1193	0.1282	0.1155	0.1258
Jobsite	322	1.33	0	3.33	0	0.2957	0.3461	0.2967	0.2895
Off		90	90	90	90	0.0548	0.0589	0.0522	0.0644
Total		480	480	480	480				

5 Discussion

The aim of this thesis was to quantify the WBV attenuation characteristics of an active and passive suspension seat through multi axis frequency response testing. From the frequency response data, we sought to compare the performance of active and passive suspension seat technologies. Additionally, we wanted to evaluate whether commercially available active and passive suspension seats effectively attenuate WBV for exposures representing long-haul trucking on Canadian roads. This thesis found that the Bose Ride® seat was more effective attenuating z-axis WBV than the Legacy seat. Also, the predicted daily vibration exposure was lower for the Bose Ride® seat than Legacy across all A(8) tests. However, both seats were below the lower boundary of the ISO 2361-1 HCGZ, where health effects are not objectively observed. This suggests that health risks are unlikely for users of either seat.

5.1 Evaluation of WBV Attenuation Characteristics

5.1.1 Frequency response evaluation

The Bose Ride® seat had a dominant frequency of 0.5 Hz on the z-axis for all excitation amplitudes. This is similar with previous work that determined that the dominant frequency of an active suspension seat was between 0 and 1 Hz[44]. They observed chassis-to-seatpan transmissibility values close to 0.1 when exposure frequency was greater than roughly 8 Hz[44].This differs from our results as we observed platform-to-seatpan transmissibility magnitudes close to 0.1 when exposure frequencies were greater than 5 Hz. Transmissibility for exposure frequencies greater than 8 Hz seemed similar between that study and this thesis (0-0.1)[44]. Blood et al. (2015) also investigated the frequency response of a passive seat on city streets[44]. They determined that chassis-to-seatpan transmissibility was greater than 1 when exposure frequency was less than 7 Hz and it was less than 1 when exposure frequency was greater than 7 Hz[44]. This is somewhat consistent with this thesis as median platform-to-seatpan transmissibility of the passive suspension seat was approximately 1 when excited at 7 Hz with an amplitude of

0.2 m/s^2 r.m.s. However, this thesis determined that transmissibility was less than 1 when excited at greater than approximately 4 and 5 Hz for 1.0 and 1.5 m/s^2 r.m.s. excitation amplitudes respectively. The Blood et al (2015) study determined that the passive seat had a z-axis dominant frequency between 2 and 4 Hz [44]. This is congruent with the findings from this thesis as the dominant frequency was between 1.75 and 3.75 Hz depending on the excitation amplitude.

Blood et al. (2015) investigated the frequency response of active and passive suspension seats using replicated field exposures on a motion platform[44]. They also used a PSD method for calculating the frequency response[44]. The PSD method of calculating the frequency response requires that there is vibration energy at all frequencies tested. When using field-based exposures, it is difficult to guarantee that this requirement is met as it is likely that some frequency components of the exposure will have low vibrational energy. In the present thesis, white noise stochastic vibration was used to evaluate the frequency response of the seats to ensure that energy was present at all tested frequencies. Also, the CSD method was used to calculate the transfer function in the present thesis which is more reliable than the PSD method[24]. The differences in frequency response could be due to the differences in evaluation methods between this thesis and Blood et al[44]. Another note is that the Blood et al. (2015)[44] study does not identify the seat model, therefore the differences in frequency response of active suspension seats might also be attributed to a difference in models.

5.1.2 X-Axis effects

There was no difference in x-axis WBV attenuation performance between seats, BMIs, and exposure frequencies of 5, 7, and 9 Hz at any of the three excitation amplitudes tested. This is backed by the analysis performed, as the outcome of no statistically reliable interactions or main effects infers that platform-to-seatpan transmissibility can be described by a general population mean ± the variance. The x-axis transmissibly at 0.2, 1.0, and 1.5 m/s^2 r.m.s. is 0.61 ± 0.012, 0.60 ± 0.27, and 0.60 ± 0.38 (sample mean ± sample variance) respectively. When observing the transmissibility traces for the x-axis

(Figures 4.7, 4.8, and 4.9), we see similar patterns between seats over the 0.5 – 20 Hz frequency range for 0.2 m/s^2 excitation amplitude. The same can be said for the transmissibility traces between seats at 1.5 m/s^2 r.m.s. excitation amplitude up until roughly 12.5 Hz where the seats response starts to diverge. The transmissibility traces between seats for the 1.0 m/s^2 r.m.s. excitation amplitude diverges earlier around 7.5 Hz and the gap is larger after the divergence. With all of this, there is little support for there being a meaningful difference between seats in x-axis WBV attenuation performance. These results do not support the hypothesis that the Bose Ride® is more effective in attenuating x-axis WBV compared to the Legacy seat.

5.1.3 Y-Axis effects

The seats performed differently in Y-axis stochastic WBV tests based on the transfer function traces of the seats within all the excitation amplitudes (Figures 4.4, 4.5, & 4.6). Both seats performed consistently across excitation amplitudes as highlighted by the frequency response traces. The statistical analysis only highlighted a difference between seats at 0.2 m/s^2 r.m.s. while statistically reliable differences were not observed at higher excitation amplitudes. However, these statistical tests were performed only at 5, 7, and 9 Hz. To really understand where the differences in platform-to-seatpan transmissibility lie, a more thorough analysis will be required. This evidence does not support the hypothesis that the Bose Ride® seat is more effective in attenuating y-axis WBV than the Legacy seat.

5.1.4 Z-axis effects

The Bose Ride® seat had lower peak z-axis platform-to-seatpan transmissibility at the most impactful frequencies for human health (5-9 Hz) compared to the Legacy seat. This was determined by evaluating the main (at 1.0 and 1.5 m/s^2 r.m.s.) and simple (averaged over levels of BMI within levels of frequency at 0.2 m/s^2 r.m.s.) effects comparing the Bose Ride® seat to the Legacy seat. The difference in peak mean transmissibility between the Bose Ride® and Legacy seats were between 0.24 and 0.60 depending on excitation amplitude and frequency. All contrasts between the seats on the z-axis were statistically reliable. Further, based on analysis of the frequency response traces, the Bose Ride® seat's transmissibility was only higher than the Legacy seat's at roughly 0.5 to 1 Hz across excitation amplitudes. With all of this in mind, the findings support part of the first hypothesis - that the Bose Ride® seat is more effective at attenuating WBV in the z-axis than an industry standard passive suspension seat.

The findings above are a consequence of the Bose Ride® seat having a superior z-axis suspension design compared to the Legacy seat. However, the active suspension is only implemented in the z-axis. This could be the reason that no differences are reported in x-axis vibration attenuation performance when comparing between seats. The lack of any suspension in the y-axis could be the cause of transmissibility magnitudes being close to 1 between 0.5 to 20 Hz for the Bose Ride® seat. Any dampening seen could be a consequence of lateral compliance in the linkage for the vertical suspension. The Legacy seat is similar as it lacks y-axis suspension.

5.1.5 Effects of BMI

The seats perform consistently regardless of BMI group. This was highlighted by the lack of reliable main effects of BMI in all but one vibration condition. Even when BMI was included in the frequency-BMI interaction of the z-axis 1.5 m/s^2 r.m.s. repeated measures ANOVA, the group F scores evaluating if there is a difference between BMI groups within frequencies was not reliable. This can be observed in Figure 4.13 where peak platform-to-seatpan transmissibility between BMI groups was well within error bands. As well, as illustrated in Figures 4.16 and 4.17, BMI groups responded similarly when comparing daily vibration exposure. Although BMI was used previously as it better predicted WBV attenuation of seats[33], our results do not indicate that there were any substantial differences in seat performance between the BMI groups .

5.2 Active and Passive Suspension Seats and Health Risks

Daily vibration A(8) exposures were below ISO 2631-1 caution and action levels, and EU directive action limits, for both seats across all predicted daily exposures. The Legacy seat had higher daily vibration exposures than the Bose Ride® seat. However, there would be no recommended intervention based upon WBV exposure metrics as neither seat was above the ISO 2631-1 caution level of 0.45 m/s^2 r.m.s.

Previous work found that active seats had significantly lower z-axis A(8) exposure compared to passive counterparts in long haul trucking applications[44–46]. One of these studies determined that pre-intervention passive seat z-axis exposures on the roughest roads (A(8) magnitudes at and above the 75^{th} percentile) were above the ISO 2631-1 caution threshold[45]. This same study determined that there was no difference in A(8) exposure for x and y-axis between passive and active seats, and the 75^{th} percentile of these exposures did not exceed the ISO 2631-1 caution threshold on these axes[45]. This is congruent with the Blood et al. (2015) study that tested active and passive suspension seats on city streets, freeways, and rough roads[44]. They determined that the z-axis passive suspension seat exposures were within the HCGZ, and the active suspension seat was below the HCGZ caution limit, for rough road vibration exposures[44]. While on city streets and freeways, no seat had z-axis A(8) exposure that was above the EU action limit or ISO 2631-1 caution limits[44]. Both of these studies are similar to a third study determining that median z-axis exposures were above ISO 2631-1 caution levels when truck drivers were using a passive suspension seat[46]. Following active suspension seat intervention, z-axis WBV exposure decreased significantly to below caution levels[46]. There was no difference in x and y-axis WBV exposures following active suspension seat intervention[46]. Considerations need to be taken when comparing these findings with this thesis. The methods for calculating A(8) in these papers were not the same as methods used in this thesis. In the intervention studies, no dominant axis was selected when calculating A(8). Rather, calculations were made for each axis, and the vector sum of all axes[44–46]. In this thesis, A(8) was derived from a mosaic of laboratory simulated exposures with the dominant axis method preferred by ISO-2631. It is also of note that two of the studies field vibration exposures were collected from roads in the pacific northwest and east coast of USA[44,45]. Geographical location of exposure was not reported in one of the studies[46]. Roads in different geographical locations can have different exposures potentially attributed to differences in road maintenance and construction. Accordingly it is not possible to rigorously compare the magnitudes of the transmissibilities between these studies and this thesis, but it is possible to evaluate the trends. Our observations from stochastic vibration exposures indicated that the Bose Ride® seat was more effective than the passive suspension seat in z-axis WBV attenuation. Furthermore, our findings are in line with two of the studies finding no difference between passive and active suspension seats in x-axis WBV attenuation performance[45,46]. Differences in performance of y-axis WBV attenuation were not observed in the studies mentioned. This is in contrast with the findings of this thesis as the passive seat was more effective in attenuating y-axis vibration between 5 to 9 Hz. However, from evaluating the y-axis transmissibility traces, we know that the performance of the seats change based on exposure frequency.

Previous work evaluating the performance of passive air suspension seats on frequency weighted WBV exposures of long haul truck drivers in northern Ontario determined that smooth roads rarely (3 out of 50 exposures) exceeded the lower boundary of the ISO 2631-1 HCGZ[52]. However, it was more common that exposures on rough roads were either in or exceeded the HCGZ (2 of 49 exposures over the HCGZ; 14 of 49 exposures in the HCGZ)[52]. Interestingly, the researchers did not normalize vibration exposures to eight hours[52]. Instead, researchers took a random 5-minute exposure every 30 mins from a truck driver's work day and averaged them together to predict a representative daily vibration exposure[52]. This is similar to the present thesis that calculated A(8) using a mosaic of representative vibration exposures. Regardless, none of the daily vibration exposures in this thesis were above the lower boundary of the ISO 2631-1 HCGZ or the EU action limit. With that said, we included 90 mins of no vibration exposure in our calculations of A(8) designed to simulate when a truck driver wouldn't be driving (e.g. truck loading, breaks) which effectively reduced the A(8) magnitudes.

5.2.1 Health Outcomes

Although no health outcomes were evaluated in this thesis, previous work looked exclusively at health and LBP outcomes between active and passive suspension seat interventions[53]. Kim et al. (2018) suggested positive health outcomes for truck drivers using an active suspension seat that were not realized in passive suspension counterparts [53]. Such health outcomes included a LBP percent change from baseline that reached clinical significance (25% reduction) 3-months post active suspension seat intervention (35% lower) while clinically significant LBP change was not observed in the passive seat intervention group (16% lower)[53]. In the 6-month follow up, the percent change from baseline was not clinically significant in the active seat intervention group (17% lower). This change in LBP for the active seat intervention group was still an improvement over the passive seat intervention group which observed 0% change from baseline testing at 6 months post intervention[53]. The active suspension intervention group had a significant improvement (5.3 point increase) in physical health as evaluated by the 12 item short-form (SF-12) survey 6 months post intervention[53]. The passive seat intervention group had an improvement in physical health evaluated by SF-12 (3 point increase) although this improvement was not statistically reliable. Participants of this study completed the Work Limitation Questionnaire (WLQ) evaluating limitations due to health problems[53]. The active seat intervention group had a statistically reliable reduction in the time (limitations in managing time) and physical (limitations of job tasks that involve physical strength/stamina) demand at 3 months post intervention compared to baseline[53]. They also observed a reduction in time and output (how much work quality and quantity were limited) demand 6 months post intervention relative to baseline[53]. Given that this thesis tested the same active suspension seat as was used for the active suspension intervention group by Kim et al. (2018), it is not surprising that we observed similar WBV attenuation performance[45]. We can speculate that long haul truck drivers would get similar benefits as what has been observed in their study.

Another previous study determined that smaller decrements in reaction time over the course of a workday were realized by truck drivers that were using an active suspension seat compared to when they used a passive suspension seat[46]. Truck drivers also experienced significantly lower increases in lower back discomfort (2.5 vs 0.2, passive vs active) and wrist/forearm discomfort (1.0 vs 0.1, passive vs active) over the course of a workday when using an active suspension seat instead of a passive suspension seat[46].

5.3 Limitations

This thesis only performed statistical analysis on vibration measures for a narrow frequency range (5–9 Hz). Although other frequency ranges are relevant for consequences such as motion sickness, and the ISO 2631-1 standard considers that exposure frequencies from 0.5-80 Hz have an impact on health[1], 5-9 Hz is the most impactful frequency range on human health for z-axis exposures. It would also be insightful to evaluate a wider range of frequencies in order to determine if true differences lie outside of 5-9 Hz.

This thesis evaluated unweighted and A_w exposures for both seats. However, these are not the only methods for evaluating WBV. Johnson et al. (2018) used VDV_{total} and static spinal compression dose (S_{ed}) as well as A_w methods[45]. They determined that the difference in performance between the Bose Ride® and Legacy seats was largest when evaluated with A(8) methods[45]. Evaluating the seats with other methods for quantifying vibration would offer a more complete model of how the Bose Ride® compares with passive seats.

This thesis evaluated participants that were seated with hands either in their lap or on the arm rests of the seat and feet were flat atop the motion platform. This not a fully accurate recreation of driving in the real world, as drivers' hands would be on the wheel or shifter and their feet would be operating the pedals. These differences could have affected the outcome measures in this thesis.

This thesis evaluated a limited number of healthy males that had no history of low back pain and did not experience discomfort while sitting. Truck drivers can have a wide variety of health status and can also be female. Evaluating seats exclusively with healthy males makes it difficult to generalize the findings of this thesis.

This thesis only looked at field exposures recorded in Manitoba. Differences in road maintenance and weather conditions between regions can exist and thus the vibration environment can be different between geographical areas.

It is likely that the Bose Ride® seat has a dominant frequency below 0.5 Hz. The lowest frequency that was used in this thesis was 0.5 Hz, and that was also the frequency with the largest platform-to-seatpan transmissibility for the Bose Ride® seat. If the true dominant frequency of the Bose Ride® seat is less than 0.5 Hz then it would not have been captured with the range of frequencies tested in this thesis. Therefore, I cannot be confident that 0.5 Hz is the true dominant frequency.

6 Conclusion

This thesis investigated the frequency response of an active and passive suspension seat between 0.5 to 20 Hz. It was observed that the active suspension seat attenuated z-axis whole body vibration more effectively than a passive suspension seat. This is comparable to previous work evaluating active and passive suspension seats.

It was hypothesized that the active suspension seat would be more effective than the passive suspension seat in the attention of WBV. Our results supported part of this hypothesis as the Bose Ride® seat was more effective attenuating z-axis WBV but was not more effective attenuating x and y-axis WBV. It was also hypothesized that vibration exposure simulating Canadian long-haul trucks would be below HCGZ caution limits and EU action limits. The results support this hypothesis. In conclusion, the Bose Ride® seat is more effective at attenuating WBV but, this better performance may not result in reduced health risks for long-haul truck drivers in Manitoba as both seats were below the ISO 2631-1 HCGZ and EU directive action limits. Accordingly, both seats resulted in vibration exposures where health effects are not objectively observed.

It's my hope that this thesis sparks more interest in the evaluation of controls and interventions for the reduction of whole body and hand arm vibration, leading to improved quality of life for members of our society. Development of a library for vibration simulations will aid scientists in evaluating potential interventions to reduce vibration injury.

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Appendices

Appendix A: BMI Equation

$$Body\ Mass\ Index = mass\ (Kg)/Height\ (m)^2 \quad (A.1)$$

Appendix B: Coherence Traces

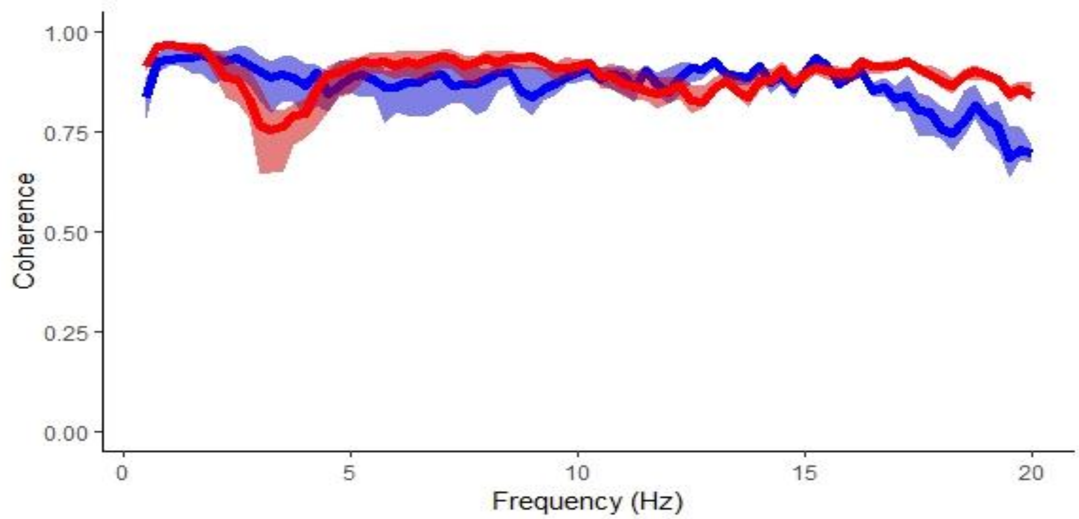

Figure B.1: X-axis coherence of Bose Ride® (blue trace) and Legacy (red trace) seats excited at 0.2 m/s^s r.m.s. Solid lines represent the median value while the shaded area represents the 25th and 75th percentile.

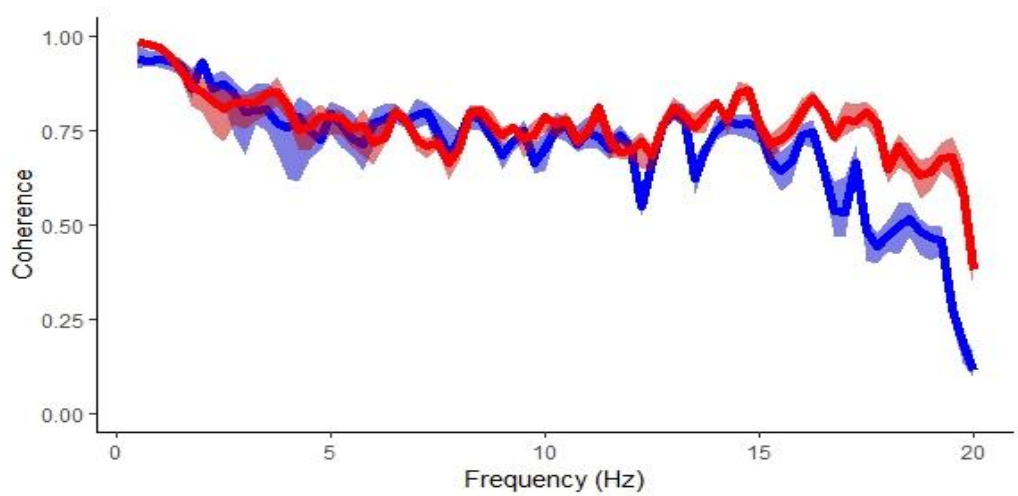

Figure B.2: X-axis coherence of Bose Ride® (blue trace) and Legacy (red trace) seats excited at 1.0 m/s^s r.m.s. Solid lines represent the median value while the shaded area represents the 25th and 75th percentile.

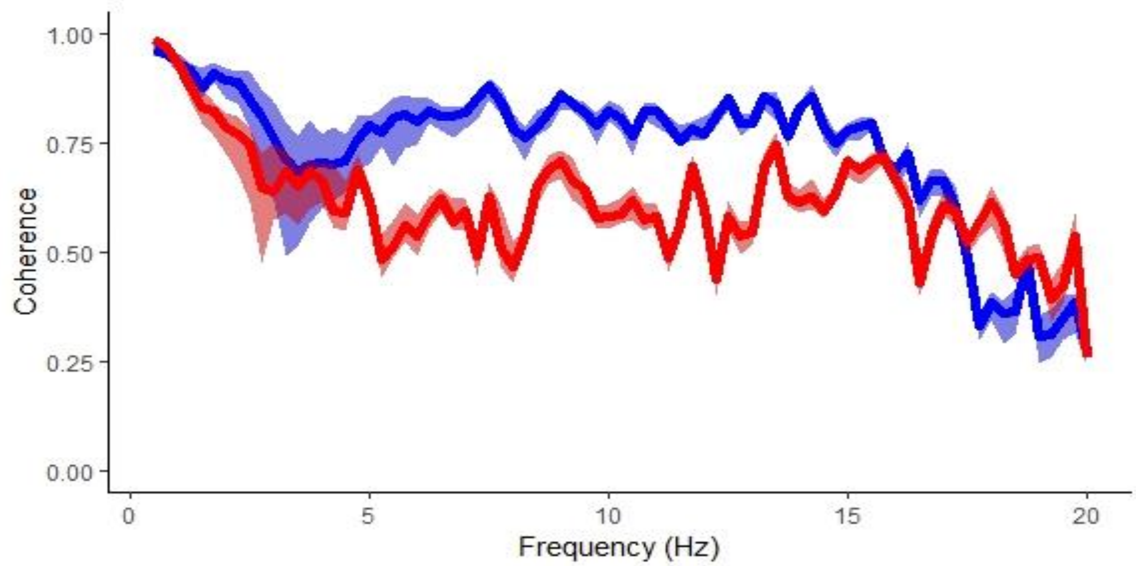

Figure B.3: X-axis coherence of Bose Ride® (blue trace) and Legacy (red trace) seats excited at 1.5 m/s^s r.m.s. Solid lines represent the median value while the shaded area represents the 25th and 75th percentile.

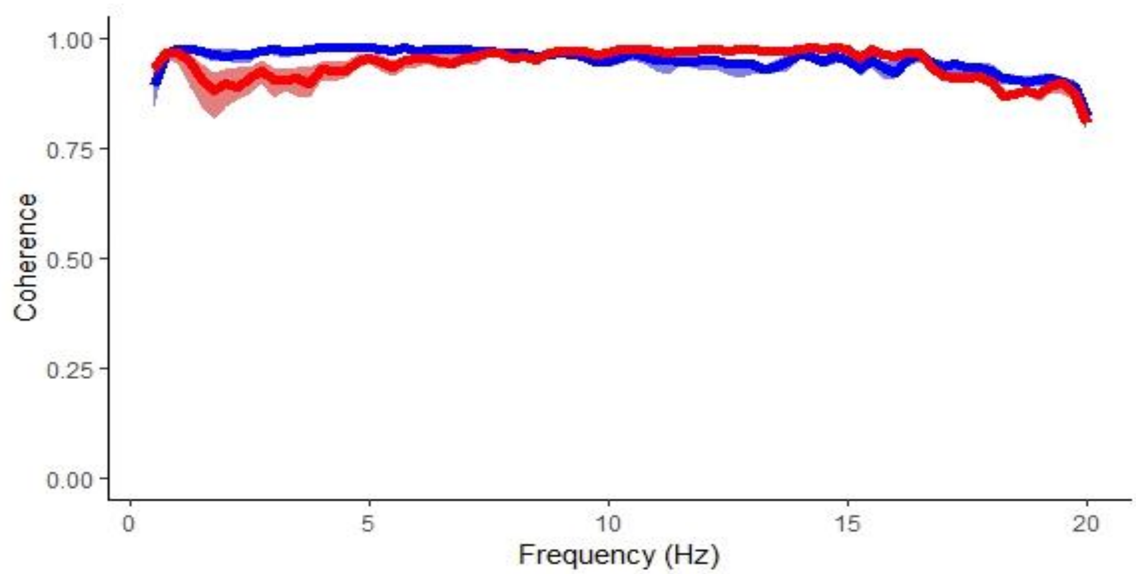

Figure B.4: Y-axis coherence of Bose Ride® (blue trace) and Legacy (red trace) seats excited at 0.2 m/s^s r.m.s. Solid lines represent the median value while the shaded area represents the 25th and 75th percentile.

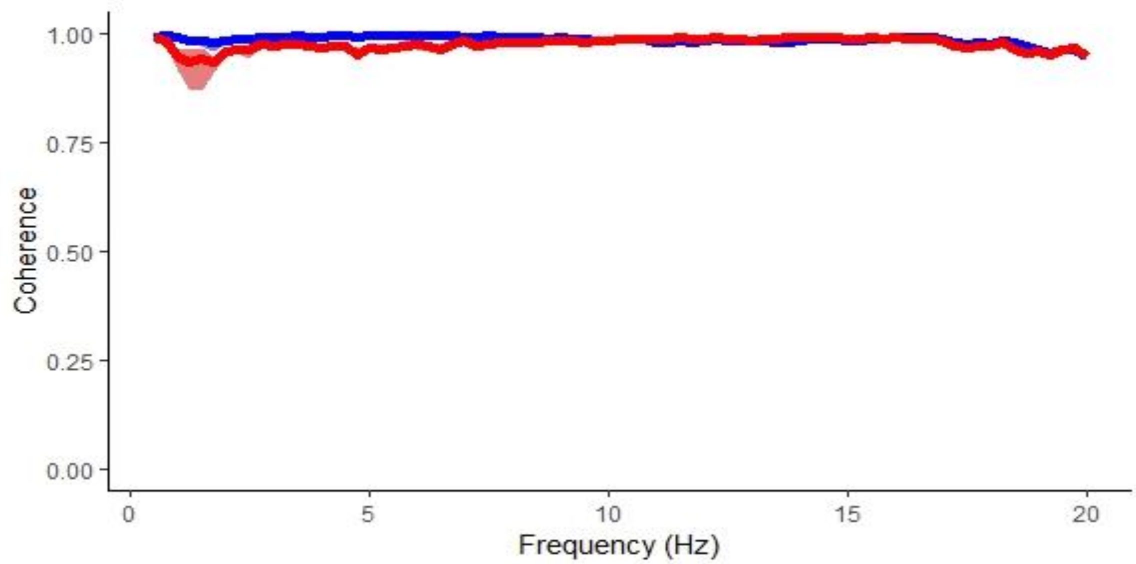

Figure B.5: Y-axis coherence of Bose Ride® (blue trace) and Legacy (red trace) seats excited at 1.0 m/s^s r.m.s. Solid lines represent the median value while the shaded area represents the 25th and 75th percentile.

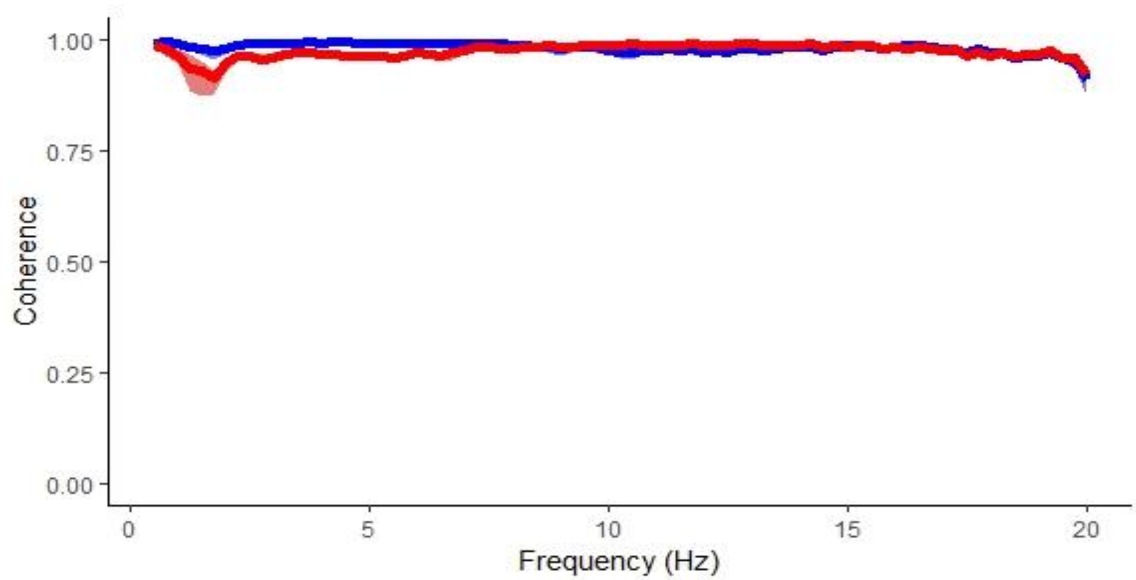

Figure B.6: Y-axis coherence of Bose Ride® (blue trace) and Legacy (red trace) seats excited at 1.5 m/s^s r.m.s. Solid lines represent the median value while the shaded area represents the 25th and 75th percentile.

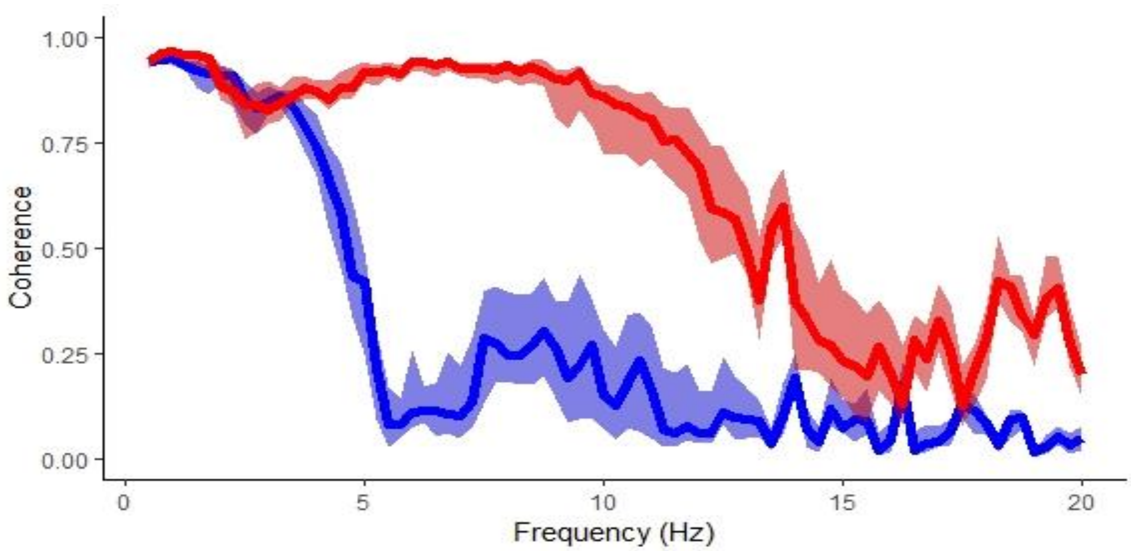

Figure B.7: Z-axis coherence of Bose Ride® (blue trace) and Legacy (red trace) seats excited at 0.2 m/s^s r.m.s. Solid lines represent the median value while the shaded area represents the 25th and 75th percentile.

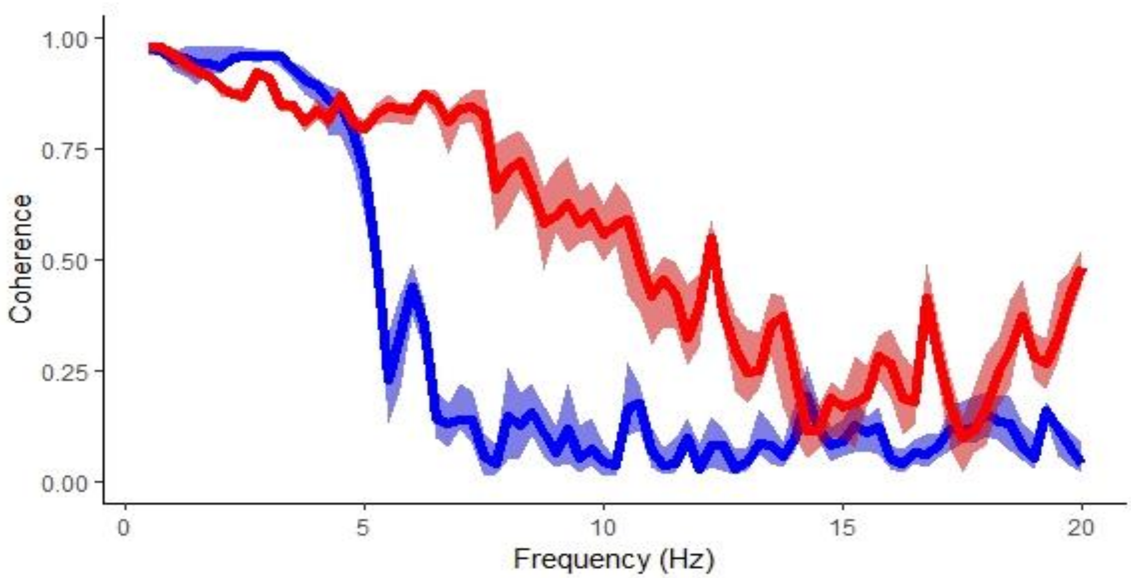

Figure B.8: Z-axis coherence of Bose Ride® (blue trace) and Legacy (red trace) seats excited at 1.0 m/s^s r.m.s. Solid lines represent the median value while the shaded area represents the 25th and 75th percentile.

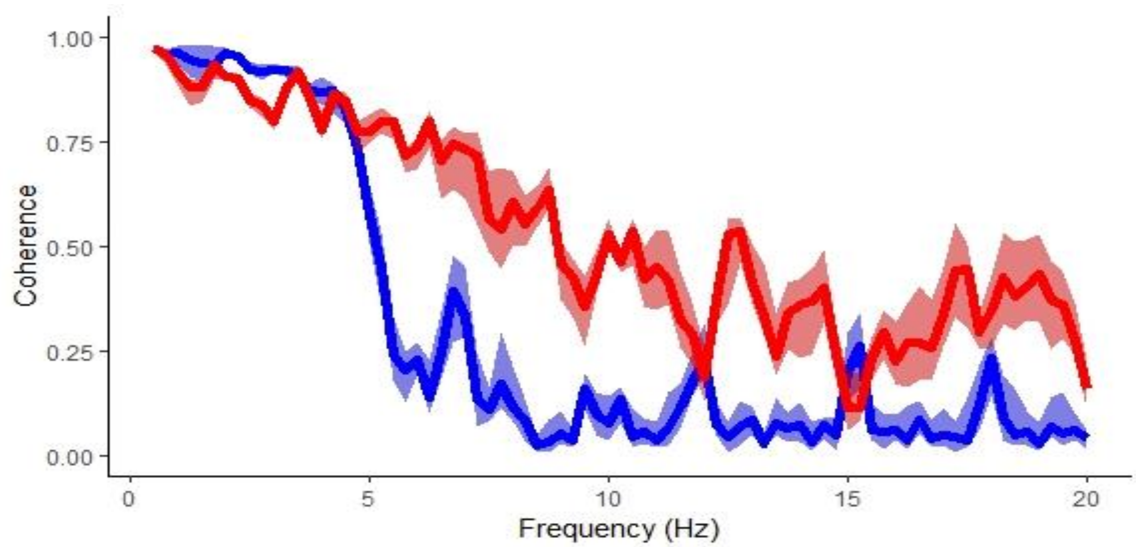

Figure B.9: Z-axis coherence of Bose Ride® (blue trace) and Legacy (red trace) seats excited at 1.5 m/s^s r.m.s. Solid lines represent the median value while the shaded area represents the 25th and 75th percentile.

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DOI: http://dx.doi.org/10.5206/wurjhns.2016-17.11

Available at: https://ir.lib.uwo.ca/wurjhns/vol7/iss1/12