Improving Ergonomic Interventions to Reduce Whole-Body Vibration Exposures among Professional Drivers

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Abstract

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Assessing physical exposures in occupational health studies proves challenging regardless of the industry. In transportation, however, the problem is exacerbated by the fact that subjects are literally on the move. To improve the understanding of the link between chronic whole-body vibration exposure and adverse health outcomes, this study evaluated epidemiologic trends, comparing injury events among employees in a large metropolitan transit agency. The epidemiology results indicate that bus drivers are at increased risk for injury compared to a referent group of administrative workers.

This study also presents the technological advancements in field-based, whole-body vibration (WBV) exposure assessment by comparing three generations of WBV data collection equipment. This study presents the ISO 2631 Part 1 and Part 5 results for field-based WBV exposure studies among professional truck drivers, bus drivers, and heavy equipment operators.

Finally, this study applied field-collected vibration signal data to research on a vibration simulation hexapod. The final phase of this study evaluated vibration attenuation, comparing the current industry standard (an air-ride suspension seat) to a newly developed technology (an electromagnetically active seat) across city streets, freeways, and rough roads. This comparison of seat suspension technologies was conducted for evaluation between professional truck drivers and bus drivers, and it included a measure of vibration transmission through the spines of subjects. The results indicate that the electro-magnetically active seat is a promising engineering control that may prevent injuries over the long term.

This study combined several research approaches that are important to the field of occupational health. The goal of this research was to improve the understanding of injury risk and intervention options, with the ultimate goal of improving the lives of professional bus drivers.

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DEDICATION

To my wife Dusti and our children, Nolan and Natalia

You are the source of my strength.
I cannot put into words how much I owe you for my success.
Your love and patience helped me with the stressful times.
Even when I was sleep deprived, grouchy, and talking about giving up, you were there.

You are the source of happiness and pride in my life.
We got through this together, and the completion of this is a shared accomplishment.

Nolan Zachary, you will always be my little man, even as you grow up too fast,
challenge me as a father, and are a constant source of humor in my life.

Natalia Alexis, you are my sweet baby girl who always makes me smile.
Don't worry – despite my declarations, I will allow you to date one day (in your thirties).

Dusti Luisa, my wife, thank you for your love, patience, and support.
I promise to make up all these long hours to you in the form of many hours of happiness.
I treasure the thought of growing old with you.
I love you!

Chapter 1: Introduction and Literature Review

Occupational Physical Exposure Assessment

Occupational exposures to physical ergonomic hazards such as whole-body vibration (WBV) can cause debilitating physical disorders. However, health care providers and safety professionals may not link physical exposures to occupational injuries when the exposures are not well quantified [1]. Complicating matters in the assessment of occupational exposures is the fact that much of the research on occupational exposures insufficiently balances variation within and between subjects, thus reducing the efficiency of exposure-disease association [2, 3]. Also of importance is that measuring ergonomic exposures in the workplace can be more costly than measuring other occupational exposures. These increased costs add to the difficulty of accurately measuring and testing interventions for such exposures [4].

Application of the “validity hierarchy” approach indicates that direct measures are the best method for assessing biomechanical exposures, with direct observation and self-reported exposures also being viable assessment methods [5-9]. Direct measurement, however, is also the most expensive method, and researchers often have to consider such costs when planning ergonomic exposure studies. To assist researchers efficiently plan efforts to quantify physical exposures, a comprehensive model to compare costs associated with video observation options has been developed [10]. This method of ergonomic exposure assessment is considered more accurate than self-reporting methods, albeit not as accurate as direct measurement. Unfortunately, due to the significant investment associated with the direct measurement of physical exposure, researchers and employers often rely on less reliable quantifying methods, such as self-reporting [4].

Occupational Low Back Injuries

Injuries to the low back are considered the most significant non-lethal medical condition affecting the American workforce [11-13]. It is estimated that nearly 80% of working adults will experience back pain during their lives and that 4-5% of the population has acute low back pain (LBP) episodes every year [14]. Recent research on the global burden of occupational LBP attributes 37% of all LBP to occupational exposures, corresponding to an estimated annual loss of over 800,000 disability-adjusted life years. The LBP burden is higher among men than women, partially due to the high concentration of men in jobs that require heavy lifting and/or involve WBV exposure [15, 16]. A significant challenge in determining the link between LBP development and occupational exposures is the fact that genetic predisposition can have a significant impact on disc degeneration regardless of life experiences [17, 18]. Overall physical fitness and low back strength are also significant determinants in the development of LBP among members of the workforce [19-22]. As well, research has identified that obesity is also a common contributor to LBP development in occupational settings, and a linear relationship has been established between higher body mass index (BMI) and both higher injury rates and workers' compensation costs [23-25]. The link between LBP and obesity is particularly concerning, given the increasing obesity rates in both the United States (nearly 30% of adults) and the rest of the world [26, 27].[1]

Treatment of Back Injuries

Injuries to the low back require extensive treatment, which often results in long periods of absence from work for injured workers. Work-related back injuries account for approximately 20% of U.S. workers' compensation claims and 33-45% of U.S. workers' compensation costs. These effects represent a multi-billion dollar drain on the American economy each year [28-30]. Back injuries continue to be one of the most common work-related injuries year after year, despite significant efforts by employers to reduce the occurrence of this type of injury. Back injuries are also identified as a major cause of long-term disability [31]. In addition to higher medical costs relative to other occupational injuries, back

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1 Obesity is defined to exist when an individual's BMI ≥ 30 kg/m^2 [26].

injuries often generate costs from indemnity, employee wage loss, employer replacement and overtime pay, and legal fees. Combined, these costs have a substantial impact on injured workers, their families, employers, and the workers' compensation system worldwide [32]. The costs associated with workers' compensation claims for back injuries are higher than those of other occupational injuries due to extended treatment requirements [33-35]. An injury to the low back is considered a chronic health outcome (as are diabetes and hypercholesterolemia), meaning that it cannot be cured but must be aggressively managed [36]. Management of LBP commonly includes treatment by pain treatment centers (PTCs) and/or spine clinics (SCs), both of which generally administer proven modalities of treatment, including spinal injections and pain medication. Some PTCs and SCs, however, also provide psychological and/or behavioral therapy, although these techniques have yet to be evaluated for successful outcomes for work-related chronic LBP [37]. Recent research examining the ability of PTCs and SCs to increase return-to-work outcomes for a cohort of 230 workers reporting chronic occupational LBP "did not yield improved functional outcomes" [37].

WBV and LBP Development

Research has shown that long-term exposure to WBV significantly contributes to LBP injuries, including sciatic pain, degenerative changes to the spine, and lumbar intervertebral disc disorders [38-40]. However, unlike the acute presentation of back pain associated with manual material handling (MMH) tasks, the onset of LBP from chronic WBV exposure may be gradual and insidious [41]. Epidemiological studies have shown a strong association between occupational LBP and long-term exposure to WBV [39, 42, 43], with risk increasing as the dose of WBV increases [44]. The exposure-response relationship between WBV and back disorder development is not currently well understood, and there is no universally accepted exposure threshold to WBV that results in LBP development [45]. Despite being discussed in previous research on WBV, the dose-response relationship has not been definitively quantified [46]. The difficulty of assessing causality for workplace exposures leading to the development of LBP was highlighted in a recent systematic review that did not identify evidence to support the Bradford-Hill [47] criteria to establish overall causality for workplace activities (e.g., lifting) leading to LBP [48].

WBV Standards and Regulations

ISO 2631 is an international, health-related standard that was first published in 1997. Entitled, "Mechanical vibration and shock − Evaluation of human exposure to whole-body vibration," the standard defines general requirements for quantifying WBV in relation to human health and comfort, the probability of vibration perception, and motion sickness. Part 1 of the standard (entitled "General Requirements") outlines the requirements for measurement techniques and establishes health guidelines that can be used as a baseline for the prediction of injury outcomes. ISO 2631 also suggests that increased vibration duration (within the workday or daily over working years) and intensity lead to an increased risk of injury outcome, while periods of rest are considered to reduce risk. The standard establishes a "health guidance caution zone" for occupational exposures that could be used by researchers and employers to predict injury outcomes [49]. Part 5 of the standard (entitled "Method for evaluation of vibration containing multiple shocks") addresses the existence of multiple shocks and attempts to address the effect of shocks on human health outcomes. The workplace examples provided in Part 5 include machinery traveling over rough surfaces, small boats in rough seas, and mechanical hammers. Part 5 also addresses an issue that was largely unaddressed in Part 1: that adverse effects on the lumbar spine are often the result of vibrations containing multiple shocks. The addition of this effect arose from the predicted response of the bony vertebral endplates in an individual regularly exposed to repeated shocks [50]. Neither Part 1 nor Part 5 of ISO 2631 has any force of regulation to require employers to address WBV exposures in the workplace.

In 2004, the European Union (EU) published a directive requiring employers to measure and address WBV exposures in the workplace. This directive established daily action values and exposure limit values that were standardized to an 8-hour day. Employers in EU member states were required to comply with the directive [51]. The WBV exposure limits published by the American Conference of Governmental Industrial Hygienists (ACGIH) are based upon the guidelines established by ISO 2631 [52]. In the U.S., standards related to WBV are strictly voluntary. The Occupational Safety and Health Administration (OSHA) is responsible for publishing standards for general industry (Part 1910), maritime (Part 1915), construction (Part 1926), and agriculture (Part 1928). However, despite extensive WBV exposures in all of these industries, there is no inclusion of WBV in the OSHA standards [53].

WBV Exposures among Professional Drivers

Professional drivers, such as taxi drivers, truck drivers, bus drivers, and policemen, are regularly exposed to seated WBV, thus placing them at a higher-than-average risk for developing LBP and other health outcomes associated with chronic LBP exposures [28, 54-61]. Professional operators of light- and heavy-duty equipment are also exposed to seated WBV, which elevates their risk of developing musculoskeletal disorders, including LBP [62-67]. Among these populations, professional truck drivers and bus drivers are two groups who spend the majority of their working lives performing tasks that require extended periods of WBV exposure [68-71]. Professional truck drivers regularly work extended hours, which leads to increased fatigue and decreased physical activity, limits their access to health care, and results in higher rates of occupational injury [72, 73]. A German study found that "lumbar syndrome" occurs in approximately 60% of professional truck drivers [46].[2]

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[2] "Lumbar Syndrome" is "any kind of symptom (like lumbago or sciatica) in the lumbar region and in the sacral area for which a vertebral cause could be assumed after differential diagnosis" [46].

A study of self-reported symptoms among professional urban bus drivers found that musculoskeletal disorders in the lower back occurred in 40% to 82% of respondents [74]. Research has shown that employment as a professional bus or truck driver is associated with increased risk of work-related LBP development [75]. In addition to their physical exposure, bus drivers are regularly pressured by psychosocial stressors, including traffic congestion, lack of access to bus stops due to the illegal parking of other motorists, and passenger hostility, all of which have been shown to significantly contribute to LBP development [76]. In a critical review of musculoskeletal disorders and workplace factors, the National Institute of Occupational Safety and Health (NIOSH) found strong evidence of a positive association between WBV exposure and low back disorders affecting professional driver populations [42]. (The study adjusted for potential confounders, such as smoking and physical and psychosocial work-related factors.) Field-based WBV research has shown that the types of routes and road surfaces contribute significantly to the amount of daily WBV exposure professional bus drivers receive [69, 77].

The above findings provided the motivation for the current study, which was designed to reduce LBP injuries among professional bus drivers through the development of an improved exposure assessment method for WBV exposures and interventions. The goals of this research effort were threefold:

1. To examine the epidemiologic injury trends by utilizing a long-term injury database from a large metropolitan transit agency to determine the risk of back injury to professional bus drivers;

2. To apply previously developed direct measurement techniques to accurately measure WBV exposures in the work environment for use in engineering intervention testing in a laboratory setting; and

3. To utilize field-measured WBV exposures to evaluate a recently developed seat suspension (engineering control intervention) in a laboratory setting to determine WBV exposure reduction potential.

The results of this research can be used to evaluate options to reduce WBV exposures among professional bus drivers, potentially reducing the LBP burden within the group.

Literature Search Criteria

An electronic search of MEDLINE (1960 to March 2013) and the Web of Knowledge (1960 to March 2013) was conducted to identify relevant articles. A comprehensive search strategy using indexed terms and free text was employed to identify articles with three main components: (1) exposure assessment (whole-body vibration), (2) etiology (driving exposure), and (3) injury outcome (LBP).

For inclusion in this study, articles were required to be:

1. Published in English,
2. Related to occupational exposure,
3. Related to LBP development, and
4. Related to driving exposures.

Excluded from this study were articles that were:

1. Nonscientific studies (e.g., commentaries and letters to the editor),
2. Literature reviews, or
3. Unrelated to seated driving or exposure.

Overview of this Dissertation

Chapter 2 describes how a portion of this research effort was predicated upon the acquisition of a comprehensive, 13-year injury database from a large metropolitan transit organization. The data were analyzed to capture the burden of injury among professional bus drivers. More specifically, the database was compared for injury reports by job title, time in job, demographic variables, and injury type. The resulting analysis quantified the relationship between those exposed to seated WBV (bus drivers) and those not exposed to seated WBV (non-driver occupations). Occupational counts by job title were acquired for the years spanning the database in order to develop injury rates per full-time equivalents by year. Differences in injury trends between groups were evaluated based on injury outcomes and whether the groups were exposed to WBV. A hazard ratio was developed to compare the risk of injury between populations within the same public agency. This method had been applied in previous research that examined injury trends within a military population [78].

Chapter 3 describes the advancement in techniques for field-based WBV exposure measurements. Field-based studies of professional bus and truck drivers are described, and the development of exposure assessment methods is compared, as advancements were made in the capabilities of WBV exposure-assessment technology. The acquisition of field-based exposures for use in a laboratory-based, engineering-control intervention evaluation are described, and a presentation is made of WBV exposures measured among professional bus drivers, truck drivers, and heavy equipment operators. The ability to capture WBV exposures at a high sampling rate for use in a vibration simulation hexapod is described, and a comparison of ISO parameters of vibration exposures between populations is made.

Chapter 4 evaluates engineering interventions – specifically seat suspension designs – for their ability to reduce WBV exposures among professional drivers, as measured on a vibration simulation hexapod in a laboratory setting. WBV exposures were measured for healthy professional drivers (n = 12) who were exposed to real world, field-measured WBV vibrations that were downloaded and used to stimulate the vibration simulation hexapod. As discussed in Chapter 3, WBV exposures were taken from actual road data that had been collected on a transit bus and a large semi-truck[3] over three main types of roads: city streets, a freeway, and a section of rough road. The exposure measurements were evaluated by road types, by seat suspension designs (a passive air-ride suspension and an electromagnetically active suspension), and by subject weight category (light drivers < 102 kg and heavy drivers >128 kg). WBV exposures were evaluated for statistical significance using a repeated-measure analysis of variance (RANOVA) method.

[3] The words "truck" and "semi-truck" are used interchangeably throughout this dissertation.

Chapter 5 presents the results and conclusions of the research, with an emphasis on their relevance to – and potential impact on – the fields of ergonomics, industrial hygiene, and occupational health.

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Chapter 2: Injuries among a Professional Metropolitan Bus Driver Population

Introduction

In the United States during 2011, musculoskeletal disorders (MSDs), accounted for 33% of all work-place injuries and illnesses that required days away from work. Among reported workplace MSD injuries, professional drivers (including truck drivers and bus drivers) had a higher median number of days away from work than those in other occupations, a clear sign that professional drivers spend more time in recovery than those in other occupations with similar injuries spend [1].[4] Also in 2011, back injuries accounted for 42% of all MSD cases, requiring a median of 7 days of recuperation across all occupations. Back injuries are the most significant musculoskeletal problem affecting the American workforce [1, 2].

Professional drivers have an elevated risk for the developing LBP due to a number of factors, including the sedentary nature of their work, prolonged sitting postures, poor physical fitness, and WBV trans-mitted through the vehicle [3-8]. Research among sedentary worker populations has found that 81% of bus drivers in the U.S. and 49% of bus drivers in Sweden experienced work-related LBP [4]. Additionally, research has found that 80% of bus drivers experienced MSDs (including back and neck pain), compared to 50% of non-drivers [3]. Occupational MSD development among bus drivers has been linked to a combination of physical and psychosocial factors [9]. The associated psychosocial factors include mental demands, poor job satisfaction, and high stress levels caused by traffic condi-tions, irate passengers, short breaks, and lack of access to restroom facilities [4, 5, 9, 10]. Bus drivers are also required to perform MMH tasks – such as loading handicapped passengers and bicycles and

[4] In 2011, professional truck drivers and bus drivers spent a median of 21 and 15 days out of work, respectively, for each workplace MSD injury they suffered.

performing minor bus maintenance activities – that contribute to LBP [11]. Individual factors, including age, gender, BMI, and pre-existing ailments have also been identified as contributors to LBP development among drivers [4, 12].

The goal of this study was to assess LBP injury trends by examining a comprehensive, 13-year occupational injury database that was obtained from a large metropolitan transit agency. This study employed a retrospective cohort design in order to evaluate the hypothesis that bus drivers are at elevated risk of LBP injuries relative to administrative workers.

Methods

This study utilized a database of injury claims obtained from the King County Department of Transportation, Metro Transit Division, Seattle, Washington. The database covered the period from 1998 to 2010, inclusive. Injury data were extracted from the electronic injury claim system and included all reported occupational injury claims among Metro Transit Division employees during the 13 years included in the study. Employee counts by job titles for the years 1998-2010 were provided by the King County Department of Transportation and were used to compare injuries by job title. Study procedures were approved by the University of Washington's Human Subjects Division.

The Metro Transit Division's injury database contained basic demographic and employment history information for each employee who was included in the injury database. Demographic variables included gender and age. Employment and injury variables included job title, date of hire, age at date of injury, total years of service at time of injury, loss type (medical only or time loss), work status after injury (full duty, job transfer, light duty, or off work), body part injured, injury type, and a general description of the injury's cause. Annual summary information was also utilized (e.g., full-time employee counts within occupational categories by job title). Claimants were de-identified and assigned a unique claimant ID by King County prior to delivery of the database for use in this study.

Study Sample and Grouping Criteria

Analyses of injury claims were restricted to employees filing claims from 1998 to 2010 (n = 8,018) because claims covering those years were considered both stable and accurate, and they represented complete filing years at the onset of the study. The injury database was extracted from the electronic database during the second quarter of 2011, thus allowing for the inclusion of complete data for all 2010 injury claims. Metro Transit Division occupational injuries were reviewed manually across all claims in order to review the file for accuracy and to identify missing data fields and incomplete entries. Injury claims were grouped into five categories using the OSHA Injury and Illness Classification Manual as a guideline [13]. The following injury groups were defined and used for analysis in this study. (Note: these groups differ slightly from OSHA's categories.)

- Head and neck,
- Back,
- Upper extremities,
- Lower extremities, and
- "All Other Injuries," including claims for hips and pelvis, chest, respiratory system, abdomen, groin, ribs, internal organs, buttocks, heart, multiple body parts, mental distress, and claims listed as "other."

Occupations were grouped into the following categories by job title.

- Bus drivers,
- Other manual laborers, including electricians and carpenters,
- Mechanics, and
- Administrative positions, including desk jobs and management positions.

Data Analysis

The review of individual medical records for the 8,018 individual claims was not practical, and individual claim medical records were not made available for this study. Instead, available electronic data that included injury diagnoses (as reported by medical providers and coded by the Metro Transit Division) were used to identify injury categories. Claims were identified as "medical only" claims or "time loss" claims (lost workdays) by the Metro Transit Division, based on diagnosis and treatment recommendations of medical providers. Claim incidence rates within job categories and injury categories were calculated using employee counts. To achieve full-time equivalent workers by job title, it was assumed that a full-time worker was on the job 2,000 hours annually. Injury database accuracy was verified by Metro Transit Division prior to providing the database for use in this study.

The distribution of most of the variables was not normal, thus requiring the use of medians and interquartile intervals (IQI, 25^{th} to 75^{th} percentiles) for descriptive statistics. Between groups (bus drivers, mechanics, other manual laborers, and administrative jobs), comparisons used Pearson's chi-squared test to assess statistical significance. Development of the regression model utilized a stepwise forward entry approach, first testing occupational category variables by injury category and then by a demographic (gender and age) variables and two-way interaction terms. Model refinement was guided by goodness of fit and minimization of interaction. The final statistical analysis model was developed for compliance with the assumptions of the Cox Proportional Hazards Model, which states that the hazard functions for any two individuals at any point in time are proportional. This approach was verified using Kaplan-Meier survival curve plots.

Results

Subject Demographic Features

This study analyzed a 13-year occupational injury claim database from a cohort of employees working for a metropolitan transit agency. The study period was restricted to occupational injuries that claimants identified occurred during the period between January 1, 1998, and December 31, 2010, with a final tally of n = 8,018 after exclusions. All claims were included in which claim information was available for the categorical variables included for analysis in the study. Injury claims were excluded from the original database extraction if they did not include the claimant's date of hire (n = 317), age at injury (n

= 15), occupation (n = 24), body part injured (n = 5), or gender (n = 22). Additionally, all claims from a pilot "pre-care" program established by the Metro Transit Division that covered three years of the study period were excluded (n = 1,147). These claims were excluded because: (1) the pilot program targeted pre-injury interventions and did not include medical injury claims, and (2) the program was cancelled.

Table 1 shows the demographic data of the injury claimants included in the study. Males represented 2,090 (73%) of all claimants in the database. The gender breakdown varied significantly across occupational categories. For example, very few claims were filed by female mechanics (1.0%), while most claims in the administrative occupation category were filed by females (55.3%). The mean (SD) age at injury for all claimants was 46.3 years (SD 9.7), with 37% of injury claims filed by employees in the 40-49 age range. The mean (SD) number of years of service before an employee's first injury claim was 10.1 (SD 8.2). Among all injury claimants included in the database, 43% had reported three or more injury claims. Examining the breakdown of injuries by category, across all occupations, shows the following distribution of claims: upper extremities 27.8%, back 22.7%, lower extremities 17.7%, head and neck 13.0%, and 18.9% "all other injuries."

Injury Claim Costs Analysis

Table 2 shows that, as expected, the injury cost varied significantly between the medical-only claims and time-loss claims. Among time-loss claims, the median injury cost was highest among injuries to the upper extremities ($6,524), while head and neck injuries were the least expensive ($3,596). Not shown in the table is that females had a higher median cost for upper extremity claims, head and neck claims, and claims for "all other injuries."

Table 1
Metro Transit Division injury database demographics by occupational category, 1998-2010, (first claims, n = 2,843)

	Occupational Category									
	Bus Drivers		Other Manual		Mechanic		Admin		Total	
Characteristic	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**
Gender										
Male	1,265	*68.0%*	466	*86.8%*	291	*99.0%*	68	*44.7%*	2,090	*73.5%*
Female	595	*32.0%*	71	*13.2%*	3	*1.0%*	84	*55.3%*	753	*26.5%*
Sub-Total	*1,860*	*100%*	*537*	*100%*	*294*	*100%*	*152*	*100%*	*2,843*	*100%*
Age at Injury ***(years)***										
< 30	88	*4.7%*	37	*6.9%*	13	*4.4%*	3	*2.0%*	141	*5.0%*
30 - 39	382	*20.5%*	100	*18.6%*	69	*23.5%*	19	*12.5%*	570	*20.0%*
40 - 49	680	*36.6%*	207	*38.5%*	116	*39.5%*	51	*33.6%*	1,054	*37.1%*
50 - 59	546	*29.4%*	160	*29.8%*	69	*23.5%*	62	*40.8%*	837	*29.4%*
> 60	164	*8.8%*	33	*6.1%*	27	*9.2%*	17	*11.2%*	241	*8.5%*
Sub-Total	*1,860*	*100.0%*	*537*	*100.0%*	*294*	*100.0%*	*152*	*100.0%*	*2,843*	*100.0%*
Duration of Service at Injury ***(years)***										
< 1	112	*6.0%*	42	*7.8%*	42	*14.3%*	10	*6.6%*	206	*7.2%*
1 - 5	591	*31.8%*	143	*26.6%*	69	*23.5%*	28	*18.4%*	831	*29.2%*
5 - 10	452	*24.3%*	105	*19.6%*	51	*17.3%*	17	*11.2%*	625	*22.0%*
10 - 20	444	*23.9%*	165	*30.7%*	90	*30.6%*	53	*34.9%*	752	*26.5%*
> 20	261	*14.0%*	82	*15.3%*	42	*14.3%*	44	*28.9%*	429	*15.1%*
Sub-Total	1,860	*100.0%*	537	*100.0%*	294	*100.0%*	152	*100.0%*	2,843	*100.0%*
Claims Counts ***(all years, all claims)***										
1	1,860	*35.3%*	537	*35.7%*	294	*29.4%*	152	*63.6%*	2,843	*35.5%*
2	1,118	*21.2%*	344	*22.9%*	205	*20.5%*	46	*19.2%*	1,713	*21.4%*
3 or More	2,296	*43.5%*	623	*41.4%*	502	*50.1%*	41	*17.2%*	3,462	*43.2%*
Sub-Total	*5,274*	*100.0%*	*1,504*	*100.0%*	*1,001*	*100.0%*	*239*	*100.0%*	*8,018*	*100.0%*
Injury Categories ***(all years, all claims)***										
Upper Extremities	1,458	*27.6%*	413	*27.5%*	281	*28.1%*	73	*30.5%*	2,225	*27.8%*
Back	1,202	*22.8%*	341	*22.7%*	225	*22.5%*	49	*20.5%*	1,817	*22.7%*
All Others	996	*18.9%*	279	*18.6%*	194	*19.4%*	48	*20.1%*	1,517	*18.9%*
Lower Extremities	942	*17.9%*	266	*17.7%*	166	*16.6%*	44	*18.4%*	1,418	*17.7%*
Head and Neck	676	*12.8%*	205	*13.6%*	135	*13.5%*	25	*10.5%*	1,041	*13.0%*
Sub-Total	*5,274*	*100.0%*	*1,504*	*100.0%*	*1,001*	*100.0%*	*239*	*100.0%*	*8,018*	*100.0%*

Among the occupation of interest in this study – bus drivers – the highest median cost was for upper extremity claims ($6,533), while the injury of interest (back claims) was third in median injury cost ($4,163), behind claims for "all other injuries" ($5,503). Injuries to bus drivers represented 64.8% of the total paid costs among all injured Metro Transit Division employees. Low back injuries among bus drivers represented over $11,000,000 in costs (12.8% of total costs paid) during the 13-year period covered by the database.

Injury Trends by Loss Type

The annual number of injury claims among all Metro Transit Division employees declined from 1998 to 2001 (Figure 1). The number then held fairly constant for the next five years (2002-2006), before beginning a slight upward trend from 2007 to 2010. In addition, the annual incidence of claims (per 1,000 employees) trended slightly downward from 1998 to 2010.

Mechanics generally had the highest annual incidence rate across all injury types, with other manual occupations and bus drivers second and third, respectively (Figure 2). Administrative workers had the lowest injury rate across all years and were selected as the referent group in the Cox Proportional Hazards Model. This decision was based on the nature of the group's work experience and low injury rate.

Bus driver employment increased steadily over the 13 years of the study (Figure 3). The incidence rate of back injuries increased every year from 2000 to 2004, but trended downward from 2005 to 2010, with the exception of 2008. Back injuries among bus drivers remained significantly higher than the referent group (administrative jobs) throughout the entire study period. Upper extremity injuries among mechanics consistently resulted in the highest incidence rate across most of the years covered by this study (Table 3).

Table 2
Metro Transit Division injury cost by claim type, 1998-2010, (all claims, n = 8,018)

	Injury Type					
Claim Type	**Upper Ext.** (n = 2,225) Median ($) (25th - 75th)	**Back** (n = 1,816) Median ($) (25th - 75th)	**All Other Injuries** (n = 1,518) Median ($) (25th - 75th)	**Lower Ext.** (n = 1,418) Median ($) (25th - 75th)	**Head and Neck** (n = 1,041) Median ($) (25th - 75th)	**Total** (n = 8,018) Median ($) (25th - 75th)
Medical Only §	$343.18	$300.00	$312.50	$280.58	$295.16	$302.78
	($189 - $498)	($150 - $450)	($171 - $454)	($146 - $415)	($140 - $450)	($153 - $453)
Loss Time †	$6,523.57	$4,295.20	$5,503.56	$4,111.06	$3,595.50	$4,939.18
	($4,772 - $8,276)	($2,773 - $5,817)	($3,836 - $7,171)	($2,869 - $5,353)	($2,659 - $4,532)	($3,463 - $6,416)

§ Injury claim that incurred a cost, but no days away from work.

† Injury claim that involved days away from work.

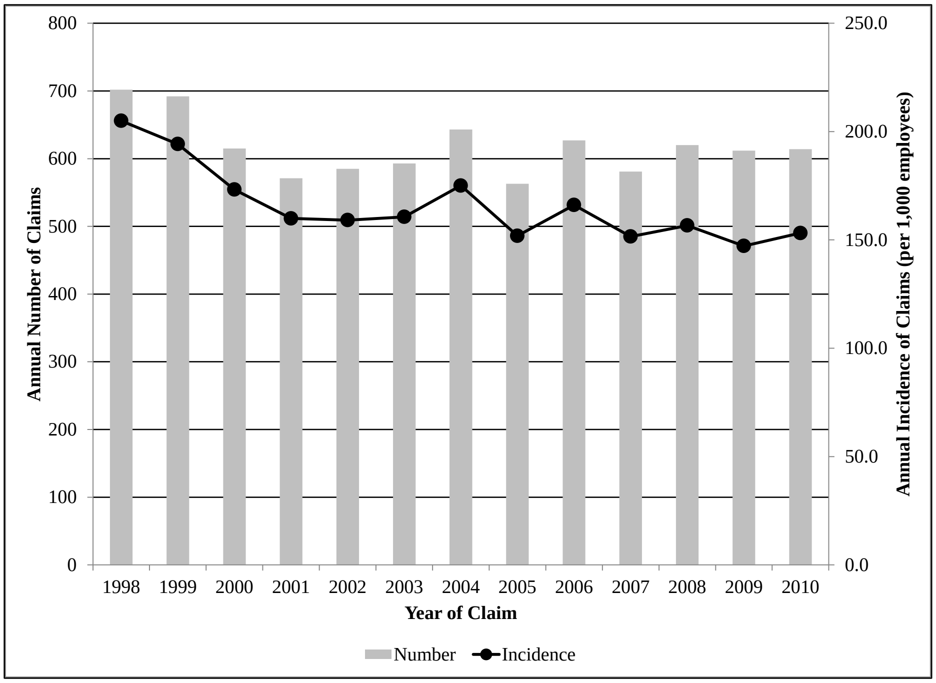

Figure 1
Annual injury counts and incidence for all Metro Transit Division employees, 1998-2010

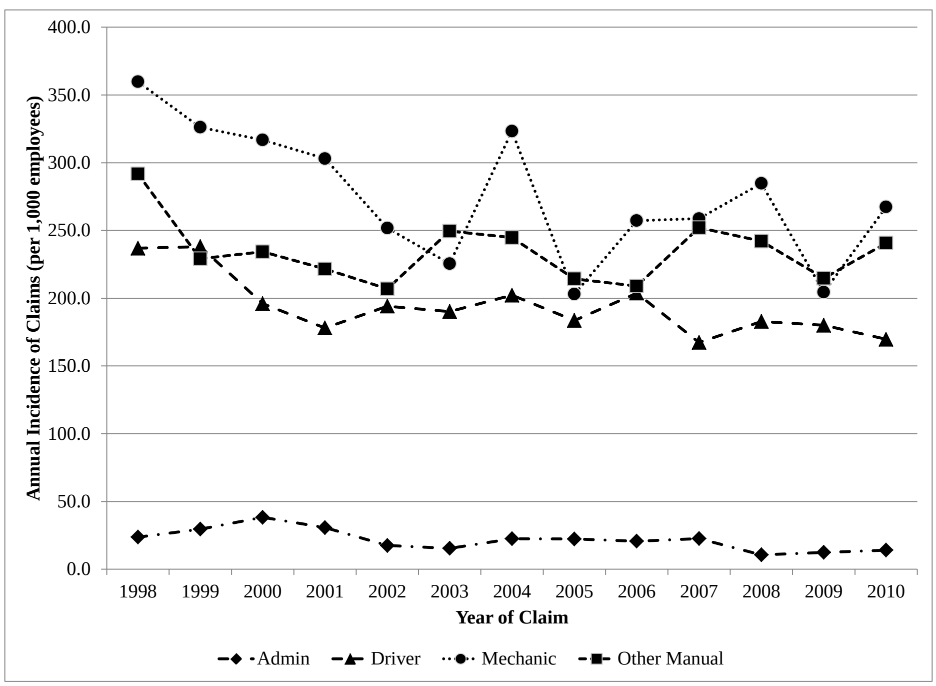

Figure 2
Annual incidence of injury claims for all Metro Transit Division employees by occupational category, 1998-2010

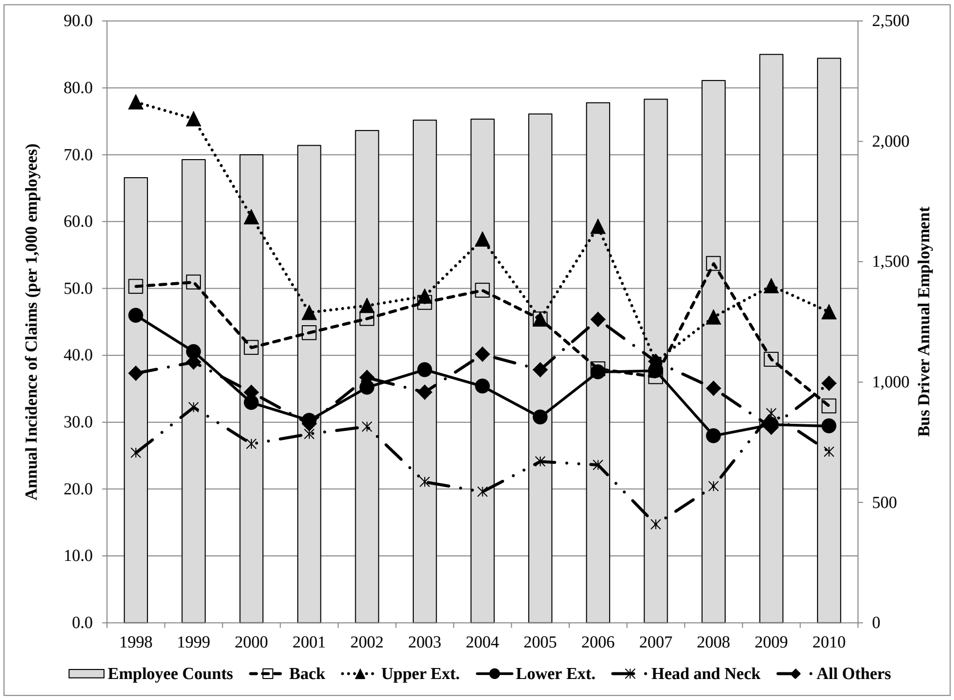

Figure 3
Annual employment and incidence of injury claims for all Metro Transit Division bus drivers by injury category, 1998-2010

The median number of days away from work was not significantly different across occupational categories when comparing all injury types (“All Claims”) (Table 4). The highest number of median days away from work for all occupation categories involved injuries to the upper extremities. The data show that males and females had similar results in median (IQI) days away from work: 26.0 (18.0 – 34.0) for males and 27.0 (20.0 – 34.0) for females.

Table 3
Metro Transit Division injuries incidence (per 1,000 employees) by job category, 1998-2010, (all claims, n = 8,018)

Job Category	Injury Category	Year												
		1998	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Drivers	***Employee Counts***	***1,849***	***1,924***	***1,944***	***1,983***	***2,045***	***2,088***	***2,092***	***2,114***	***2,160***	***2,175***	***2,253***	***2,361***	***2,345***
	Back	50.3	50.9	41.2	43.4	45.5	47.9	49.7	45.4	38.0	36.8	53.7	39.4	32.4
	Upper Ext.	77.9	75.4	60.7	46.4	47.4	48.9	57.4	45.4	59.3	39.1	45.7	50.4	46.5
	Lower Ext.	46.0	40.5	32.9	30.3	35.2	37.8	35.4	30.7	37.5	37.7	28.0	29.6	29.4
	Head and Neck	25.4	32.2	26.7	28.2	29.3	21.1	19.6	24.1	23.6	14.7	20.4	31.3	25.6
	All Other Injuries	37.3	39.0	34.5	29.8	36.7	34.5	40.2	37.8	45.4	39.1	35.1	29.2	35.8
Administrative	***Employee Counts***	***801***	***845***	***836***	***814***	***856***	***844***	***845***	***851***	***870***	***885***	***939***	***967***	***850***
	Back	2.5	4.7	6.0	9.8	2.3	5.9	4.7	3.5	3.4	5.6	3.2	1.0	3.5
	Upper Ext.	5.0	14.2	10.8	8.6	7.0	2.4	10.7	7.1	4.6	3.4	4.3	4.1	3.5
	Lower Ext.	2.5	5.9	7.2	6.1	3.5	3.6	2.4	2.4	6.9	5.6	1.1	2.1	2.4
	Head and Neck	7.5	1.2	4.8	2.5	1.2	1.2	-	3.5	-		4.5	3.1	-
	All Other Injuries	6.2	3.6	9.6	3.7	3.5	2.4	4.7	5.9	5.7	3.4	2.1	2.1	4.7
Other Manual Labor	***Employee Counts***	***497***	***515***	***508***	***510***	***493***	***485***	***470***	***476***	***469***	***488***	***471***	***517***	***511***
	Back	60.4	50.5	65.0	41.2	44.6	37.1	57.4	54.6	49.0	61.5	74.3	48.4	48.9
	Upper Ext.	86.5	64.1	53.1	70.6	58.8	82.5	63.8	50.4	57.6	73.8	51.0	54.2	70.5
	Lower Ext.	52.3	48.5	41.3	33.3	28.4	49.5	51.1	29.4	32.0	36.9	53.1	38.7	45.0
	Head and Neck	44.3	23.3	37.4	33.3	42.6	37.1	29.8	29.4	23.5	30.7	25.5	34.8	23.5
	All Other Injuries	48.3	42.7	37.4	43.1	32.5	43.3	42.6	50.4	46.9	49.2	38.2	38.7	52.8
Mechanic	***Employee Counts***	***278***	***279***	***262***	***264***	***282***	***275***	***266***	***266***	***276***	***286***	***295***	***313***	***303***
	Back	82.7	60.9	64.9	72.0	53.2	43.6	63.9	56.4	50.7	59.4	94.9	41.5	59.4
	Upper Ext.	107.9	107.5	103.1	72.0	81.6	90.9	90.2	33.8	68.8	62.9	54.2	63.9	69.3
	Lower Ext.	68.3	46.6	61.1	53.0	39.0	32.7	56.4	18.8	47.1	55.9	44.1	28.8	42.9
	Head and Neck	43.2	50.2	38.2	37.9	28.4	36.4	45.1	33.8	21.7	28.0	33.9	51.1	33.0
	All Other Injuries	57.6	60.9	49.6	68.2	49.6	21.8	67.7	60.2	68.8	52.4	57.6	19.2	62.7

With respect to back injuries, bus drivers had a median (IQI) number of days away from work of 21.0 (14.0 – 28.0). However, drivers with a low back injury had a median (IQI) number of days away from work of 23.5 (16.5 – 30.5), which was higher than the corresponding value for the other types of back injuries, 16.5 days (10.3 – 22.8). With respect to back injuries, males experienced a median (IQI) number of days away from work of 23.0 (15.0 - 31.0), which was close to the value for females, 21.0 days (15.0 – 27.0). Both males and females with upper extremity injuries missed the most time from work, with medians (IQI) of 36.0 days (27.0 – 45.0) and 42.0 days (33.0 – 51.0), respectively. Across all occupations, shoulder injuries resulted in the highest median (IQI) number of days away from work: 54.0 (40.0 – 68.0).

Hazards Analysis

For all injury claims, a Kaplan-Meier "survival" plot comparing drivers, mechanics, and other manual labor positions to the referent group (administrative positions) revealed that there was not a crossover between curves (Figure 4). This effect suggests that individuals in administrative positions generally work longer before developing an injury. In addition, males work slightly longer than females before developing an injury.

Adjusted hazard ratios were calculated to compare drivers, mechanics, and other manual labor positions to administrative positions, stratifying by gender and categorical age at injury (Table 5). Compared to administrative jobs, drivers have an increased hazard of developing back injuries in the workplace. This observation is also true for mechanics and other manual labor jobs, which resulted in an increased hazard relative to administrative jobs. However, the hazard ratios were not statistically significant.

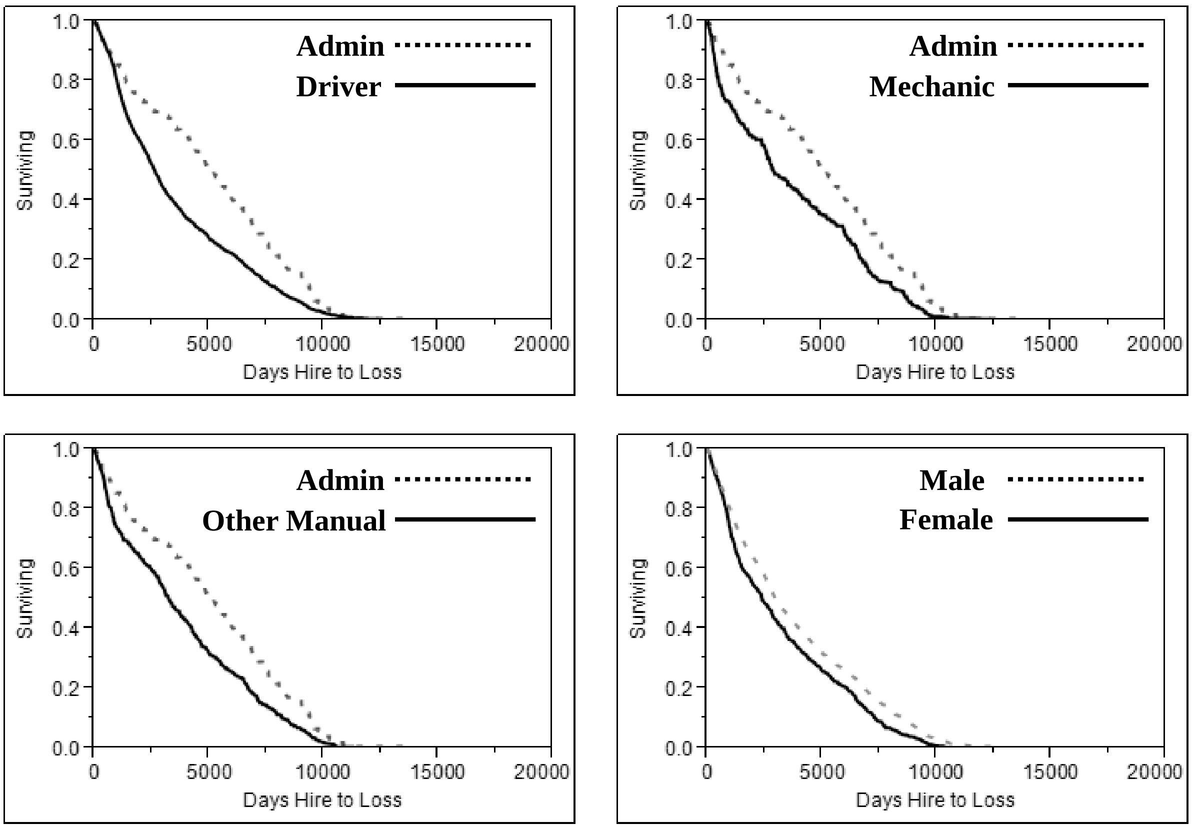

Figure 4
Kaplan-Meier survival plots comparing occupational categories and gender for first injury claims among Metro Transit Division injury claims

Table 4
Metro Transit Division median time loss days by occupational category, 1998-2010, (all loss time claims, n = 4,349)

	Injury Type					
Occupational Category	**Upper Ext.** (n = 1,235) Median (days) (25th - 75th)	**Back** (n = 1,013) Median (days) (25th - 75th)	**All Other Injuries** (n = 934) Median (days) (25th - 75th)	**Lower Ext.** (n = 841) Median (days) (25th - 75th)	**Head and Neck** (n = 326) Median (days) (25th - 75th)	**All Claims** (n = 4,349) Median (days) (25th - 75th)
Drivers	35.0	21.0	25.0	25.0	17.0	**25.0**
	(26.0 - 44.0)	*(14.0 - 28.0)*	*(16.0 - 34.0)*	*(19.0 - 31.0)*	*(13.0 - 21.0)*	***(18.0 - 32.0)***
Administrative	49.0	31.0	25.0	12.5	9.0	**27.0**
	(33.5 - 64.5)	*(19.5 - 42.5)*	*(22.0 - 28.0)*	*(7.5 - 17.5)*	*(5.5 - 12.5)*	***(19.0 - 35.0)***
Other Manual	41.5	26.0	27.0	23.5	19.0	**27.0**
	(31.5 - 51.5)	*(17.0 - 35.0)*	*(19.8 - 34.3)*	*(16.5 - 30.5)*	*(15.0 - 23.0)*	***(19.0 - 35.0)***
Mechanic	38.0	20.0	28.5	24.0	8.0	**26.0**
	(25.0 - 51.0)	*(13.0 - 27.0)*	*(22.5 - 34.5)*	*(15.0 - 33.0)*	*(5.0 - 11.0)*	***(18.0 - 34.0)***
All Occupations	**38.0**	**22.0**	**26.0**	**24.0**	**16.0**	**26.0**
	(29.0 - 47.0)	***(15.0 - 29.0)***	***(18.0 - 34.0)***	***(17.0 - 31.0)***	***(12.0 - 20.0)***	***(19.0 - 33.0)***

Table 5
Cox Proportional Hazards for Metro Transit Division employees, 1998-2010, (first claim per category, n = 5,569)

	Injury Type					
	Upper Ext.	**Back**	**All Others**	**Lower Ext.**	**Head and Neck**	**All Combined**
	(n = 1,445)	(n = 1,283)	(n = 1,078)	(n = 1,040)	(n = 823)	(n = 5,569)
Category	**HR (95% CI)**	**HR (95% CI)**	**HR (95% CI)**	**HR (95% CI)**	**HR (95% CI)**	**HR (95% CI)**
Job Category[1]						
Driver	1.21[b] (0.94 - 1.59)	1.40[a] (1.04 - 1.94)	1.37[a] (1.02 - 1.89)	1.71[a] (1.24 - 2.43)	1.11[b] (0.75 - 1.72)	1.35[a] (1.19 - 1.57)
Other Manual	1.16[b] (0.88 - 1.55)	1.13[b] (0.82 - 1.59)	1.29[b] (0.93 - 1.82)	1.56[a] (1.10 - 2.26)	1.03[b] (0.68 - 1.62)	1.23[a] (1.06 - 1.43)
Mechanic	1.20[b] (0.89 - 1.63)	1.33[b] (0.95 - 1.90)	1.60[a] (1.13 - 2.30)	1.79[a] (1.23 - 2.66)	1.16[b] (0.75 - 1.87)	1.41[a] (1.21 - 1.66)
Gender[2]						
Male	0.84[a] (0.75 - 0.95)	0.86[a] (0.76 - 0.98)	0.84[a] (0.73 - 0.97)	0.84[a] (0.73 - 0.98)	0.89[b] (0.76 - 1.06)	0.85[a] (0.80 - 0.91)
Age at Injury (years)[3]						
30 - 39	2.51[a] (1.90 - 3.27)	2.34[a] (1.72 - 3.14)	2.72[a] (1.78 - 4.01)	2.69[a] (1.90 - 3.74)	2.86[a] (1.91 - 4.15)	2.59[a] (2.24 - 3.00)
40 - 49	5.79[a] (4.40 - 7.50)	5.25[a] (3.87 - 6.98)	6.26[a] (4.12 - 9.15)	6.04[a] (4.29 - 8.30)	6.34[a] (4.27 - 9.12)	5.85[a] (5.06 - 6.74)
50 - 59	10.24[a] (7.73 - 13.37)	8.30[a] (6.07 - 11.12)	10.98[a] (7.17 - 16.17)	9.27[a] (6.50 - 12.93)	14.37[a] (9.53 - 21.06)	10.13[a] (8.72 - 11.71)
> 60	12.17[a] (8.87 - 16.57)	8.44[a] (5.94 - 11.86)	12.54[a] (7.91 - 19.33)	11.16[a] (7.53 - 16.33)	15.65[a] (10.02 - 23.97)	11.42[a] (9.66 - 13.47)

[1] Referent group - Administrative employees
[2] Referent group - Females
[3] Referent group - Employees < 30 years of age
[a] Statistically significant at P < 0.05 Pearson's chi-squared test.
[b] Not statistically significant at P < 0.05, Pearson's chi-squared test.

In addition to incurring back injuries, drivers were found to be at an increased risk for lower extremity injuries and "all other injuries" (Table 5). Mechanics and other manual labor positions were both at an increased risk of lower extremity injuries and "all other injuries." However, the hazard ratio was not statistically significant for other manual labor employees, relative to administrative positions for "all other injuries." Drivers, mechanics, and other manual labor positions were found to be at an elevated risk for injuries to the upper extremities, as well as for injuries to the head and neck, although the hazard ratio was not significantly different from that for administrative positions. Examining the effect of gender, males were found to be at a reduced hazard of all injuries relative to females, except for injuries to the head and neck. That effect, however, was not statistically significant. Additional analysis splitting out males and females for the proportional hazards model is presented in the Chapter 2 Appendix. Also included in the Chapter 2 Appendix is an analysis excluding all injuries that occurred less than five years from the date of hire. The resulting hazard ratios were similar to those for the data set that included the five-year lag, except for lower extremity injuries among mechanics and other manual laborers. These ratios, however, were not significantly different from those of the administrative employees after a five-year lag. Categorical age at injury showed that as age increased, the risk of all injury types increased relative to employees under the age of 30.

Discussion

To the author's knowledge, this is the first study to use a metropolitan transportation agency's injury database to explore the injury risk among professional bus drivers relative to other occupations. The study suggests that drivers are at approximately a 35% increased risk for occupational injury, compared to administrative positions at the same agency. Although this analysis does not examine specific injury causes, the results suggest that further analysis of bus driver injuries is warranted in order to explore possible interventions that could reduce injury incidence and loss-time costs. The study's findings have several important implications for employers of professional drivers. First, additional work is needed to examine the specific cause(s) of back injuries and other occupational injuries among drivers. Second, these results provide a baseline that can be utilized to test whether interventions in the workplace reduce the occurrence and cost of several types of injuries. Engineering interventions, as well as enhanced training programs and other administrative controls, could be developed and the injury trends then re-examined to determine if there is a reduction in the injury hazard ratios. Third, this approach could be utilized to analyze other injury databases (for both drivers and other occupations) to identify hazard ratios and injury prevention strategies.

This study showed that bus drivers were more likely to develop an occupational injury than were individuals in administrative positions. Mechanics and other manual laborers are also at an increased risk of injury relative to administrative workers. Although this study did not attempt to model injury causes – due to the lack of access to root cause information in the database – it is likely that the observed differences between occupations are due to differences in occupational exposures. These differences exist even after taking gender and age differences into account. The inclusion of other demographic variables (e.g., height, weight, marital status, smoking habits, and underlying medical conditions) in future studies would allow for more dissection of the contributions to injury. Unfortunately, while the study considered a fairly homogenous cohort of employees who had access to high-quality health care, it was not possible to assess the contribution of physical fitness or medical history to injury experience, and it was thus assumed that the observed injuries developed solely due to work activities. Previous research has shown that physical fitness is an important factor in the development of LBP among industrial populations, even when adjustments are made for MMH work tasks [14]. The fact that all Metro Transit Division employees have health insurance makes the differences in injury outcomes unlikely to be the result of poor health care, as is frequently the case with other professional driving occupations, such as truck drivers [15].

Although data limitations prevented a detailed explanation of specific injury causes, bus drivers are regularly required to perform high stress, repetitive work that often includes long hours of driving and exposure to WBV, both of which increase a driver's risk of occupational injuries [16, 17]. While the data on injury causes was limited in this study, the majority of the bus driver back injuries noted the cause of injury as either "driving" or "jarring/bouncing," which suggests that the majority of drivers considered the cause of their back injury to be related to driving exposures. These findings are consistent with other studies that have found high stress work and WBV exposure result in an increased risk for back injuries [18, 19].

These results must be interpreted within the limitations of the available data. The study utilized electronic injury and employment data collected for administrative purposes rather than an epidemiology study. There is a possibility that injury misclassification arose from the use of drop-down selections in entering occupational injuries, and that an injury type was selected for the expediency of the person completing the injury report. Occupations were stable for multiple claimants throughout the 13-year period of the study. However, these data did not allow for analysis of previous job titles or determine if the injured person selected a new career path based on his/her experience following the initial injury. The level of training among individuals assigning injury codes and types is unknown, and access to medical records was not available to crosscheck the type of injury selected with an actual medical diagnosis. Finally, it was not possible to identify a specific cause of injury other than what was noted. Hence, an assumption was made that injuries were the result of workplace activities. This assumption is likely valid, since (1) the hazard ratios presented were adjusted for available factors that may have contributed to injury and (2) although the physical fitness of claimants was not available, access to health care was universal across all employees.

This study had a number of strengths that validate its analysis approach. Included in the final database were 8,018 occupational injury claims over a 13-year period. This sample size allowed for significant power in the examination of the interaction between injury and job category. Using an electronic database of injury claims – as opposed to self-reported injury claims collected via a survey – minimized the possibility of recall bias. Employees have company-provided health care access, which most likely reduces the potential for claims to be associated with events that actually occurred outside the workplace.

In summary, the proportional hazard approach successfully identified bus drivers to be at an increased risk for back injuries, relative to other sedentary workers employed by the Metro Transit Division. While the limitations identified do not allow for the analysis of specific causes, the assumption of work-related exposure differences appears valid. The nationwide costs associated with back injuries to bus drivers total many millions of dollars annually. Administrative data that were not initially collected for use in an epidemiologic study can be used to calculate proportional hazard risks among occupations and possibly provide a basis for assessing the impact of injury prevention interventions.

Conclusions

Professional bus drivers are at an increased risk of developing back (40%), lower extremity (24%), and other occupational injuries (37%), relative to administrative employees working for the same metropolitan transit agency. Occupational injuries among bus drivers cost millions of dollars over the course of the 13-year period that the data were collected. These findings justify further exploration and allocation of resources to identify specific interventions to protect drivers from work-related exposures known to cause back injuries. The results presented in this study will permit prevention specialists, occupational health professionals, and management personnel to obtain a better understanding of the occupations that have an increased risk of developing occupational injuries.

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Chapter 2 Appendix

Table 6
Cox Proportional Hazards for Metro Transit Division
Male employees, 1998-2010, (first claim per category, n = 4,063)

	Injury Type				
	Upper Ext.	**Back**	**All Others**	**Lower Ext.**	**Head and Neck**
	(n = 1,028)	(n = 918)	(n = 771)	(n = 738)	(n =608)
Category	**HR (95% CI)**	**HR (95% CI)**	**HR (95% CI)**	**HR (95% CI)**	**HR (95% CI)**
Male					
Job Category[1]					
Driver	1.29[b] (0.91 - 1.91)	1.49[a] (1.00 - 2.36)	1.31[b] (0.87 - 2.11)	1.44[b] (0.85 - 2.71)	0.90[b] (0.56 - 1.56)
Other Manual	1.23[b] (0.85 - 1.84)	1.22[b] (0.80 - 1.95)	1.25[b] (0.81 - 2.03)	1.29[b] (0.75 - 2.46)	0.83[b] (0.51 - 1.44)
Mechanic	1.27[b] (0.87 - 1.92)	1.42[b] (0.92 - 2.28)	1.54[b] (0.99 - 2.52)	1.51[a] (0.87 - 2.90)	0.94[b] (0.57 - 1.66)
Age at Injury (years)[2]					
30 - 39	3.42[a] (2.43 - 4.74)	2.55[a] (1.71 - 3.70)	2.79[a] (1.63 - 4.49)	2.63[a] (1.73 - 3.89)	3.24[a] (2.02 - 5.04)
40 - 49	7.67[a] (5.49 - 10.54)	5.37[a] (3.63 - 7.68)	6.75[a] (3.97 - 10.79)	5.78[a] (3.82 - 8.45)	7.32[a] (4.61 - 11.18)
50 - 59	13.64[a] (9.67 - 18.88)	8.64[a] (5.81 - 12.44)	12.30[a] (7.20 - 19.81)	9.88[a] (6.45 - 14.67)	17.20[a] (10.64 - 26.85)
> 60	16.64[a] (11.39 - 24.02)	8.14[a] (5.26 - 12.31)	14.33[a] (8.12 - 24.08)	10.75[a] (6.76 - 16.73)	19.68[a] (11.80 - 31.94)

[1] Referent group - Administrative employees

[2] Referent group - Employees < 30 years of age

[a] Statistically significant at $P < 0.05$ Pearson's chi-squared test.

[b] Not statistically significant at $P < 0.05$, Pearson's chi-squared test.

Table 7
Cox Proportional Hazards for Metro Transit Division
Female employees, 1998-2010, (first claim per category, n = 1,506)

	Injury Type				
	Upper Ext.	**Back**	**All Others**	**Lower Ext.**	**Head and Neck**
	(n = 417)	(n = 365)	(n = 307)	(n = 302)	(n = 215)
Category	**HR (95% CI)**	**HR (95% CI)**	**HR (95% CI)**	**HR (95% CI)**	**HR (95% CI)**
Female					
Job Category[1]					
Driver	1.19[b] (0.83 - 1.77)	1.29[b] (0.84 - 2.11)	1.68[a] (1.09 - 2.74)	2.08[a] (1.40 - 3.23)	1.48[b] (0.77 - 3.28)
Other Manual	1.17[b] (0.73 - 1.89)	0.96[b] (0.56 - 1.70)	1.32[b] (0.74 - 2.36)	0.95[b] (0.62 - 1.44)	1.40[b] (0.65 - 3.37)
Mechanic	5.67[b] (0.91 - 19.14)	1.11[b] (0.06 - 5.41)	***No Females***	***No Females***	1.66[b] (0.25 - 6.69)
Age at Injury (years)[2]					
30 - 39	1.63[a] (0.99 - 2.56)	2.03[a] (1.23 - 3.23)	2.80[a] (1.34 - 5.26)	2.76[a] (1.43 - 4.98)	2.00[a] (0.87 - 4.03)
40 - 49	4.06[a] (2.49 - 6.32)	5.16[a] (3.11 - 8.20)	6.01[a] (2.90 - 11.15)	6.56[a] (3.44 - 11.57)	4.47[a] (1.95 - 8.96)
50 - 59	7.29[a] (4.38 - 11.66)	7.75[a] (4.56 - 12.64)	9.15[a] (4.34 - 17.46)	7.30[a] (3.74 - 13.26)	9.51[a] (4.03 - 19.93)
> 60	7.22[a] (3.97 - 13.05)	10.64[a] (5.55 - 20.49)	7.95[a] (3.36 - 18.17)	13.37[a] (6.07 - 29.02)	4.93[a] (1.84 - 12.81)

[1] Referent group - Administrative employees

[2] Referent group - Employees < 30 years of age

[a] Statistically significant at $P < 0.05$ Pearson’s chi-squared test.

[b] Not statistically significant at $P < 0.05$, Pearson’s chi-squared test.

Table 8
Five-Year Lag, Cox Proportional Hazards for Metro Transit Division employees, 1998-2010, (first claim per category, n = 4,120)

	Injury Type					
	Upper Ext.	**Back**	**All Others**	**Lower Ext.**	**Head and Neck**	**All Combined**
	(n = 1,035)	(n = 926)	(n = 805)	(n = 736)	(n = 618)	(n = 4,120)
Category	**HR (95% CI)**	**HR (95% CI)**	**HR (95% CI)**	**HR (95% CI)**	**HR (95% CI)**	**HR (95% CI)**
Job Category[1]						
Driver	1.31[b] (0.98 - 1.79)	1.51[a] (1.08 - 2.18)	1.58[a] (1.13 - 2.30)	1.64[a] (1.16 - 2.40)	1.24[b] (0.80 - 2.07)	1.47[a] (1.26 - 1.73)
Other Manual	1.20[b] (0.88 - 1.68)	1.06[b] (0.74 - 1.57)	1.41[b] (0.97 - 2.11)	1.42[b] (0.97 - 2.14)	1.09[b] (0.69 - 1.85)	1.24[a] (1.05 - 1.47)
Mechanic	1.17[b] (0.84 - 1.68)	1.39[b] (0.95 - 2.10)	1.71[a] (1.15 - 2.62)	1.51[b] (0.99 - 2.35)	1.21[b] (0.73 - 2.10)	1.41[a] (1.18 - 1.70)
Sex[2]						
Male	0.81[a] (0.70 - 0.94)	0.87[b] (0.74 - 1.01)	0.80[a] (0.68 - 0.95)	0.87[b] (0.73 - 1.05)	0.90[b] (0.74 - 1.09)	0.84[a] (0.78 - 0.91)
Age at Injury (years)[3]						
30 - 39	2.37[a] (1.24 - 4.11)	2.16[a] (1.13 - 3.75)	3.26[a] (1.14 -7.29)	2.90[a] (1.13 - 6.10)	3.22[a] (1.34 - 6.59)	2.55[a] (1.83 - 3.45)
40 - 49	6.17[a] (3.25 - 10.60)	4.62[a] (2.43 - 7.90)	8.21[a] (2.89 - 18.20)	6.96[a] (2.72 - 14.50)	8.06[a] (3.37 - 16.31)	6.12[a] (4.42 - 8.25)
50 - 59	10.89[a] (5.72 - 18.81)	7.47[a] (3.93 - 12.83)	15.03[a] (5.28 - 33.54)	11.44[a] (4.46 - 24.00)	19.11[a] (7.93 - 39.09)	10.92[a] (7.86 - 14.74)
> 60	12.97[a] (6.68 - 23.01)	7.09[a] (3.65 - 12.57)	15.05[a] (5.20 - 34.42)	12.79[a] (4.90 - 27.55)	20.24[a] (8.24 - 42.65)	11.65[a] (8.32 - 15.90)

[1] Reference group - Administrative employees

[2] Referent group - Females

[3] Referent group - Employees < 30 years of age

[a] Statistically significant at P < 0.05 Pearson’s chi-squared test.

[b] Not statistically significant at P < 0.05, Pearson’s chi-squared test.

Chapter 3: Development of Field-based WBV Exposure Assessment

Introduction

Back injuries are considered the most significant non-lethal medical condition afflicting American workers [1], with over 80% of adults experiencing back pain at some point in their lives [2]. Research has shown that there is an increased risk of low back pain (LBP) injury associated with increases in dose and duration of whole-body vibration (WBV) exposures [3]. There are numerous spinal injury mechanisms associated with WBV exposures, including structure damage to the boney endplates of the lumbar vertebral body [4]. The association between fatigue-induced micro-fractures and WBV exposure has been illustrated in in vitro studies of lumbar vertebral endplates. WBV may lead to subsequent disc degeneration [5-7]. Biomechanical and biological research has found that an increase in spinal load is associated with WBV exposure [8, 9], and that such loading causes muscle fatigue in the supporting musculature [10]. WBV-induced fatigue is linked to thinning of the intervertebral discs and subsequent disc herniation [11, 12]. Chronic occupational vibration exposure can lead to histological changes in cartilage, discs, muscle, and bone. The development of LBP is often gradual and insidious, which is to be contrasted to the acute development of LBP that is associated with MMH and lifting tasks [13].

In addition to musculoskeletal problems, WBV exposure also can affect the body’s cardiovascular, cardiopulmonary, metabolic, endocrine, nervous, and gastrointestinal systems [12]. Several WBV-associated disorders are strongly associated with impulsive shocks, which are particularly damaging to the body. Examples of impulsive shocks include machinery traveling over concrete roadway transitions and other rough surfaces, vehicles traveling over speed humps, and small boats impacting waves in rough seas. Recent research has shown that subjects have experienced short-term discomfort when exposed to multiple shocks [14]. Acute shocks are believed to have an adverse effect on the boney endplates of the lumbar vertebrae, with effects that are similar to those caused by long-term vibration exposures [4].

Background and WBV Standards and Regulations

Development of standards for WBV exposure began in the 1960s, and the ISO published ISO 2631 (“Mechanical vibration and shock − Evaluation of human exposure to whole-body vibration”) in 1974. The primary purposes of the current version of this standard are: (1) to define methods of quantifying WBV in relation to human health and comfort, (2) to establish a probability of vibration perception, and (3) to address the issue of motion sickness [15]. As research on WBV exposure has advanced, standards have evolved to address vibrations containing multiple shocks [4]. For example, ISO 2631 Part 5 (“Method for evaluation of vibration containing multiple shocks”) specifically addresses the adverse effects of multiple shocks on the lumbar spine, a dominating health risk of long-term exposure to WBV.

In the U.S., regulations governing the characterization, monitoring, and control of WBV exposures have yet to be established. However, both ANSI and ACGIH have adopted the ISO’s measurement and exposure evaluations for the purpose of suggesting exposure action and limit values, albeit without the force of regulation. In Europe, WBV monitoring and exposure limits have been established, and mandatory standards for employers have been implemented via regulatory directives. For example, EU Directive (2002/44/EC) was published to incorporate ISO 2631 Part 1 and previously published British standards into a regulation establishing an 8-hour average vibration exposure action limit (EAL) of 0.5 m/s^2 and an exposure limit value (ELV) of 1.15 m/s^2 [16].

Work Populations Exposed to WBV

Truck drivers, heavy equipment vehicle operators, and professional bus drivers are three of the many occupations in which workers are exposed to seated WBV during the course of their normal workday and that have been shown to result in the development of LBP [17-19]. These occupations provide a vital service to the economy, as they move goods to market, support construction projects, and provide safe transport of the public.

Professional Truck Drivers

Professional truck drivers deliver approximately 95% of the nation's goods to market, a task that is completed by a combination long-haul and short-haul drivers. This population of drivers consistently works long hours, often up to 11 hours per day and more than 60 hours per week. Truck drivers in the transportation and warehousing sector have consistently high injury rates, with the largest proportion of injuries occurring in the low back. Recent figures released by the U.S. Bureau of Labor Statistics (BLS) show that, among related job categories, truck drivers rank third in injury and illness incidence rates and sixth in the total number of injuries [20]. As well, when drivers are injured, they miss an average of 16 days from work, a figure that is twice the average of all workers.

Truck Driver Health Outcomes and Disease Risk

Truck drivers have been shown to have high rates of musculoskeletal disorders (MSDs), with a high prevalence of LBP [21]. Recent research has attributed this high injury rate to a combination of continuous WBV exposure, prolonged sitting, and MMH [22]. A recent prospective cohort study found strong associations between WBV exposure and driving-related LBP, while reporting evidence for a dose-response pattern among truck drivers [23]. Research on self-reported MSDs among professional truck drivers has shown that approximately 60% of drivers report LBP [21]. Additionally, in a recent prospective cohort study that included professional truck drivers, daily and cumulative vibration exposures were found to be associated with the risk of developing LBP over time [24].

In addition to establishing an association between WBV exposure and elevated MSDs, research has shown that the working conditions experienced by professional truck drivers are strongly linked to a variety of lifestyle-related diseases. For example, truck drivers have been shown to have high rates of alcohol-related diseases, increased Body Mass Index (BMI) relative to non-truck driver populations, high smoking rates, and an elevated risk of developing diabetes [25]. Increased rates of depression, occupational stress, and obesity (associated with drivers eating heavy meals at the end of the day and getting little exercise) have also been reported as increasing the disease risk for truck drivers [26]. Sleep apnea is also a condition associated with professional truck driving, and it has been identified as a risk to the general public, since it can result in vehicle crashes [27].

Professional Bus Drivers

Professional bus drivers serve a vital role in the public transportation system by working in urban and rural settings to transport large numbers of people between locations. In 2009, the BLS estimated that 417,000 people were employed in the transit and ground-passenger transportation industry in the U.S. This figure encompasses all interurban and rural bus transportation systems, urban transit systems, and school bus and charter bus transportation systems. The BLS further notes that this industry reported over 15,700 recordable injury cases in 2009, with approximately 9,700 (62%) of those cases involving days away from work. In 2009, the incidence rate of nonfatal occupational injuries for professional bus drivers was 7.3 (per 100 full-time workers), compared to an overall industry average of 3.7 [28].

Professional Bus Driver Health Outcomes and Disease Risk

Long-term exposure to WBV and postural stress have been identified as two leading causes of LBP among professional bus drivers [29]. In addition to WBV exposures and poor posture associated with driving, bus drivers are occasionally tasked with MMH, which generally occurs in this population when drivers assist elderly and wheel chair-bound passengers. Compared to other work populations, bus drivers have comparatively light MMH exposures; however, muscle fatigue associated with driving activity can result in an elevated risk of acute lifting injuries.

Recent research employing a prospective cohort designed to explore the relationship between city bus driving and low back injury revealed an exponential dose-response relationship between hours of weekly driving and low back injury risk. While the study did not involve the direct measurement of WBV exposures, it does illustrate the importance of reducing WBV exposures. Specifically, the study's authors found that each 10-hour increase in weekly driving was associated with a 12% increase in the risk of injury. The authors also found that part-time drivers were injured at much lower rates than full-time drivers were. These findings support the theory that administrative controls, such as limiting the number of hours of driving, have the potential to reduce injury rates [30].

Comparison to Non-Driver Population – HEV Operators

Heavy equipment vehicle (HEV) operators work in a variety of industries in support of construction projects and manufacturing operations; they are also employed by government agencies to keep streets clear of snow, for example. HEV operators commonly use front-end wheel loaders, graders, and other heavy equipment to perform their jobs.

HEV Operator Health Outcomes and Disease Risk

Recent epidemiology research employing a meta-analysis study design found the relative risk of LBP among HEV operators is 2.21, indicating that this work population has over twice the risk of developing LBP as do workers not employed as HEV operators [31]. The current body of research indicates that a causal relationship exists between WBV exposure and LBP for HEV operators [32]. However, the problem of determining the link between WBV and LBP outcomes is complicated by the fact that HEV operators frequently are required to perform physical labor, such as lifting and MMH tasks. Combined WBV and MMH exposures highlight the multi-factorial nature of LBP injuries among this working population [33].

In addition to the vertical impulsive exposure present in professional driving jobs and passenger vehicle travel, HEV operators' exposures are compounded by impulsive fore-and-aft exposures. The level of WBV experienced by professional HEV operators has been shown to be significantly affected by the speed of travel and by tire conditions, such as the inflation level and tire style (i.e., hard versus pneumatic) [34, 35].

Work assignments have a significant effect on the level of WBV exposure reaching HEV operators at the seat pan, and the magnitude of the tasks vary significantly with the size of the equipment being operated [36, 37]. Advancements in controls layout have been made to minimize upper extremity MSDs associated with repetitive reaching tasks. Some postural exposures associated with the layout and orientation of the cab remain and are continuously being improved through redesign [38].

Adding to the health risk of HEV operators is a significant obesity epidemic among this worker population. For example, from 1986 to 1995, obesity prevalence among HEV operators was among the highest (>19.2%) of any occupation in the United States, and this figure is increasing annually [39]. HEV operators' highly irregular work shifts contribute to difficult sleep schedules, thus increasing the risk for this work population to develop sleep disorders, which can result in occupational accidents [40].

Challenges in Quantifying WBV Exposure

Quantifying the risk of LBP from professional driving and operating equipment has proven challenging, largely because WBV exposure varies greatly between vehicle types. A recent study looking specifically at HEV operators determined that there is high variability in WBV exposure among vehicle types, and that more research is needed for an accurate classification of WBV exposures by vehicle [41]. Further complicating WBV exposure assessment among professional drivers and HEV operators is the fact that road type and seat construction have been found to significantly affect WBV exposure [42]. Additionally, driver weight significantly affects the ability of a seat to attenuate WBV exposure [43].

Current Control Options for Reducing WBV Exposures

ACGIH recommends the use of air-ride suspension seats, suspended cabs, proper maintenance of vehicle shock systems, proper tire inflation, and remote control of vibrating processes to remove the operator from the source. ACGIH also recommends the use of fully adjustable seats with arm rests and lumbar support to reduce WBV exposure [44].

As shown in Figure 5, there are several places on a vehicle or piece of heavy equipment where WBV can be reduced [38]. The vehicle suspension system (including the selection of tires) is the first place designers look to reduce vibration in a vehicle or piece of equipment. Vehicle suspension and proper tire selection are usually adequate to control WBV exposures in passenger vehicles. The next point for attenuating WBV in larger vehicles (such as long-haul semi-trucks and HEV equipment) is the cab of the vehicle. Many long-haul semi-truck manufacturers offer an air-suspended cab to reduce WBV exposures and increase ride comfort for truck drivers. Heavy-duty semi-trucks, urban transit buses, and pieces of heavy equipment use enhanced suspension systems to handle large amounts of weight. These enhanced suspensions, however, can limit the ability of the tires and suspension to attenuate vibrations, especially when the vehicle is empty. The last line of defense for attenuating vibrations reaching the operator’s seat pan is the suspension of the driver’s seat. Modern seat designs for most large trucks and pieces of heavy equipment rely on an air-ride suspended seat to accomplish this goal.

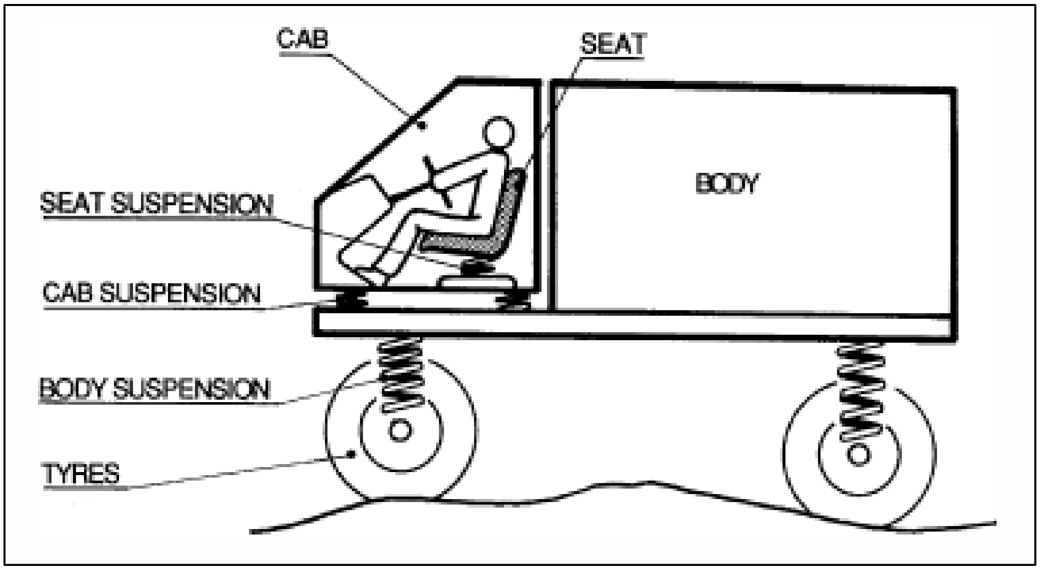

Figure 5
Potential vehicle suspension systems to reduce WBV [38]

Research on the use of Magneto-Rheological (MR) fluid damper seats has been conducted with the goal of evaluating the potential for preventing shocks from large impulsive events. MR fluid technology has been shown to reduce the potential for top-out and bottom-out events in the seat suspension, a source of great shock to drivers [45]. Additionally, within the agriculture industry, active seats that use electrohydraulic technology in combination with an air suspension have been introduced with the goal of smoothing the ride experience for tractor operators.

Hierarchy of Controls to Reduce WBV

Reducing WBV exposure can be accomplished using the accepted hierarchy of controls that is commonly applied to chemical and other physical hazards [46]. These controls are listed below, ranked in order of decreasing effectiveness.

1. Eliminate hazards and risk through system design and redesign (WBV: Vehicle and seating design)
2. Reduce risks by substituting less hazardous methods or materials (WBV: Surface maintenance and road design)
3. Incorporate safety devices

4. Provide warning systems (WBV: Prototype seat alarms when a driver exceeds an 8-hour WBV exposure)

5. Apply administrative controls (WBV: Route selection, work hour limitations, and job rotation)

6. Provide personal protective equipment (WBV: Aftermarket shock-resistant seat pads and additional seat cushions on the seat pan)

Categorizing WBV exposures by vehicle design, heavy equipment tire configuration, and seat suspension design attempts to address WBV exposure at the highest level in the hierarchy of controls. This field-based study uses a repeated measures design to compare WBV exposures among bus and truck drivers, specifically examining the influence of road type and seat suspension design. The hypothesis being tested is that there are not significant differences between vehicles and seat suspension designs in the attenuation of WBV exposures.

The first goal of this testing was to determine the viability of these systems to accurately evaluate the vibration exposure experience for professional drivers and HEV equipment operators who are regularly exposed to seated WBV. The second goal of the studies presented was to acquire data for use in the laboratory to test engineering interventions across WBV-exposed populations. The final goal was to compare field-based exposures with laboratory-based exposures as measured on a vibration simulation hexapod (Chapter 4).

Methods

Study Population

All participants in the research reported upon here were qualified to drive or operate the vehicle or HEV equipment tested, with qualifications determined by participating employers. The participant employer qualification attempted to minimize the variability associated with poor driving or operating skill that could be introduced by randomly recruiting drivers or HEV operators from the general population. To participate in the study, all bus and truck drivers were required to possess a commercial driver's license (CDL) and to have had a current bi-annual physical. The studies included in this analysis relied on the following study populations by work groups.

- Professional Truck Drivers (n = 16)
- Professional Bus Drivers (n = 12)
- Professional HEV Operators (n = 12)

Industry Collaboration

All data collection took place in conjunction with established working relationships between the University of Washington and several government and private entities that were interested in improving working conditions for their employees. King County Metro Transit (Seattle, Washington) provided resources to this research effort, including access to buses for data collection. The City of Valdez, Alaska, provided access to front-end loaders with three tire configurations for the testing and evaluation of WBV exposures among professional HEV operators. Industry participation was essential to the successful completion of this project, and several manufacturers of commercially available seats provided seats for testing purposes to evaluate the ability of varying seat designs to attenuate WBV exposures.

Subject Recruitment

Professional drivers and/or HEV operators who were employed by (or contracted through) the participating industry partners were recruited for participation in the field-based exposure evaluations. Subjects were recruited through word of mouth and with flyers posted at employer locations. The following inclusion criteria were used to select study participants:

1. For field-data collection activities, all subjects had to be licensed and/or qualified to drive the study vehicle. (Licensing and qualification were verified by the participating employers.)

2. All participants had to be willing to return for multiple data collection periods, as needed by the parameters of the individual data collection designs.

3. All participants had to be willing to commit and consent to participate in the study as part of the informed consent process.

4. To avoid a conflict of interest, employees of the OEM seat manufacturers were not included as subjects in the exposure assessment study.

5. All study subjects had to be willing to answer questions about demographic topics and their driving and/or operating habits.

Participation eligibility was assessed during the initial recruitment process with the help of industry partners. No information was gathered on interested participants who were found to be ineligible.

Informed Consent Process

As an integral component of the informed consent process, study participants were required to write their names and sign appropriate consent forms. The forms were the only documentation containing personal information, and the remaining data collection documents were coded to de-identify the subjects from their demographic, driving habit, and exposure information. Consent forms were retained for three years before being destroyed in compliance with the University of Washington Institutional Review Board.

Statistical Design

All processed WBV data files were exported to JMP Statistical Discovery Software (Version 10.0.0., SAS Institute, Cary, SC) for statistical analysis. In order to quantify exposure differences between test conditions and types of road or work tasks, repeated measures analysis of variance (RANOVA) methods were used. Each road type and work task was identified separately; seat suspension was a fixed effect, while subject was a random effect. Comparisons are made between field-collected WBV exposures among professional bus and truck drivers, as well as a comparison group of HEV operators. Models were fit to each of the regulated WBV exposure parameters (A(8), VDV(8), and S_{ed} (8)), and differences were considered significant when p-values were less than 0.05.

Instrumentation for WBV Measurement

Over the past decade, technological advancements have made the process of collecting WBV data increasingly efficient and less error prone. Portable, commercially available data collection systems are capable of collecting and storing vibration data at increasingly higher sampling rates. Additionally, the process of instrumenting vehicles and equipment for WBV data collection has become less arduous, since new systems are easier to deploy and troubleshoot and are more durable in field data collection settings.

First-Generation WBV Measurement Platform

Figure 6 shows the schematic and setup of the first-generation WBV data collection system. A Personal Digital Assistant (PDA)-based portable WBV data acquisition system was used to collect WBV exposures in accordance with ISO 2631 Parts 1 and 5. Raw, unweighted, tri-axial WBV measurements were collected at 640 Hz using a seat pad accelerometer (Model 356B40; PCB Piezotronics; Depew, NY) mounted on the driver's seat. Simultaneous z-axis measurements were collected with an identical accelerometer mounted with a thin layer of beeswax, designed to secure the accelerometer to the floor of the bus, immediately adjacent to the driver's seat [43]. This system was designed in the University of Washington's Ergonomics Laboratory and was successfully tested and used for two studies that evaluated WBV seat interventions [43, 47].

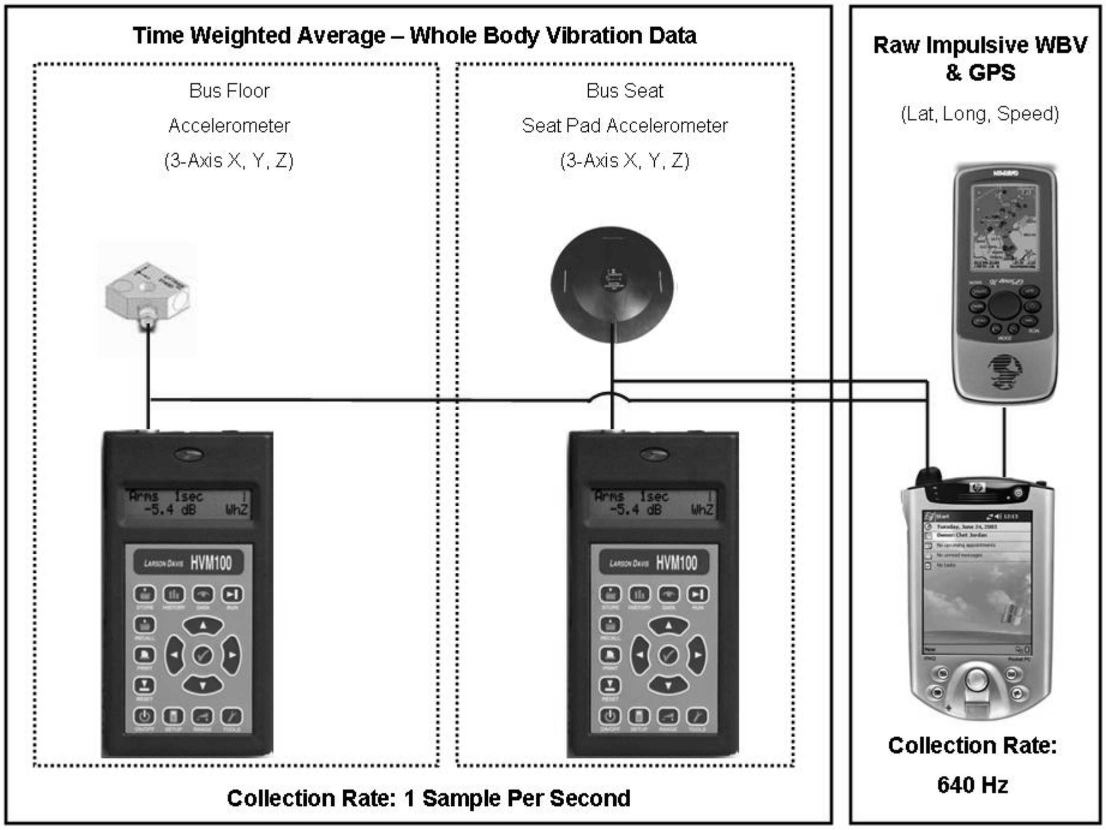

Figure 6
First-generation WBV data collection system (Tri-axial Seat and Z-axis Floor) [43]

Second-Generation WBV Measurement Platform

Figure 7 shows the schematic and setup of the second-generation WBV data collection system. A four-channel data recorder (Model DA-20; Rion Co.; Tokyo, Japan) was used as the data acquisition system to collect WBV exposures in accordance with ISO 2631 Parts 1 and 5. Raw, unweighted tri-axial WBV measurements were collected at 1,280 Hz per channel using a seat-pad ICP accelerometer (Model 356B40; PCB Piezotronics; Depew, NY) mounted on the driver's seat. Simultaneous z-axis measurements were collected with an identical magnet-mounted accelerometer secured to the floor of the vehicle, under the driver's seat. This system was designed in the University of Washington's Ergonomics Laboratory and was successfully tested and used to evaluate WBV interventions in HEV operators focused on tire conditions [48].

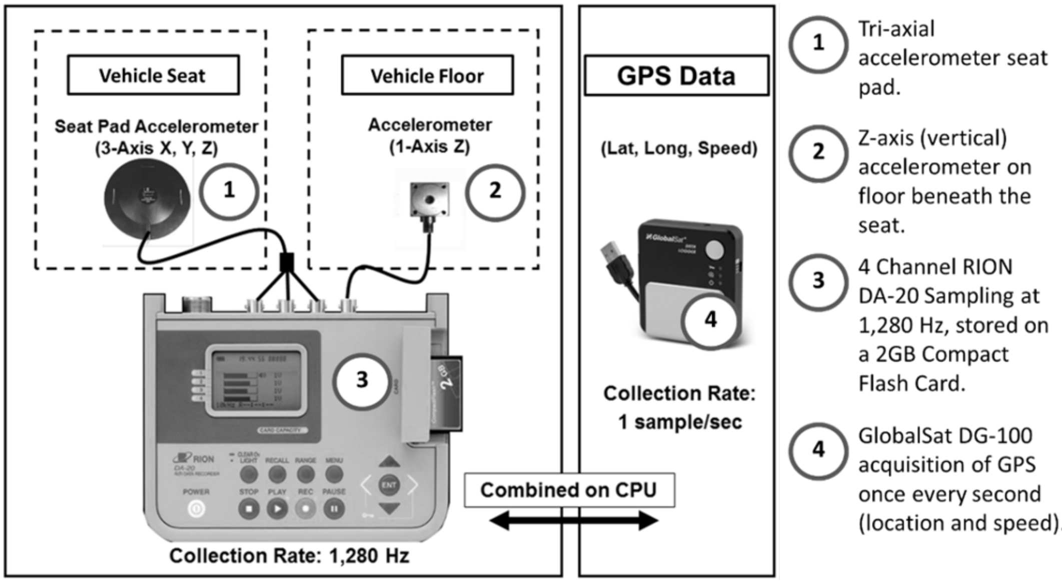

Figure 7
Second-generation WBV data collection
system (Tri-axial Seat and Z-axis Floor) [48, 50]

Third-Generation WBV Measurement Platform

Figure 8 shows the schematic and setup of the third-generation WBV data collection system. An eight-channel data recorder (Model DA-40; Rion Co.; Tokyo, Japan) was used to collect WBV exposures in accordance ISO 2631 Parts 1 and 5. The third data collection system provided the ability to collect tri-axial measurements at both the floor and the seat pan. This system was designed and tested in the University of Washington's Ergonomics Laboratory, and it was successfully used for a study to evaluate WBV interventions for professional bus drivers that focused on seat and road conditions [49].

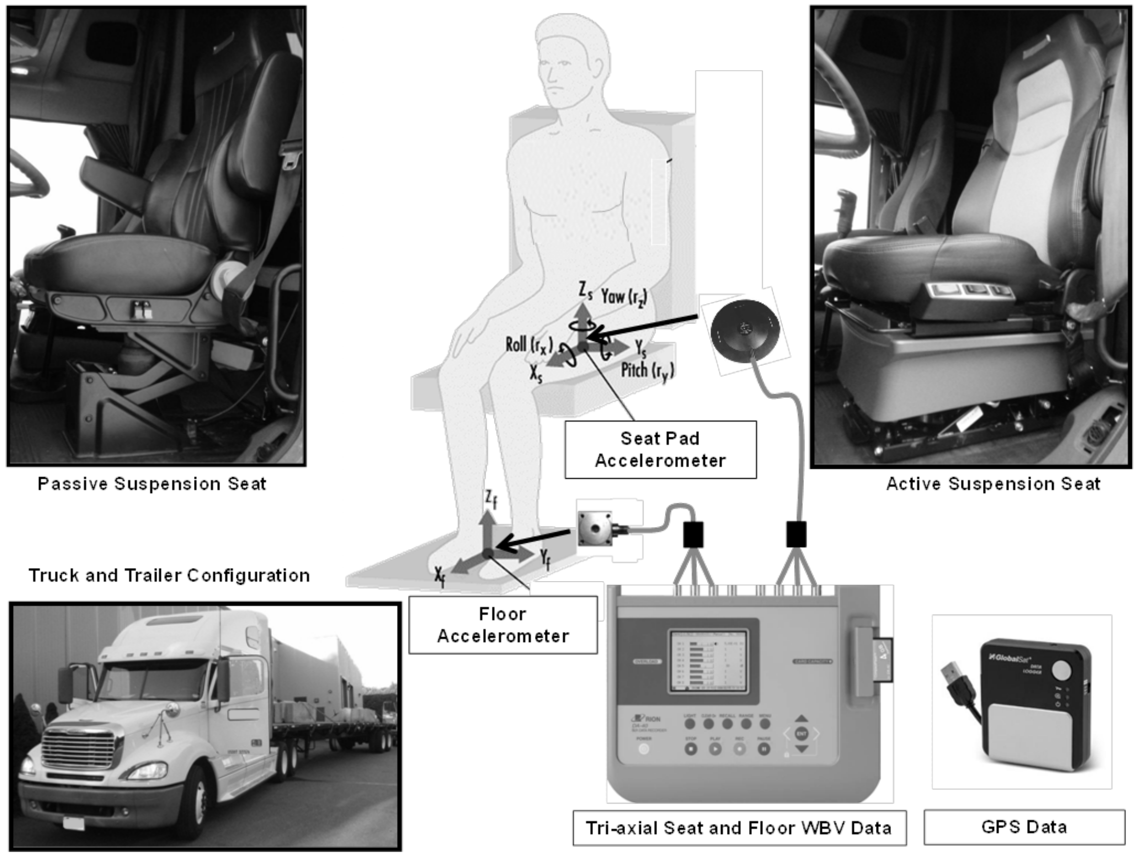

Figure 8
Third-generation WBV data collection system, seats, and truck configuration (Tri-axial Seat and Floor) [49]

As illustrated in Figures 7 and 8, a Global Positioning System (GPS) data recorder (Model DG-100; USGlobalSat, Inc.; Chino, CA) collected data to identify the location, velocity, and type of road associated with the WBV exposures. The sampling rate was 1 Hz. Data were stored on a 2-GB compact flash memory card (Model Extreme III; SanDisk Corp.; Milpitas, CA). In a post-processing program (LabVIEW; National Instruments; Austin, TX), the GPS and vibration measurements were synchronized. Accelerometer calibrations were conducted prior to all data collection sessions using Calibration Exciter (Type 4294, Bruel & Kjaer; Nærum, Denmark), with a 10 m/s^2 (rms), 159.2 Hz oscillation frequency. System calibrations were evaluated using a LabVIEW program written to analyze and verify calibration exciter measurements.

Data Analysis

Data collected on the data logger were downloaded to a PC after each run and processed with a LabVIEW routine. To facilitate the analysis of data by road type, the beginning and ending GPS coordinates were used to identify the beginning and end of the WBV data for each type of road segment. The start and stop times derived from the GPS data were also cross referenced with the start and stop times that were manually recorded by the researcher who observed the data collection process.

WBV measures were calculated over the whole route (all road segments), as well as by the individual segments or work tasks, depending on the work population. The individual segments were then weighted by duration to calculate a whole-route exposure for each of the WBV parameters. The ISO 2631 Part 1 parameters that were evaluated were normalized to an 8-hour exposure and compared based upon vehicles and road types. The parameters include the following:

- The root mean square average vibration, A(8), was calculated at both the floor and the seat pan of the vehicle (m/s^2).

$$A(8) = \left[\frac{1}{T} \int_0^T a_w^2(t)\, dt \right]^{\frac{1}{2}} \qquad (1)$$

- The vibration dose value, VDV(8), which is more sensitive to impulsive vibration and reflects the total vibration, not the average vibration, was calculated over the measurement period at both the floor and the seat pan of the vehicle (m/s$^{1.75}$).

$$VDV(8) = \left\{ \int_0^T \left[a_w(t) \right]^4 dt \right\}^{\frac{1}{4}} \qquad (2)$$

- The time-weighted average (TWA) peak, which is the highest magnitude of average vibration observed during the measurement period, was calculated (m/s^2). (The TWA peak is also referred to as the maximum transient vibration value, or MTVV.) The average daily dose (D_k) which is designed to be an estimate of daily vibration dose (m/s^2), was calculated using Eq. 3.

$$D_k(8) = \left[\sum A_{ik}^6 \right]^{\frac{1}{6}} \qquad (3)$$

- The static compressive dose, S_{ed}, which has been developed through biomechanical modeling to capture the linear relationship between peak acceleration and input shocks to responses in the spine, was calculated using Eq. 4. S_{ed} is measured in megapascals (MPa).

$$S_{ed}(8) = \left[\sum_{k=x,y,z} (m_k \, D_{kd})^6 \right]^{\frac{1}{6}} \tag{4}$$

where m_x = 0.015 MPa/(m/s^2), m_y = 0.035 MPa/(m/s^2), and m_z = 0.032 MPa/(m/s^2).

In addition to the WBV measures covered by Parts 1 and 5 of ISO 2631, the Raw (+) Peak (the highest vibration measured in the positive z-direction), the Raw (-) Peak (the highest average vibration measured in the negative z-direction), and the Seat Effective Amplitude Transmissibility (SEAT) values were calculated. The SEAT value provides a measure of how well a seat is suited to the spectrum of vibrations applied to it [42]. The calculation of the SEAT values for A(8) and VDV(8) are:

$$SEAT\ A(8)\ (\%) = \frac{A(8)_{seat}}{A(8)_{floor}} \times 100 \tag{5}$$

$$SEAT\ VDV(8)\,(\%) = \frac{VDV(8)_{seat}}{VDV(8)_{floor}} \times 100 \tag{6}$$

Finally, the vibration total value or vector sum has been proposed for exposure scenarios where there is more than one dominant axis of vibration exposure [15]. Vector sum exposures for A(8), VDV(8), and S_{ed}(8) were calculated using the following equation and variable values.

$$vector\ sum = ((a * \mathrm{Exp}(8)_x)^n + (b * \mathrm{Exp}(8)_y)^n + (c * \mathrm{Exp}(8)_z)^n)^{\frac{1}{n}} \tag{7}$$

where

for A(8):	*a* = 1.4	*b* = 1.4	*c* = 1	*n* = 2
for VDV(8):	*a* = 1.4	*b* = 1.4	*c* = 1	*n* = 4
for S_{ed}(8):	*a* = 0.015	*b* = 0.035	*c* = 0.032	*n* = 6

Results

Professional Truck Driver Field Study

Table 9 contains computations from a field-based study of professional truck drivers that was conducted on a standardized route in Framingham, Massachusetts. Data were collected with the third-generation WBV measurement platform. Images of the trucks and seats tested in the field-based professional truck driver study can be seen in Figure 9. Table 9 also shows the performance of two truck seats (an EM-active seat and a passive air-ride suspension seat), showing the daily vibration exposures – A(8), VDV(8), and S_{ed} (8) – by axis of exposure and road type.

There was a significant performance difference between seats in this study, particularly along the z-axis (vertical direction) (Table 9). Specifically, the EM-active suspension seat resulted in a 30-50% greater reduction in vibration exposure than the air-ride passive suspension seat across all road types. The vibration exposure differences between seats along the x- and y-axes were small – typically less than 10% – and they were not statistically significant [49].

Professional Bus Driver Field Study

Further results were obtained in a field-based study of professional bus drivers conducted on a standardized route in Seattle, Washington. Using the first-generation WBV measurement platform, data were collected for three types of bus seats: a passive air-ride suspension seat, a second air-ride passive suspension seat with a foam seat pan, and the same second passive air-ride suspension seat with a silicone seat pan. The bus and seats used in the study are shown in Figure 9.

Table 9
Professional Truck Drivers. Mean (±SE) seat-measured WBV exposures by axis and road type comparing the EM-active and passive air-ride suspension seats (n = 16) [49]

		1.4X ‡			1.4Y ‡			Z		
Parameter	**Segment**	**EM-Active**	**Air-Ride**	**p-value***	**EM-Active**	**Air-Ride**	**p-value***	**EM-Active**	**Air-Ride**	**p-value***
A(8) (m/s^2)	**Rough Road**	0.32 (±0.01)	0.38 (±0.02)	<0.01	0.49 (±0.01)	0.47 (±0.01)	NS	0.30† (±0.01)	0.64 (±0.02)	<0.001
	City Streets	0.20 (±0.01)	0.19 (±0.01)	NS	0.21 (±0.01)	0.21 (±0.00)	NS	0.13 (±0.00)	0.32 (±0.01)	<0.001
	Highway	0.22† (±0.01)	0.21† (±0.01)	NS	0.26 (±0.01)	0.25 (±0.01)	NS	0.16† (±0.00)	0.39† (±0.01)	<0.001
	Freeway	0.24 (±0.01)	0.23 (±0.01)	NS	0.27 (±0.01)	0.26 (±0.01)	NS	0.17† (±0.01)	0.38 (±0.01)	<0.001
VDV(8) ($m/s^{1.75}$)	**Rough Road**	6.5 (±0.2)	7.5 (±0.3)	<0.01	9.0 (±0.2)	8.6 (±0.2)	NS	7.0 (±0.3)	12.6 (±0.4)	<0.001
	City Streets	4.8 (±0.3)	4.4 (±0.3)	NS	4.4 (±0.2)	4.2 (±0.1)	NS	2.8 (±0.1)	6.6 (±0.2)	<0.001
	Highway	5.0 (±0.2)	4.9 (±0.3)	NS	5.0 (±0.1)	5.0 (±0.1)	NS	3.3 (±0.1)	7.7 (±0.1)	<0.001
	Freeway	4.7 (±0.2)	4.3 (±0.1)	NS	4.8 (±0.2)	4.7 (±0.1)	NS	3.7 (±0.1)	7.2 (±0.1)	<0.001
S_{ed}(8) (MPa)	**Rough Road**	0.12 (±0.01)	0.14 (±0.01)	<0.05	0.32 (±0.01)	0.29 (±0.01)	<0.05	0.30 (±0.03)	0.42 (±0.04)	<0.05
	City Streets	0.09 (±0.01)	0.08 (±0.01)	NS	0.15 (±0.01)	0.14 (±0.01)	NS	0.09 (±0.00)	0.19 (±0.01)	<0.001
	Highway	0.09 (±0.01)	0.1 (±0.01)	NS	0.17 (±0.01)	0.16 (±0.01)	NS	0.12 (±0.01)	0.23 (±0.01)	<0.001
	Freeway	0.09 (±0.01)	0.08 (±0.00)	NS	0.15 (±0.01)	0.14 (±0.00)	<0.05	0.13 (±0.01)	0.18 (±0.00)	<0.001

† Indicates crest factors were above 9.

‡ Multiplying factor of 1.4 was applied only to the A(8) and VDV(8) exposures.

* P-value compares EM-active and air-ride seats by axis.

Figure 9
Seats and bus tested in professional bus driver study [43]

The results of the performance of the seats by presenting the daily vibration exposures – A(8), VDV(8), and $D_k(8)$ – along the z-axis (the dominant axis) over the whole route can be found in Table 10. The performance differences between seats in this study were largely insignificant. That is, the three passive air-ride suspension bus seats had approximately equal abilities to attenuate floor-measured vertical vibrations.

Table 10
Professional Bus Driver. Mean (±SE) seat-measured WBV measurements over the whole route comparing z-axis floor- and seat-measured exposures by seat type (n = 12) [43]

Parameter	Accelerometer Location	p-value Seat 1 v. 2	Air-Ride 1 (Foam Pan)	Air-Ride 2 (Foam Pan)	Air-Ride 2 (Silicone Pan)	p-value Seat 2 v. 3
A(8) (m/s^2)	Floor	NS	$0.45^{\dagger}$ (± 0.01)	$0.43^{\dagger}$ (± 0.01)	$0.48^{\dagger}$ (± 0.02)	0.02
	Seat	NS	$0.41^{\dagger}$ (± 0.01)	$0.40^{\dagger}$ (± 0.02)	$0.40^{\dagger}$ (± 0.01)	NS
VDV(8) ($m/s^{1.75}$)	Floor	NS	12.0 (± 0.38)	12.2 (± 0.43)	11.9 (± 0.77)	NS
	Seat	NS	9.26 (± 0.27)	9.24 (± 0.42)	9.33 (± 0.36)	NS
D_k(8) (m/s^2)	Floor	NS	14.0 (± 1.06)	13.3 (± 0.67)	12.4 (± 1.10)	NS
	Seat	0.01	9.01(± 0.39)	11.5 (± 0.84)	12.1 (± 0.74)	NS
Speed (km/h)	–	0.13	55.7 (± 1.56)	53.1 (± 1.58)	57.5 (± 1.03)	0.04

† Crest factors were above 9.

Professional HEV Operator Field Study

The third set of results presented is from a field-based study of professional HEV operators that was conducted on a standardized route in Valdez, Alaska. Data were collected with the second-generation WBV measurement platform. Figure 10 shows the front-end loader that was used, while Figure 11 shows the three tire configurations that were analyzed: (1) tires without chains, (2) tires with chains in a ladder configuration, and (3) tires with chains in a basket configuration.

Figure 10
Front-end loader used to evaluate WBV exposures among professional HEV operators [48]

Figure 11
Tire configurations used to evaluate WBV exposures among professional HEV operators [48]

The WBV exposure performance across three tire configurations (rubber tires, ladder chains, and basket chains), showing the daily vibration exposures [A(8), VDV(8), and S_{ed}(8)] by axis of exposure over a standardized driving task suggests there is a significant performance difference. This is shown by comparing tire configurations in this study in the vertical direction (z-axis). The ladder style chains resulted in higher vibration exposures relative to the rubber tire and basket style chains (Table 11). The differences between tire conditions in the x- and y-axis vibration exposures were smaller, with the ladder tire condition consistently resulting in the highest y-axis vibration exposures and the rubber tire condition highest in x-axis exposures. There were small but statistically significant differences in speed between runs across tire conditions, with the rubber tire runs slightly faster than the ladder and basket chain tire conditions [48].

Table 11
Professional HEV Operators. Mean (±SE) WBV exposures by axis for a standardized driving task grouped by tire condition. Conditions with different superscripts are significantly different (n = 12) [48]

Parameter	Axis	Tire Conditions			p-value*
		Rubber	Ladder	Basket	
A(8) (m/s^2)	1.4 X	0.59^a (±0.01)	0.49^b (±0.02)	0.44^b (±0.02)†	0.01
	1.4 Y	0.39^a (±0.01)	0.59^c (±0.02)	0.45^b (±0.01)	<0.0001
	Z	0.47^a (±0.03)	0.74^b (±0.04)	0.46^a (±0.03)†	<0.0001
	Vector Sum	0.86^a (±0.03)	1.07^b (±0.05)	0.78^a (±0.04)	<0.0001
VDV(8) ($m/s^{1.75}$)	1.4 X	12.0^a (±0.2)	10.1^b (±0.4)	12.1^a (±0.7)	0.07
	1.4 Y	8.9^a (±0.4)	10.8^b (±0.4)	8.7^a (±0.3)	0.01
	Z	9.2^a (±0.9)	12.7^b (±0.8)	10.1^a (±1.1)	0.01
	Vector Sum	13.6 (±0.9)	14.9 (±0.8)	14.0 (±1.1)	NS
S_{ed}(8) (MPa)	1.4 X	0.26^a (±0.01)	0.21^b (±0.01)	0.28^a (±0.03)	0.04
	1.4 Y	0.40 (±0.03)	0.40 (±0.02)	0.37 (±0.03)	NS
	Z	0.37^a (±0.07)	0.36^a (±0.03)	0.48^b (±0.10)	<0.0001
	Vector Sum	0.44 (±0.07)	0.43 (±0.03)	0.50 (±0.10)	NS
Speed (km/h)	–	30.3^a (± 0.2)	26.6^b (± 0.2)	25.0^b (± 0.3)	<0.0001

† Crest factors were above 9.
* P-values compares all three tire conditions.

Discussion

The performance of three generations of WBV data collection systems in the quantification of vibration exposure differences were evaluated across a variety of vehicles, seats, and occupational exposure scenarios. The major finding of the testing (across the three generations of WBV data collection systems) was that the equipment is capable of accurately measuring WBV exposure differences between test conditions. As the data collection equipment advanced from the first to the third generation, it gained more ability to capture tri-axial vibrations at the floor and seat and make accurate speed and GPS positioning measurements. In large part, these improved capabilities resulted from the systems' increased data storage capacities and sampling speeds, which collectively have expanded the possibilities for quantifying occupational vibration exposures. As a result, engineering controls and administrative controls could be identified and applied with the goal of limiting or distributing WBV exposures based on road type, work tasks, and vehicle configurations. This technological advancement enables employers to identify interventions to reduce vibration exposures in a real world, field-based exposure setting.

The data collected were used to stimulate a vibration simulation hexapod to test engineering interventions across work groups in a controlled setting (Chapter 4). The data from the individual road segments (e.g., city streets, freeway, rough roads) were used to test the WBV attenuation performance of seats designed for the trucking market by testing the seats' ability to reduce vibration for professional bus drivers. These data were applied to a separate study with different worker populations in Framingham, Massachusetts. Finally, field-based exposures acquired using these technologies were compared to laboratory-based exposures on the vibration simulation hexapod.

Professional Truck Drivers – WBV Results Comparing Seats

The major finding of the professional truck driver study was the identification of performance differences in vibration exposure attenuation between an EM-active suspension seat and an air-ride passive suspension seat. These findings may contribute to decisions about the length of time a professional truck driver can operate his/her vehicle before reaching exposure action limits outlined by WBV standards. The most profound finding of this study was that there was a very significant difference in the vertical (z-axis) vibration exposures between the EM-active suspension seat and the air-ride passive suspension seat. More specifically, the EM-active suspension seat transmitted 30-60% of the floor-measured, vertical (z-axis) vibration to the operator seat pan, while the air-ride passive suspension seat transmitted between 90-120% of the vibration. That is, the air-ride passive suspension seat transmitted nearly three times the vertical vibration as the EM-active suspension seat [49].

Professional Bus Drivers – WBV Results Comparing Seats

This study employed a standardized setting to evaluate two types of seats and two types of seat pans (foam and silicone) to determine their respective abilities to attenuate vibration exposures.

Significant differences were identified between seats across impulsive exposures. However, no seat performed universally better across all road types. Significant exposure differences were identified across the controlled route road segments, thus leading to the conclusion that driver WBV exposures could be reduced by implementing an administrative control that required the rotation of drivers based on road types.

The first air-ride seat performed better in the attenuation of impulsive exposures (VDV(8)) relative to the second air-ride seat. However, both seats performed comparably across TWA vibration exposures (A(8)). The testing of seat pan material (foam versus silicone) used with the second air-ride seat did not reveal a statistically significant difference in WBV exposures. This was an important finding that enabled the employer of this professional bus driver population to include WBV-exposure comparisons in its seat pan procurement decisions [43].

Professional HEV Operators – WBV Results Comparing Tire Configurations

Within a standardized experimental setting, this study evaluated three different tire configurations across three controlled tasks common to the work experience of professional HEV operators. The first major finding of this study was that there were significant differences in vibration exposures between the basket and ladder chain tire conditions and similar exposures between the rubber tire (stock condition) and the basket change condition. The results of this study also showed that there was a relationship between speed and exposure when operating a front-end loader equipped with chains. The ladder chain condition produced significantly higher speed-related WBV exposures that either the rubber tire or the basket chain condition. This finding was most prevalent on the controlled driving work task that is summarized in Table 11.

The second major finding of this study was that there was a significant task-based difference in WBV exposures across controlled driving, scooping and dumping, and plowing tasks. However, the dominant axis of exposure was not universal across work tasks. During the driving task, the vertical (z-axis) exposure was dominant. However, the fore-and-aft (x-axis) and lateral (y-axis) exposures were dominant during the scooping and dumping and the plowing tasks [48]. If this population of drivers were working in the EU, this finding would be problematic for the application of the EU directive used to evaluate WBV exposures. That is, the EU directive requires that there be one dominant axis of exposure for the assessment of health effects [16]. This study revealed that within this occupational exposure scenario, the vector sum approach outlined in the ISO standard would be more applicable in the absence of a single dominant axis of exposure [15].

All of the studies presented in this chapter relied on the normalization of WBV exposures to represent an 8-hour workday. However, it is common for professional truck drivers, bus drivers, and HEV operators to work longer days, primarily at the direction of their employers. Therefore, reliance on 8-hour estimates of WBV exposures may underestimate the actual exposure duration often experienced by these worker populations. In future studies, the analysis of long-term WBV exposures on a larger population of drivers and operators on uncontrolled route assignments throughout their entire workday may provide a more accurate assessment of WBV exposures that contribute to low back injury.

Conclusions

Professional drivers and HEV operators have WBV exposures that are both job assignment dependent and task dependent. The dominant axis of exposure is usually in the vertical direction (z-axis), but this depends on the work scenario. Multiple axes of exposure are problematic if one wants to employ the EU directive for reducing occupational injuries. Depending on the vehicle and work assignment, the vector sum approach may be more appropriate [16]. As an alternative, the vector sum approach outlined in ISO 2631 Part 1 is more straightforward for assessing health effects in scenarios where all three axes contribute to WBV exposures. Previously published research on WBV among professional drivers and HEV operators indicates that the design of the seat suspension system plays a role in the amount of WBV exposure that reaches the driver's seat pan. Other factors include road type, task assignment, tire configuration, and hours of work.

Employers of professional drivers should consider the ability of modern seating equipment to attenuate WBV exposures. Such consideration should be particularly made during the procurement process. Future research on field-based exposures should be extended to include the evaluation of commercially available active and semi-passive seat suspension designs that attenuate WBV exposures in order to reduce occupational injuries in a variety of vehicle and equipment applications. Investment in advanced seats designed to reduce the transmission of WBV from the floor of a vehicle to the seat pan has the potential to reduce occupational injury claim costs. Such an investment would both represent a net gain for employers and protect employees from debilitating occupational injuries.

Chapter 3 Acknowledgements

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Chapter 4: Lab-based Intervention Testing

Introduction

Professional semi-truck and bus drivers regularly spend long hours in the seated position driving heavy suspension vehicles, which results in continuous exposure to WBV. Long-term exposure to seated WBV is one of the leading risk factors for the development of low back disorders, specifically low back pain (LBP). A prospective cohort study of professional drivers found strong associations between WBV exposure and LBP development associated with driving, reporting evidence for a dose-response pattern [1]. Epidemiology studies have shown an association between the development of occupational back pain and long-term exposure to WBV [2-4]. The risk for low back injury has been shown to increase as the duration and dose of WBV exposure increase [5-6].

According to the U.S. Bureau of Labor Statistics, truck drivers in the transportation and warehousing sector consistently rank higher in total recordable injury cases (5.2[5]) than the total private industry rate (3.5) and jobs with extended hours in the seated position (e.g., administrative assistants) (2.7) [7]. Contributing to this increased risk for injury is the requirement for professional truck drivers to work very long hours [8-9]. Physical exposures experienced by truck drivers, include WBV and prolonged sitting in a static position, increase drivers' risks for developing low back pain, sciatic pain, and degenerative disk disease [10].

Urban bus drivers represent a large population of professional drivers who are at risk for injuries, specifically LBP, possibly associated with vibration exposure. Up to 81% of professional bus drivers in the U.S. have reported developing LBP during the course of their work [11]. Similar to the situation with

5 Recordable injuries are measured in terms of "injuries per year per 100 full-time workers."

professional truck drivers, a strong association between WBV exposure and LBP development has been shown among professional bus drivers in several studies [12-14]. Complicating the effort to isolate the LBP development trend among professional drivers is the fact that research has indicated that up to 80% of the general U.S. population will develop LBP during their lives [15].

Spinal injury outcomes that have been associated with WBV exposures include damage to the structure of bony endplates of the lumbar vertebral body [16]. Through a process of material fatigue, micro-fractures have also been reported in in vitro lumbar vertebral endplates, which can lead to disc degeneration [17-19]. Biomechanical research has found that WBV elevates spinal loads [20-21], causes muscle fatigue in the supporting musculature [14], and is linked to thinning of the intervertebral discs and subsequent disc herniation [22-23]. Continuous vibration exposure in the occupational environment can lead to changes in cartilage, discs, muscle, and bone. Development of LBP from WBV exposure may appear gradually, which is different from the acute presentation of back pain associated with lifting injuries [14]. Chronic occupational vibration exposure can lead to changes in cartilage, discs, muscle, and bone, which can be observed by applying histological techniques. The onset of LBP associated with WBV may be gradual and insidious, which is very different from the acute presentation of back pain often associated with MMH and lifting tasks [24].

Chronic exposure to WBV also can affect the body's musculoskeletal, cardiovascular, cardiopulmonary, metabolic, endocrinologic, nervous system, and gastrointestinal systems [21]. Impulsive shocks associated with large bumps are particularly damaging to the health of seated persons [16], and research has shown that acute spinal shocks are significantly damaging to the thoracic lumbar region [25]. Recent research has also illustrated significant discomfort among subjects exposed to short-term, multiple vertical (z-axis) shocks [26].

Air-ride seats currently dominate the market for semi-trucks and transit buses. This technology relies on passive vibration reduction by utilizing a compressed air bladder to attenuate WBV exposure. The air-ride seat design provides seat pan vibration isolation from vibrations measured at the road. However, impulsive shocks can cause large oscillatory vibrations, resulting in WBV exposure amplification. The air-ride seat design is often slow to respond to impulsive shocks, limiting the seat's ability to attenuate this significant exposure. The air-ride truck and air-ride bus seats both rely on an air bladder and mechanical scissor to control suspension travel and seat height.

A new technology has recently been introduced for the semi-truck market that utilizes an electromagnetically active (EM-active) seat suspension. This technology relies on a built-in microprocessor and a linear actuator to continuously and rapidly control vertical (z-axis) vibration-induced seat motion. This technology is designed to attenuate low frequency oscillations, as well as high frequency impulsive exposures. The purpose of this study is to evaluate the ability of the EM-active seat to attenuate WBV exposures, as compared to the widely available air-ride truck and air-ride bus seats. Additionally, this study compares WBV exposure by road types and subject weight classes, including the measurement of vertical vibration transmission from the floor, seat pan, and sternum of subjects. The hypothesis for this study is that the EM-active seat does not perform significantly better than the air-ride seat at attenuating WBV exposures.

Methods

Study Population

Twelve healthy subjects (including ten professional truck drivers) were recruited for this study. The subjects had a mean (± SD) age of 36.8 (± 9.4) years, were 182.0 (± 9.0) cm tall, weighed 112.0 (± 35.0) kg, and had a BMI of 34.0 (± 9.0). (See Table 12.) Subjects were approached by a recruitment flyer and, if selected, were given a monetary incentive for their participation in the study. Subjects were selected based on their body mass to compare groups at the light (<102 kg) and heavy (>128 kg) ends of the spectrum to model weight effects on vibration exposure. All subjects gave informed consent, and all study procedures were approved by the Institutional Review Board at the University of Washington.

Table 12
Subject demographics. All subjects grouped by their weight to generate two categories: light (<102 kg) and heavy (>128 kg) [n = 12]

Subject	Gender	Age *(Years)*	Height *(cm)*	Weight *(kg)*	Body Mass Index *(BMI)*	BMI Category	Professional Driver
Heavy 1	Male	40	175.3	128.2	41.7	Obese	Yes
Heavy 2	Male	43	182.9	136.3	40.7	Obese	Yes
Heavy 3	Male	41	188.0	147.4	41.7	Obese	Yes
Heavy 4	Male	43	198.1	141.6	36.1	Obese	Yes
Heavy 5	Male	32	188.0	151.5	42.9	Obese	Yes
Heavy 6	Male	48	182.9	150.0	44.8	Obese	Yes
Avg. (SD)	–	*41 (±5.3)*	*186 (±7.6)*	*143 (±9.0)*	*41 (±2.9)*	–	–
Light 1	Male	53	175.3	71.9	23.4	Normal	Yes
Light 2	Male	25	175.3	75.0	24.4	Normal	Yes
Light 3	Male	33	172.7	77.8	26.1	Overweight	Yes
Light 4	Male	26	180.3	98.2	30.2	Obese	No
Light 5	Male	35	190.5	102.2	28.2	Overweight	Yes
Light 6	Male	23	165.1	58.3	21.4	Normal	No
Avg. (SD)	–	*33 (±11.1)*	*177 (±8.5)*	*81 (±16.7)*	*26 (±3.2)*	–	–
All Avg. (SD)	–	*37 (±9.4)*	*181 (±9.1)*	*112 (±35)*	*34 (±8.7)*	–	–

Vibration Simulation Testing Procedure

The testing procedure for this study involved using a vibration simulation hexapod (Moog Inc., 6 Degree-of-Freedom Electric Motion Platform) to playback WBV exposures collected from a semi-truck and city transit bus field study (Chapter 3). The WBV exposures included in this study were 180-second signal clips taken from two separate standardized routes designed to simulate common exposures experienced by professional bus and truck drivers. The standardized route used to collect field data was developed with input from managers of bus and truck fleets, and it included three common road types. The semi-truck route used to collect data for use with the vibration simulator platform included (1) a segment of city streets, (2) a freeway segment, and (3) a section of rough streets from an industrial sector near Framingham, Massachusetts. The bus route data used with the vibration simulator platform included (1) a segment of city streets, (2) a freeway segment, and (3) a section of rough road, all of which were taken from a standardized route in Seattle, Washington [27].

To determine whether there were differences in WBV exposures due to seat suspension designs and road conditions, each subject rode the hexapod on all three seats: an air-ride suspension bus seat, an air-ride suspension truck seat, and an EM-active suspension seat currently available for the trucking industry (Figure 12).

Figure 12
Three seats used in the WBV simulations

Vibration Simulation Platform

Two subjects rode the hexapod simultaneously, with a tri-axial accelerometer mounted (1) on the floor of the platform, (2) on the seat pan of each seat, and (3) at the sternum of each subject (Figure 13).

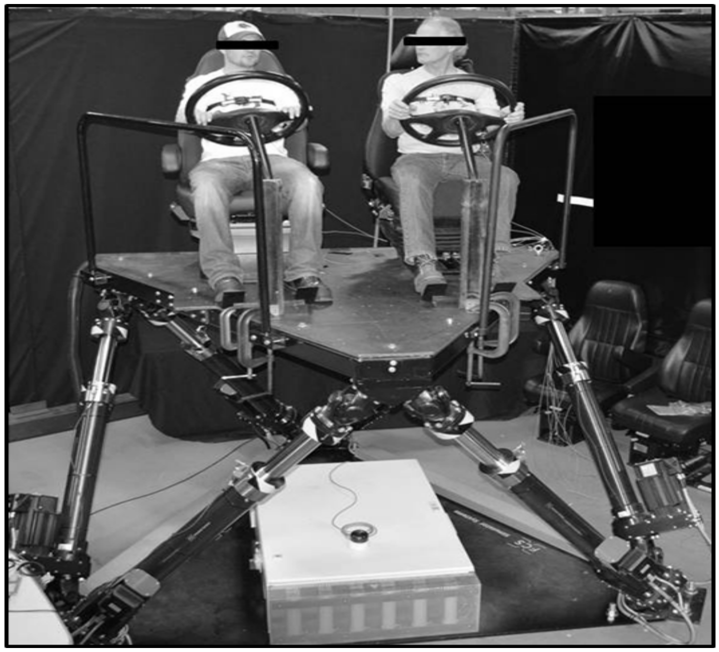

Figure 13
Light weight subjects (<120 kg) on the vibration simulator hexapod

Data Collection Hardware

An eight-channel data recorder (model CoCo 80; Crystal Instruments Inc., Santa Clara, CA) was used as the data acquisition system to collect WBV exposures per ISO 2631 Parts 1 and 5 at the seat pan and sternum of each subject. Raw, unweighted tri-axial WBV measurements were collected at 1,280 Hz per channel using a seat pad ICP accelerometer (Model 356B40; Frequency Range 0.5 – 1,000 Hz, PCB Piezotronics; Depew, NY) mounted on each subject's seat. In addition, tri-axial measurements were collected with an identical tri-axial accelerometer secured to the sternum of each subject using a heart-rate monitor strap and double-sided tape. Finally, tri-axial measurements were collected with a third identical tri-axial accelerometer secured to the floor of the platform with a magnet mounted directly between the subjects' seats. Accelerometer calibrations were verified prior to all data collection sessions.

Data Analysis

Using an interactive program (LabVIEW 2010; National Instruments; Austin, TX), the vibration measurements were combined into a single data file. They were then input into a second routine that analyzed the WBV data. The program also allowed visual verification of the simulation segments to confirm that the correct part of the data file was being analyzed.

Since it is very common for professional bus and truck drivers to work at least 8 hours a day, the ISO 2631 Part 1 time-weighted average parameters were normalized to represent an 8- hour exposure [28]. The WBV data from each simulation segment were normalized using the following equations:

$$A(8) = A_w \left[\frac{\text{exposure time (sec)}}{28{,}800\,\text{(sec)}} \right]^{\frac{1}{2}} \tag{8}$$

$$VDV(8) = VDV \left[\frac{\text{exposure time (sec)}}{28{,}800\,\text{(sec)}} \right]^{\frac{1}{4}} \tag{9}$$

$$D_{kd}(8)\ \&\ S_{ed}(8) = D_{kd}\ \text{or}\ S_{ed} \left[\frac{\text{exposure time (sec)}}{28{,}800\,\text{(sec)}} \right]^{\frac{1}{6}} \tag{10}$$

where A_w, VDV, D_{kd}, and S_{ed} are defined below.

The rms average weighted vibration, A_w, was calculated at the floor of the platform, at the seat pan of the subjects seat, and at the sternum of each subject (units m/s^2) for each road segment, as shown in Eq. 8, normalized to an 8-hour daily exposure [A(8)]. The ISO 2631 Part 1 A(8) daily action limit (AL) value (0.5 m/s^2) and exposure limit (EL) value (0.8 m/s^2) are recommended to reduce the likelihood of adverse health effects.

$$A_w = \left[\frac{1}{T} \int_0^T a_w^2(t)\, dt \right]^{\frac{1}{2}} \tag{11}$$

The vibration dose value (VDV) defined in Eq. 9 was calculated at the floor of the platform, the seat pan, and the sternum of each subject (units $m/s^{1.75}$) and then normalized to an 8-hour daily exposure [VDV(8)]. VDV is more sensitive to impulsive vibration than A_w and reflects the total, cumulative vibration, as opposed to average vibration. The ISO 2631 Part 1 VDV(8) daily AL (9.1 $m/s^{1.75}$) and EL (14.8 $m/s^{1.75}$) are recommended to prevent adverse health effects.

$$VDV = \left\{ \int_0^T \left[a_w(t) \right]^4 dt \right\}^{\frac{1}{4}} \qquad (12)$$

The crest factor was also calculated. The crest factor is defined in ISO 2631 Part 1 as the modulus of the ratio of the maximum instantaneous peak value of the frequency-weighted acceleration signal to its rms value. This measure is relevant in determining whether the rms parameter (A_w) is effective in characterizing WBV. The ISO standard states that when crest factors are greater than 9, the A_w should be interpreted with caution. Static compressive stress (S_{ed}) – as defined in ISO 2631 Part 5 – was also evaluated at the seat pan of the subject and then normalized to an 8-hour exposure [S_{ed}(8)]. (See Eq. 10.) S_{ed} has been developed through biomechanical modeling to capture the linear relationship between peak acceleration and input shocks to responses in the spine.

An intermediate step in calculating S_{ed} was calculating the acceleration dose (D_{kd}), which is designed to estimate the vibration dose. D_{kd} is measured in m/s^2.

$$D_{kd} = \left[\sum A_{ik}^6 \right]^{\frac{1}{6}} \qquad (13)$$

S_{ed} was calculated using the D_{kd} values from the x-, y-, and z-axes:

$$S_{ed} = \left[\sum_{k=x,y,z} (m_k D_k)^6 \right]^{\frac{1}{6}} \qquad (14)$$

where m_x = 0.015, m_y = 0.035, and m_z = 0.032 (units $MPa/m/s^2$).

According to ISO 2631 Part 5, $S_{ed}(8)$ values less than 0.49 MPa represent a low probability of an adverse health effect (AHE); values in the range 0.5– 0.79 MPa represent a moderate probability of an AHE, and values above 0.8 MPa represent a high probability of an AHE.

Finally, the vibration total value (vector sum) has been proposed for exposure scenarios where there is more than one predominant axis of vibration exposure (ISO 2631 Part 1, 1997). Vector sum exposures for A(8), VDV(8), and $S_{ed}(8)$ were calculated using the following equation:

$$\textit{vector sum} \; = \; ((a * \mathrm{Exp}(8)_x)^n + (b * \mathrm{Exp}(8)_y)^n + (c * \mathrm{Exp}(8)_z)^n)^{\frac{1}{n}} \tag{15}$$

where	for A(8)	$a = 1.4$	$b = 1.4$	$c = 1$	$n = 2$
	for VDV(8)	$a = 1.4$	$b = 1.4$	$c = 1$	$n = 4$
	for $S_{ed}(8)$	$a = 0.015$	$b = 0.035$	$c = 0.032$	$n = 6$

Data Processing and Statistical Analyses

The vibration platform configurations were analyzed with a LabVIEW routine, and output files with the ISO 2631 Part 1 and Part 5 summary parameters were created. These files were then used to determine whether there were differences in WBV exposures between road types (city streets, freeway, and rough roads) and the seat suspension designs (air-ride truck seat, air-ride bus seat, and EM-active seat) for both the bus and truck road signals. A repeated-measures analysis of variance was selected using JMP Statistical Discovery Software (Version 10.0; SAS Institute; Cary, SC). Differences in vibration exposure by road type and seat design were considered significant when p-values were less than 0.05.

The power spectral densities (PSDs) show the distribution of vibration over the frequency over the range of 0 to 30 Hz. The relation between the PSDs at the seat- and sternum-mounted accelerometers provides a measure of the vibration transmission from the seat to the spine of a subject. A typical PSD diagram for the seat and sternum transfer function is shown in Figure 14.

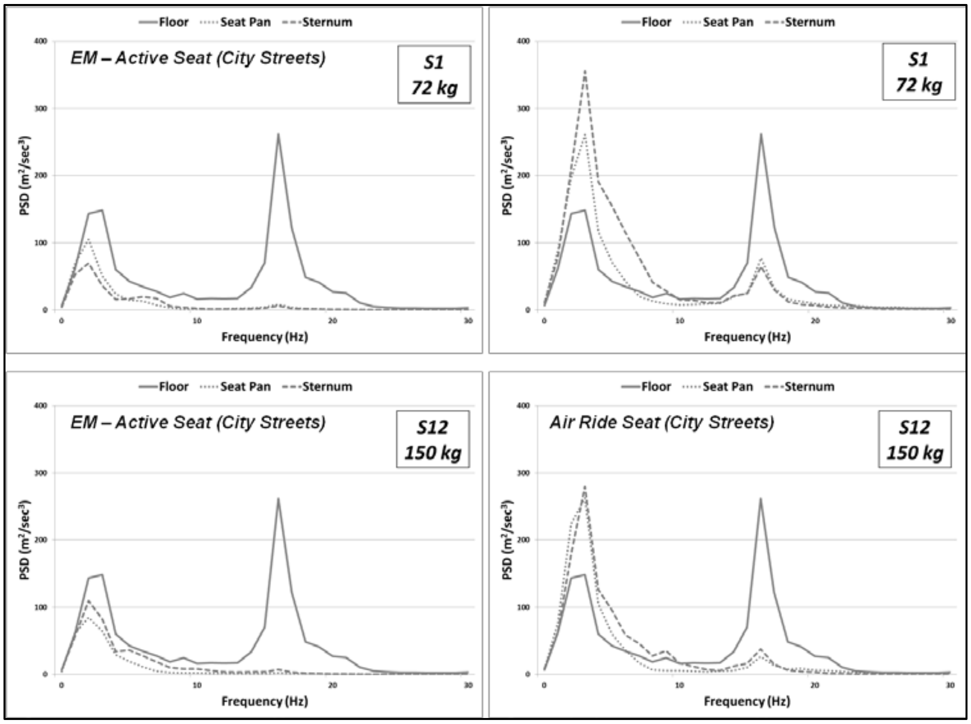

Figure 14
EM-active and air-ride seat PSD comparison in the vertical (z-axis) direction floor, seat, and sternum for a light weight subject and a heavy weight subject

Statistical comparison of the PSD analysis of vibration transmission between the EM-active and air-ride seat were calculated using JMP. A one-way analysis of variance (ANOVA) was performed at the low peak (1-5 Hz) and high peak (14-18 Hz) to study the effect of the seat on the vertical (seat pan to sternum) transmission. The null hypothesis, H_0, was that the means would be equal between seats, and the alternative hypothesis, H_1, was that they were different.

Results

Truck Signal Seat Performance by Weight Class

Table 13 shows truck signal vibration exposures by axis, averaging the exposures by seat condition and weight class. As can be seen in the table, there were significant differences in exposures between the air-ride truck and EM-active seats across the city street, freeway, and rough road segments. The air-ride truck seat universally had the highest exposures in the z-axis, with the largest exposures in the rough road segment. The EM-active seat had the highest exposures in the y-axis, with the largest exposures also coming in the rough road segment; however, the exposures were not statistically different from those of the air-ride truck seat. The trend for both the air-ride truck and EM-active seats held for both the A(8) and VDV(8) parameters. To compare exposures across seat conditions with different dominant axes, it was necessary to compare the vector sum values. Focusing on the vector sum, the EM-active seat performed significantly better than the air-ride truck seat, for both the light and heavy weight classes, across the A(8), VDV(8), and $S_{ed}(8)$ parameters on all road types ($\alpha = 0.05$).

Bus Signal Seat Performance by Weight Class

Table 14 shows bus signal vibration exposures by axis, averaging the exposures by seat condition and weight class. As with the truck signal, there were significant differences in exposures between the air-ride bus and EM-active seats across the city street, freeway, and rough road segments. The air-ride bus seat universally had the highest exposures in the z-axis, with the largest exposures in the rough road segment. The EM-active seat also had the highest exposures in the z-axis, with the largest exposures also coming in the rough road segment, although at levels significantly lower than the air-ride bus seat. The trend for both the air-ride bus and EM-active seat held for both A(8) and VDV(8). To compare exposures across the truck signal (Table 13) and bus signal (Table 14), with different dominant axes, it was necessary to compare the vector sum values. Focusing on the vector sum, the EM-active seat performed significantly better on the bus signal than the air-ride bus seat, across the A(8), VDV(8), and $S_{ed}(8)$ parameters on all road types ($\alpha = 0.05$).

Table 13
Truck signal WBV. Mean (S.E.) seat pan exposures by segment, weight group, and seat [n = 6 Light, n = 6 Heavy]

			ISO 2631-1								ISO 2631-5
			A(8) (m/s^2)				VDV(8) ($m/s^{1.75}$)				
Road Segment	Weight Class	Seat	1.4 X	1.4 Y	Z	Vector Sum	1.4 X	1.4 Y	Z	Vector Sum	$S_{ed}(8)$ (MPa)
City Streets	Light (<102 kg)	Air-Ride**	0.18 (±0.00)	0.20 (±0.00)	0.41 (±0.01)	0.45 (±0.01)	3.7 (±0.1)	3.9 (±0.1)	↑9.1 (±0.1)	↑9.3 (±0.1)	0.35 (±0.00)
		EM-Active	0.17 (±0.00)	0.22 (±0.01)	0.13 (±0.00)	0.31 (±0.01)	3.5 (±0.0)	4.0 (±0.1)	3.6 (±0.0)	4.9 (±0.1)	0.17 (±0.01)
		p-value	*0.08*	*0.09*	*<0.001*	*<0.001*	*0.09*	*0.30*	*<0.001*	*<0.001*	*<0.001*
	Heavy (>128 kg)	Air-Ride**	0.19 (±0.00)	0.21 (±0.00)	0.40 (±0.01)	0.49 (±0.01)	4.1 (±0.1)	3.9 (±0.0)	8.5 (±0.2)	8.8 (±0.2)	0.31 (±0.01)
		EM-Active	0.17 (±0.00)	0.21 (±0.00)	0.13 (±0.01)	0.30 (±0.01)	3.5 (±0.0)	4.0 (±0.1)	3.4 (±0.1)	4.8 (±0.1)	0.16 (±0.00)
		p-value	*0.01*	*0.25*	*<0.001*	*<0.001*	*0.004*	*0.12*	*<0.001*	*<0.001*	*<0.001*
Freeway	Light (<102 kg)	Air-Ride**	0.19 (±0.01)	0.24 (±0.01)	0.39 (±0.01)	↑0.50 (±0.01)	5.0 (±0.1)	5.2 (±0.1)	↑9.5 (±0.1)	↑9.8 (±0.2)	0.32 (±0.00)
		EM-Active	0.19 (±0.00)	0.25 (±0.01)	0.15 (±0.00)	0.35 (±0.01)	4.6 (±0.1)	5.0 (±0.1)	4.2 (±0.1)	6.1 (±0.1)	0.20 (±0.01)
		p-value	*0.61*	*0.38*	*<0.001*	*<0.001*	*0.15*	*0.53*	*<0.001*	*<0.001*	*<0.001*
	Heavy (>128 kg)	Air-Ride**	0.19 (±0.00)	0.25 (±0.00)	0.37 (±0.01)	0.48 (±0.01)	5.5 (±0.1)	4.8 (±0.0)	↑9.2 (±0.3)	↑9.6 (±0.3)	0.30 (±0.01)
		EM-Active	0.16 (±0.00)	0.25 (±0.01)	0.15 (±0.01)	0.33 (±0.01)	3.9 (±0.1)	5.1 (±0.2)	4.1 (±0.0)	5.9 (±0.2)	0.18 (±0.00)
		p-value	*<0.001*	*0.27*	*<0.001*	*<0.001*	*<0.001*	*0.16*	*<0.001*	*<0.001*	*<0.001*
Rough Road	Light (<102 kg)	Air-Ride**	0.29 (±0.01)	0.32 (±0.00)	↑0.75 (±0.01)	↑↑0.87 (±0.02)	5.7 (±0.3)	5.8 (±0.1)	↑14.4 (±0.2)	↑14.6 (±0.3)	0.47 (±0.01)
		EM-Active	0.22 (±0.00)	0.35 (±0.01)	0.26 (±0.00)	0.49 (±0.01)	4.1 (±0.0)	6.2 (±0.2)	5.7 (±0.1)	7.3 (±0.2)	0.25 (±0.01)
		p-value	*0.01*	*0.20*	*<0.001*	*<0.001*	*0.01*	*0.24*	*<0.001*	*<0.001*	*<0.001*
	Heavy (>128 kg)	Air-Ride**	0.32 (±0.01)	0.32 (±0.00)	↑0.71 (±0.01)	↑↑0.84 (±0.02)	6.5 (±0.3)	5.7 (±0.0)	↑13.3 (±0.3)	↑13.6 (±0.3)	0.42 (±0.01)
		EM-Active	0.19 (±0.00)	0.31 (±0.00)	0.25 (±0.01)	0.45 (±0.01)	3.6 (±0.1)	5.6 (±0.1)	5.9 (±0.6)	7.0 (±0.6)	0.28 (±0.05)
		p-value	*<0.001*	*0.34*	*<0.001*	*<0.001*	*<0.001*	*0.53*	*<0.001*	*<0.001*	*0.03*

* Crest factors greater than 9.
** Air-ride truck seat.
↑ ISO 2631 Part 1 indicates that potential health risks exist.
↑↑ ISO 2631 Part 1 indicates that health risks are likely.

Table 14
Bus signal WBV. Mean (S.E.) seat pan exposures by segment, weight group, and seat [n = 6 Light, 6 = Heavy]

			ISO 2631-1								ISO 2631-5
			A(8) (m/s^2)				VDV(8) ($m/s^{1.75}$)				
Road Segment	**Weight Class**	**Seat**	**1.4 X**	**1.4 Y**	**Z**	**Vector Sum**	**1.4 X**	**1.4 Y**	**Z**	**Vector Sum**	**S_{ed}(8) (MPa)**
City Streets	**Light (<102 kg)**	**Air-Ride****	0.18 (±0.01)	0.13 (±0.00)	0.37* (±0.01)	0.44 (±0.01)	4.2 (±0.1)	2.6 (±0.0)	8.2 (±0.2)	8.4 (±0.2)	0.34 (±0.01)
		EM-Active	0.13 (±0.00)	0.13 (±0.00)	0.19* (±0.00)	0.26 (±0.01)	2.8 (±0.0)	2.6 (±0.1)	5.7 (±0.1)	5.9 (±0.1)	0.28 (±0.01)
		p-value	***<0.001***	***0.789***	***<0.001***	***<0.001***	***<0.001***	***0.746***	***<0.001***	***<0.001***	***0.002***
	Heavy (>128 kg)	**Air-Ride****	0.18 (±0.01)	0.12 (±0.00)	0.35* (±0.01)	0.41 (±0.01)	3.8 (±0.1)	2.5 (±0.0)	7.8 (±0.2)	8.0 (±0.2)	0.31 (±0.01)
		EM-Active	0.13 (±0.00)	0.12 (±0.00)	0.18* (±0.00)	0.25 (±0.00)	2.6 (±0.0)	2.5 (±0.1)	5.6 (±0.1)	5.7 (±0.1)	0.29 (±0.01)
		p-value	***<0.001***	***0.627***	***<0.001***	***<0.001***	***<0.001***	***0.99***	***<0.001***	***<0.001***	***0.131***
Freeway	**Light (<102 kg)**	**Air-Ride****	0.20 (±0.01)	0.14 (±0.00)	0.37 (±0.01)	0.45 (±0.01)	4.7 (±0.2)	2.8 (±0.0)	7.6 (±0.2)	7.9 (±0.2)	0.27 (±0.01)
		EM-Active	0.12 (±0.00)	0.15 (±0.00)	0.16* (±0.00)	0.25 (±0.00)	2.8 (±0.1)	3.0 (±0.0)	3.9 (±0.1)	4.4 (±0.1)	0.17 (±0.00)
		p-value	***0.001***	***0.087***	***<0.001***	***<0.001***	***0.002***	***0.05***	***<0.001***	***<0.001***	***<0.001***
	Heavy (>128 kg)	**Air-Ride****	0.20 (±0.01)	0.13 (±0.00)	0.35 (±0.01)	0.43 (±0.01)	4.5 (±0.1)	2.7 (±0.0)	7.6 (±0.2)	7.9 (±0.2)	0.28 (±0.01)
		EM-Active	0.12 (±0.00)	0.14 (±0.00)	0.16* (±0.00)	0.25 (±0.00)	2.4 (±0.0)	2.9 (±0.1)	3.9 (±0.1)	4.3 (±0.1)	0.17 (±0.00)
		p-value	***<0.001***	***0.029***	***<0.001***	***<0.001***	***<0.001***	***0.086***	***<0.001***	***<0.001***	***<0.001***
Rough Road	**Light (<102 kg)**	**Air-Ride****	0.22 (±0.01)	0.16 (±0.00)	0.42 (±0.01)	↑0.50 (±0.02)	5.5 (±0.3)	3.3 (±0.0)	8.5 (±0.2)	8.9 (±0.3)	0.30 (±0.01)
		EM-Active	0.12 (±0.00)	0.18 (±0.00)	0.21* (±0.00)	0.30 (±0.01)	3.2 (±0.1)	3.7 (±0.1)	5.5 (±0.1)	5.9 (±0.1)	0.25 (±0.01)
		p-value	***0.001***	***0.048***	***<0.001***	***<0.001***	***0.002***	***0.012***	***<0.001***	***<0.001***	***0.001***
	Heavy (>128 kg)	**Air-Ride****	0.22 (±0.01)	0.15 (±0.00)	0.40 (±0.01)	0.48 (±0.01)	4.9 (±0.2)	3.1 (±0.0)	8.3 (±0.3)	8.6 (±0.3)	0.32 (±0.01)
		EM-Active	0.12 (±0.00)	0.16 (±0.00)	0.20* (±0.00)	0.29 (±0.01)	2.7 (±0.0)	3.2 (±0.1)	5.5 (±0.1)	5.7 (±0.1)	0.25 (±0.00)
		p-value	***<0.001***	***0.061***	***<0.001***	***<0.001***	***<0.001***	***0.463***	***<0.001***	***<0.001***	***<0.001***

* Crest factors greater than 9.
** Air-ride truck seat.
↑ ISO 2631 Part 1 indicates that potential health risks exist.
↑↑ ISO 2631 Part 1 indicates that health risks are likely.

Power Spectral Density Analysis

WBV Z-axis Transmission by Truck and Bus Signal — City Streets

At the low frequency peak (1-5 Hz), the EM-active seat resulted in significantly lower seat pan to sternum transmission of z-axis vibration, relative to the air-ride bus seat (Figure 15). This held for the comparison of all subjects grouped (n = 12) on the bus vibration city street input signal. For the lighter subjects (<102 kg, n = 6), the EM-active seat resulted in significantly lower z-axis vibration transmission to the sternum; however, this difference was not observed for heavy subjects (>128 kg, n = 6). There was no significant difference in z-axis vibration transmission from the seat to the sternum between the EM-active seat and the air-ride bus seat at the high peak (14-18 Hz).

At the low peak frequency (1-5 Hz), the EM-active seat did not result in significantly lower seat pan to sternum transmission of z-axis vibration, relative to the air-ride truck seat for all subjects grouped together. However, for the light subjects alone, the EM-active had a significantly lower z-axis vibration transmission to the sternum relative to the air-ride truck seat. There were no significant differences in z-axis vibration transmissions between heavy subjects on the truck city-street signal. Finally, at the high peak (14-18 Hz), the air-ride truck seat had a significantly lower z-axis vibration transmission from the seat to the sternum than the EM-active seat had.

WBV Z-axis Transmission by Truck and Bus Signal – Freeway

At the low peak frequency (1-5 Hz), the EM-active seat resulted in significantly lower seat pan to sternum transmission of z-axis vibration than the air-ride bus seat (Figure 16). This was the case for all subjects grouped (n = 12) and the light subjects alone (<102 kg, n = 6). The heavy subjects (>128 kg, n = 6) did not have a significant vibration transmission difference for the bus freeway signal at the lower peak frequency. There was no significant difference in vibration transmission between the EM-active seat and the air-ride bus seat at the higher peak frequency (14-18 Hz) for all subjects grouped. However, the EM-active seat performed significantly better for light subjects, whereas the air-ride bus seat performed significantly better for heavy subjects.

With the truck freeway signal at the lower peak frequency (1-5 Hz), the EM-active seat had significantly lower seat pan to sternum transmission of z-axis vibration than the air-ride truck seat, both for all subjects grouped and the light subjects alone. The heavy subjects did not have significant vibration transmission differences on the truck freeway signal at the low peak. Finally, at the high peak (14-18 Hz), the EM-active seat and the air-ride truck seat showed no significant difference in vibration transmission, either for all subjects grouped or for the light subjects alone. For the heavy subjects, the air-ride truck seat had significantly lower z-axis vibration transmission from the seat to the sternum than the EM-active seat.

WBV Z-axis Transmission by Truck and Bus Signal – Rough Road

At the low peak frequency (1-5 Hz), the EM-active seat had a significantly lower seat pan to sternum transmission of z-axis vibration than the air-ride bus seat (Figure 17). This was the case for all subjects grouped (n = 12) and the light subjects alone (<102 kg, n = 6). The heavy subjects (>128 kg, n = 6) did not show a significant difference on the bus rough road signal. At the high peak (14-18 Hz), there was not a significant difference between the EM-active seat and the air-ride bus seat for all the subjects, the light subjects, or the heavy subjects on the bus rough road signal.

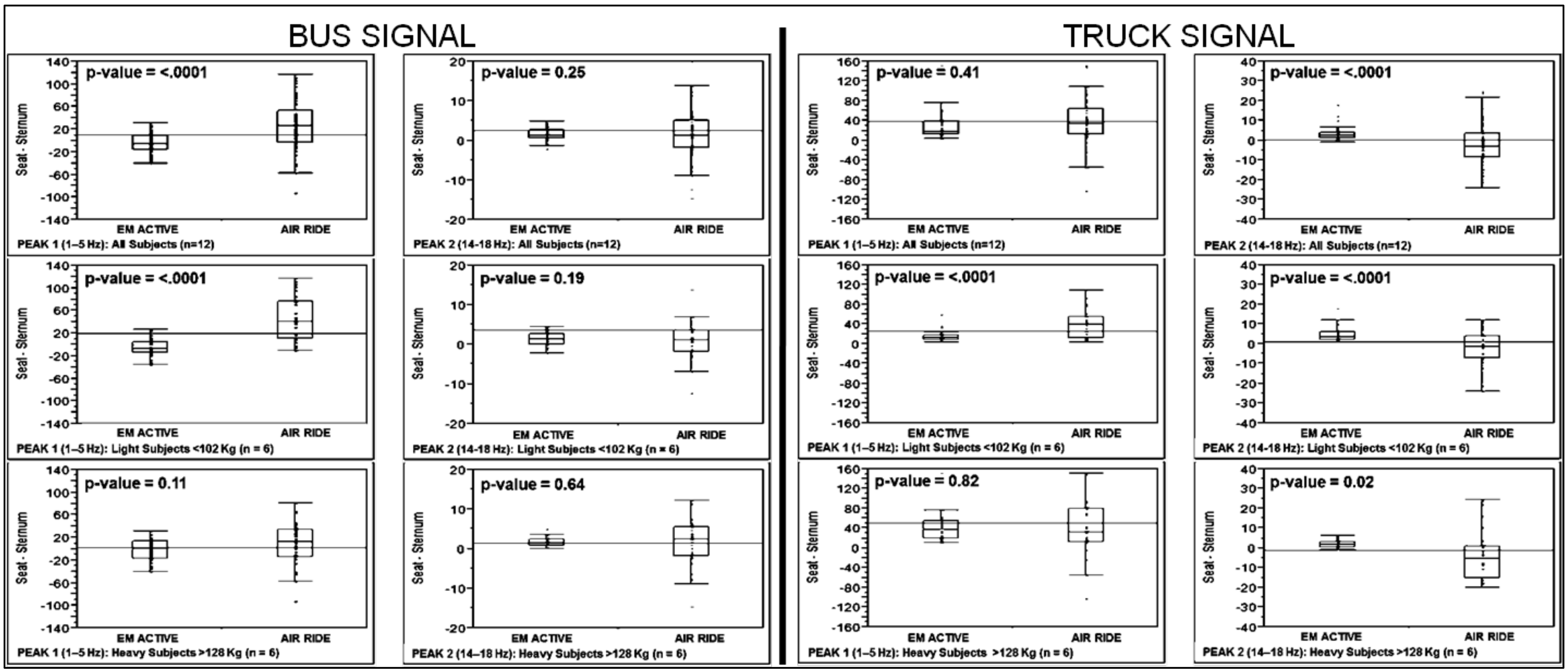

Figure 15
City streets PSD transmission seat pan to sternum over bus and truck signal, all subjects (n = 12), (light (n = 6) and heavy (n = 6) comparison)

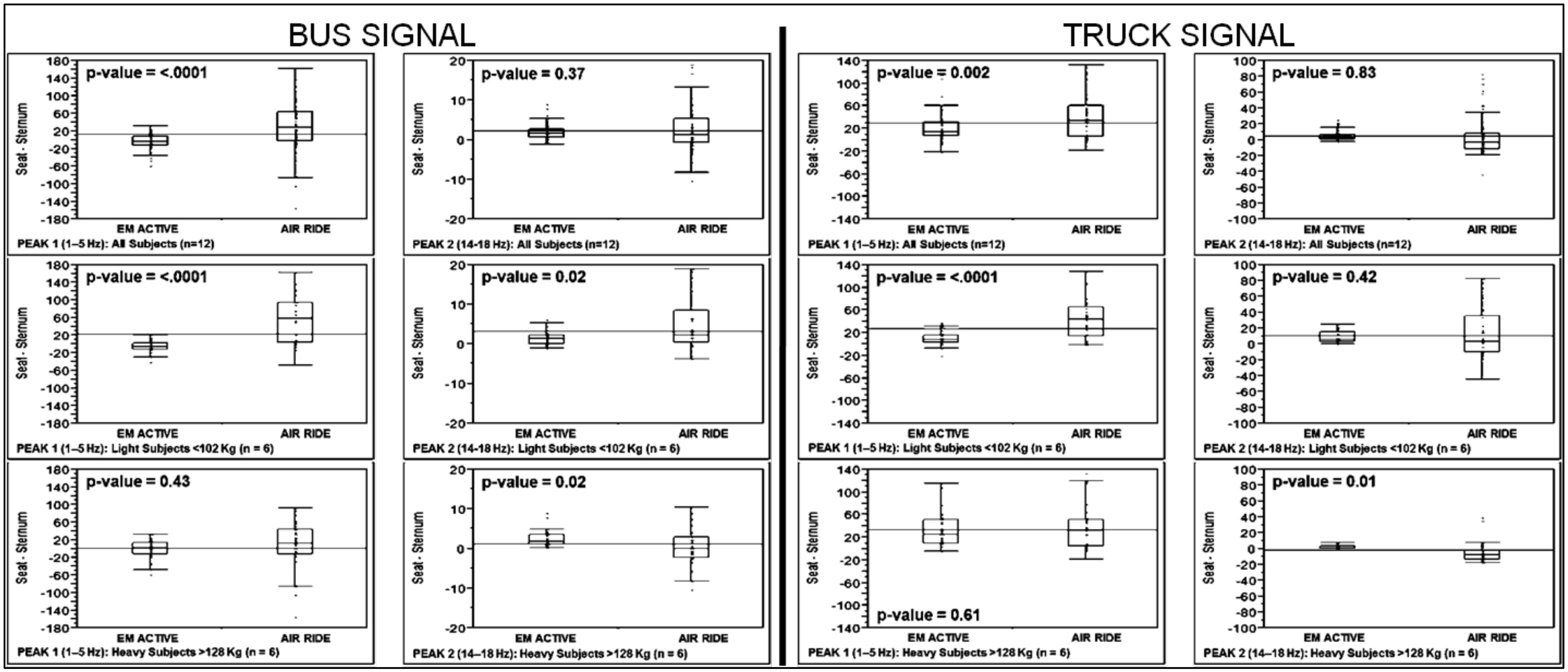

Figure 16
Freeway PSD transmission seat pan to sternum over bus and truck signal, all subjects (n = 12), (light (n = 6) and heavy (n = 6) comparison)

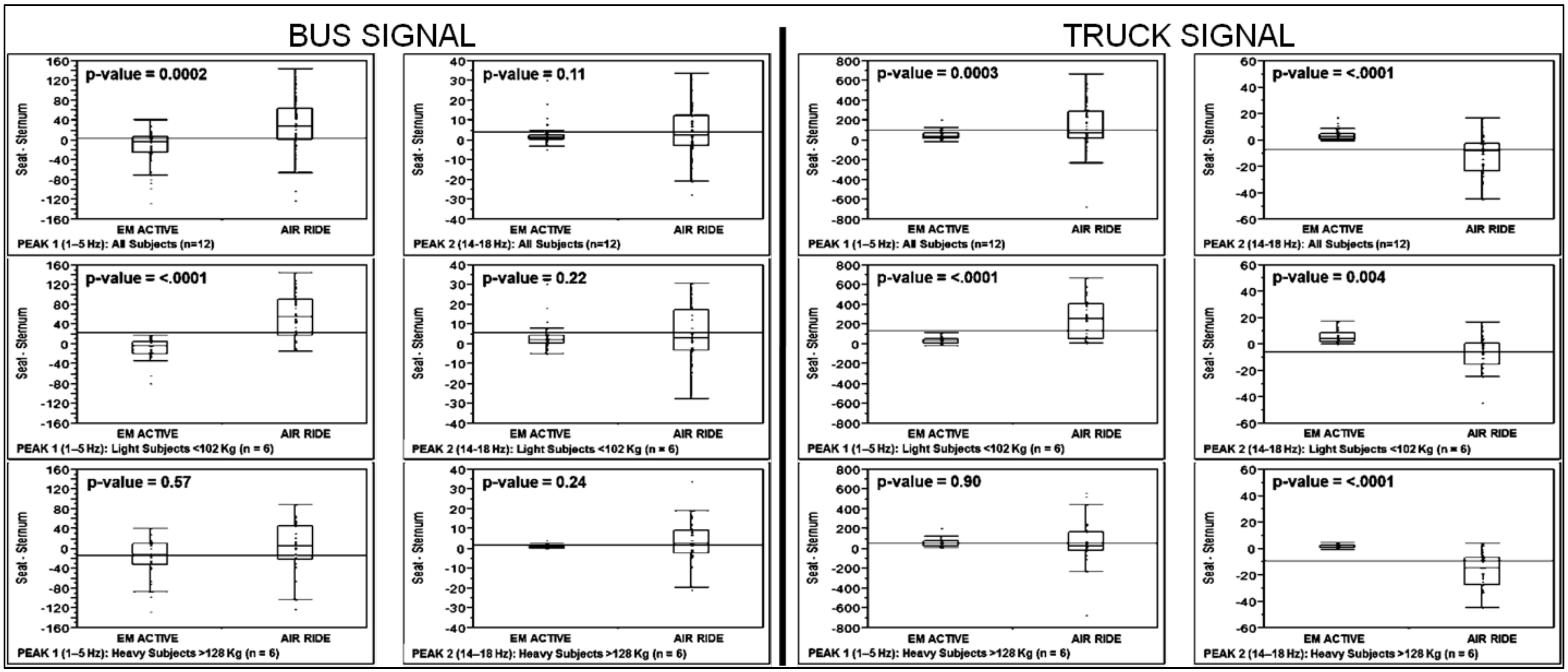

Figure 17
Rough Road PSD transmission seat pan to sternum over bus and truck signal, all subjects (n = 12), (light (n = 6) and heavy (n = 6) comparison).

At the low peak frequency (1-5 Hz) on the truck rough road signal, the EM-active seat resulted in significantly lower seat pan to sternum transmission of z-axis vibration than the air-ride truck seat, for all subjects grouped and the light subjects alone. The heavy subjects did not show significant vibration transmission differences at the low peak. Finally, at the high peak (14-18 Hz), the air-ride truck seat showed a significantly lower z-axis vibration transmission from the seat to the sternum than the EM-active seat, for all subjects grouped, the light subjects, and the heavy subjects.

Analysis of Variance by Segment and Seat Type

On the bus input signal, the EM-active seat significantly reduced vertical (z-axis) vibration transmission from seat pan to sternum, relative to the air-ride seat at the low peak frequency (1-5 Hz) (Table 15). This trend was consistent across all road segments (city streets, freeway, and rough road). There was not a significant difference between seats at the high peak (14-18 Hz) on any segment using the bus input signal.

Using the truck input signal, at the low peak frequency, the EM-active seat and the air-ride seat both amplified the vertical (z-axis) across all road segments. The EM-active seat resulted in significantly less amplification on the freeway and rough road segments than the air-ride seat. Finally, the air-ride seat resulted in significantly less vertical (z-axis) vibration transmission at the high peak than the EM-active seat on the city streets and rough road segments on the truck signal.

Discussion

Truck Signal WBV Seat Performance

The EM-active seat attenuated z-axis and vector-summed vibration better than the air-ride seats on the hexapod when stimulating the truck road input signal. This finding was consistent across all road types and all weight classes, suggesting that the EM-active design has the potential to significantly reduce WBV exposure for professional truck drivers.

Table 15
PSD Transmission seat to sternum. Means for one-way ANOVA comparing bus and truck signal by seat and segment, all subjects grouped [n = 12]

Source	Freq. Range	Seat	n	Mean	Std. Err	p-value
Bus City Streets	1-5 Hz	EM-Active	60	-4.75 ↓	4.20	<.0001
	1-5 Hz	Air-Ride Bus	60	27.06 ↑	4.20	
Bus Freeway	1-5 Hz	EM-Active	60	-4.39 ↓	5.70	<.0001
	1-5 Hz	Air-Ride Bus	60	30.57 ↑	5.70	
Bus Rough Road	1-5 Hz	EM-Active	60	-13.20 ↓	7.04	0.0002
	1-5 Hz	Air-Ride Bus	60	24.67 ↑	7.04	
Bus City Streets	14-18 Hz	EM-Active	60	1.53 ↑	1.44	0.2562
	14-18 Hz	Air-Ride Bus	60	3.85 ↑	1.44	
Bus Freeway	14-18 Hz	EM-Active	60	1.98 ↑	0.66	0.3660
	14-18 Hz	Air-Ride Bus	60	2.83 ↑	0.66	
Bus Rough Road	14-18 Hz	EM-Active	60	2.44 ↑	1.72	0.1134
	14-18 Hz	Air-Ride Bus	60	6.61 ↑	1.72	
Truck City Streets	1-5 Hz	EM-Active	60	34.84 ↑	7.80	0.4097
	1-5 Hz	Air-Ride Truck	60	43.97 ↑	7.80	
Truck Freeway	1-5 Hz	EM-Active	60	21.60 ↑	4.34	0.0016
	1-5 Hz	Air-Ride Truck	60	41.45 ↑	4.34	
Truck Rough Road	1-5 Hz	EM-Active	60	46.66 ↑	21.33	0.0003
	1-5 Hz	Air-Ride Truck	60	159.34 ↑	21.33	
Truck City Streets	14-18 Hz	EM-Active	60	3.17 ↑	1.02	<.0001
	14-18 Hz	Air-Ride Truck	60	-2.67 ↓	1.02	
Truck Freeway	14-18 Hz	EM-Active	60	5.45 ↑	2.40	0.8296
	14-18 Hz	Air-Ride Truck	60	4.71 ↑	2.40	
Truck Rough Road	14-18 Hz	EM-Active	60	3.62 ↑	2.78	<.0001
	14-18 Hz	Air-Ride Truck	60	-17.20 ↓	2.78	

↓ Indicates z-axis attenuation from seat pan to sternum.

↑ Indicates z-axis amplification from seat pan to sternum.

The EM-active seat transmitted approximately 30% less vibration than the air-ride seat (Table 13). Since both seats were mounted on the hexapod at the same time and stimulated by the same vibration input signal, this study illustrated the exposure reduction potential of this technology. The difference in vector sum values was similar across both the light (<102 kg) and heavy (>128 kg) subjects. The exposure differences between seats was more pronounced on the rough road vibration segment, with the EM-active seat transmitting approximately 46% less vibration than the air-ride seat.

Previous research on forklift operators has illustrated that seat suspension design can significantly reduce vibration transmission from the floor to the seat of the operator [29]. The EM-active seat has not been tested in heavy equipment; however, it is clear that seat suspension design can significantly affect vibration exposure in a variety of vehicles.

Bus Signal WBV Seat Performance

The EM-active seat also attenuated vibration better than the air-ride seat on the hexapod when stimulating the bus road signal. This finding was consistent across all road types and weight classes, suggesting that the EM-active design has the potential to significantly reduce WBV exposure for professional bus drivers.

As shown in Table 14, the EM-active seat transmitted approximately 44% less vibration than the air-ride seat. The difference in vector sum values was similar across both the light (<102 kg) and heavy (>128 kg) subjects on the bus signal. The exposure vibration attenuation differences between the EM-active seat and the air-ride seat remained consistent across the city streets, freeway, and rough road segments.

Previous field-based research on professional bus drivers established that the seat pan material can result in differences in WBV exposures. However, the seat pan material tested (combined with air-ride seat suspensions) did not perform universally well across all road types [27].

WBV PSD Analysis

An interesting and novel finding of this study concerned the difference in vibration transmission between the seat pan- and sternum-mounted accelerometers with the EM-active and air-ride seats. Specifically, the EM-active seat resulted in lower transmission of vertical (z-axis) vibration from the seat pan to the sternum at the low peak (1-5 Hz) on both the truck and bus vibration signals. This finding suggests there is potential to reduce the vibration measured at the sternum of drivers by equipping their vehicles with the EM-active seat suspension technology. However, this finding was not replicated at the high peak (14-18 Hz), where the air-ride seat performed better than the EM-active seat on the truck signal, and there was not a statistically significant difference between seats with the bus signal. There were differences in the transmission from seat pan to sternum between the light (<120 kg) and heavy (>128 kg) subjects. This finding illustrates that the body mass of the subject plays a role in the transmission of vertical vibration through the torso, as shown in previous research measuring WBV transmission in cadavers [30].

Additional Factors Affecting WBV

Posture has been shown to have a significant effect on the WBV exposure outcomes for the vehicle driver [14]. In addition to posture, the placement and adjustment of foot supports and the backrest can have a significant effect on the absorption of WBV for the seated driver [31]. Employers of professional drivers and manufacturers of commercial trucks and transit buses should consider the seat suspension design when laying out the design of the vehicle cab. The design of the driver cockpit area, along with the seat suspension design, can significantly affect the exposure to vibration and has the potential to reduce injury outcomes associated with chronic WBV exposure. Research on cab design characteristics has illustrated that the design and layout of the cab of a vehicle has the potential to significantly reduce vibration exposure [32]. Posture was controlled during testing, since subjects were asked (1) not to adjust the seat back and (2) to keep one hand on the steering wheel at all times, with their foot on the simulation pedals provided.

Limitations of the Study

One limitation of this study was that (due to the limited access to the vibration simulation hexapod and the labor and time required to install seats) the order of seats presented to subjects was not randomized. A second limitation was that the field-collected vibration signals used to generate the semi-truck and bus exposures were collected on different roads in different cities. Due to feasibility constraints and access to vehicles, it was not possible to measure vibration exposure from the same roadway for the semi-truck and bus exposure profiles. A third possible limitation is that the field-collected data had to be iterated for use with the hexapod, which may have underestimated field exposures slightly in order to conform to the travel limits of the hexapod. Finally, future studies that measure WBV exposure effects would benefit from more subjects at incremental weight classes to better model the effect of weight on WBV exposures.

Conclusions

The selection of seating for professional drivers is often made with durability and cost as the primary selection criteria, while vibration exposure to the driver is often a distant priority. This study suggests that the seat suspension design can have a significant effect on the overall vibration exposure transmitted from the vehicle to the vehicle operator. Given the cost of injuries often associated with chronic WBV exposure, employers and vehicle designers should consider including seat design vibration attenuation as a primary selection factor in an effort to reduce vibration-related injuries. The EM-active seat performed significantly better in attenuating WBV exposures than the air-ride seat across all road types. However, the results at the sternum did not consistently favor one seat over the other in the ability to reduce WBV exposures.

Chapter 4 Acknowledgements

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Chapter 5: Summary and Conclusions

This dissertation examined injury trends among professional bus drivers by analyzing a long-term database for workplace injuries that was provided by a metropolitan transit agency in Seattle, Washington. The analysis showed that bus drivers are at an increased risk of developing several types of occupational injuries, including LBP, relative to administrative workers. This study also explored the development of field-based data collection methods aimed at improving the assessment of WBV exposures among professional drivers and heavy equipment operators. Using data collected during field-based measurements of WBV, this study also employed a vibration simulation hexapod to test new engineering control technology designed to reduce WBV exposures among professional bus and truck drivers.

The overall goals of this study were to:

1. Quantify the risk of back injuries among professional bus drivers relative to a population not exposed to WBV;
2. Expand on the application of previously developed technologies for characterizing WBV exposure in field-based studies; and
3. Assess WBV exposure engineering controls among drivers with common WBV exposure patterns.

This study culminated in the evaluation of a prevention approach comparing the ability of seat suspension designs to attenuate WBV exposures. The information assembled during this study is intended to aid in the future development of biomechanical models of LBP injuries among occupations that are regularly exposed to WBV transmitted through a driver's seat. The information presented in this study may prove useful in (1) assisting design engineers to develop engineering controls (seat designs), (2) assisting occupational health professionals to assess LBP injuries among professional drivers, and (3) reducing injuries among professional bus drivers. The long-term goals of this research are to reduce costs to employers and to improve the quality of life for a work population that has a high rate of injury.

Data collected in administrative injury databases usually are not collected with the goal of performing accurate epidemiologic studies, and sources of significant bias may consequently be introduced. Several challenges were identified in using administrative injury databases to develop injury risk estimates. Specific challenges in the occupational setting include: (1) populations at risk may be open and dynamic, as workers enter and leave the exposure source; (2) the relevant period of exposure that leads to injury may be brief; (3) the exposure of interest and confounders may vary over time; (4) the prevalence of exposure may be low; (5) some exposures may be underreported or difficult to quantify; and (6) individuals may be injured multiple times over the course of a study [1]. Additionally, occupational injury causes often rely on self-reported exposures, which have been found to be less accurate than direct measurement techniques [2, 3]. Chapter 2 of this study successfully applied a proportional hazards model for semi-parametric entries in an occupational database to examine injuries among bus drivers. The Cox Proportional Hazards Model was selected because it accounts for the nonparametric nature of an unspecified hazard function, while allowing for the parametric form of covariates included in the hazard function calculations. The use of a proportional hazards model has been successfully applied in previous research on occupational injuries [4-7], and it has allowed for the development of accurate risk estimates in this study, despite the previously mentioned challenges associated with occupational injury epidemiology.

Quantifying risk of LBP development among professional drivers who are regularly exposed to WBV has proven challenging, largely due to the variation in the types of vehicles. Accurate assessment of WBV exposure requires direct measurement of the actual work vehicle under real world conditions. Previous research has shown that there is a high degree of variability between vehicle types and that the accurate assessment of WBV exposure is only possible through a hands-on evaluation of actual working conditions [8]. Further challenges associated with accurate WBV exposure assessment include the fact that road types and seat constructions can significantly alter WBV exposures [9]. Individual driver characteristics, such as driving style and driver weight, also contribute to variation [10]. Chapter 3 of this study presented new methods for measuring WBV exposures in the field in order to provide occupational health specialists and employers of professional drivers with a methodology for conducting accurate WBV exposure assessments. This also provides a means of collecting large amounts of field data to characterize the wide range of vibration exposures in working populations.

Since it is nearly impossible to eliminate WBV exposures associated with driving occupations, Chapter 4 of this study examined the potential effectiveness of an exposure-reduction strategy that targets the top of the industrial hygiene hierarchy of controls (engineering controls) [11]. The results presented here illustrate that WBV exposures can be significantly reduced through advances in seat suspension technology. If these observations hold in future studies, then the next step would be to apply engineering controls and measure health outcomes over time. NIOSH has long advocated the importance of going beyond investigation and quantification of workplace exposures to evaluate the impact of interventions on health outcomes [12]. Although such an evaluation of prevention was beyond the scope of this research effort, the findings presented here provide the basis for longitudinal studies measuring injury outcomes among professional bus drivers after WBV mitigation technologies are installed.

Epidemiological Findings (Chapter 2)

Epidemiologic assessments of LBP among working populations have been studied extensively, with causes identified as a combination of lifting exposures, psychosocial factors, WBV exposure, and personal factors, such as physical fitness and age [13-15]. The National Research Council (NRC) estimates that musculoskeletal injuries to the low back and upper extremities impose an economic burden on the American economy of $45-54 billion annually, after accounting for compensation costs, lost wages, and lost productivity [16]. Complicating the problem is the debate among occupational health professionals that most of the common MSDs are not caused by work exposures alone. The

World Health Organization (WHO) refers to occupational factors as "work-related conditions," asserting that the development of MSDs results from a combination of work exposures and personal factors. The NRC identifies several factors that should be considered when assessing the cause of MSD development, including: (1) the physical, organizational, and social aspects of the workplace, (2) the physical and social aspects of life outside the workplace (e.g., sports, exercise programs, household exposures), economic incentives, and cultural values, and (3) the physical and psychological characteristics of the individual reporting an MSD injury [16].

The current study determined that professional bus drivers are at an elevated risk of developing LBP and other workplace injuries relative to a referent group (administrative jobs). This finding agrees with previously published research on the long-term health outcomes among professional drivers [17-19]. Researchers have identified that bus drivers are at elevated risk of LBP development due to a number of factors, including poor posture and unsupported torso, the requirement to perform light MMH tasks, and the exposure to discomforting shock and vibration events [20, 21].

Although the analyses presented in Chapter 2 do not explore specific causes of injury, the results suggest that further evaluation of bus driver injuries – with specific attention to targeting prevention strategies – is warranted. Back injuries to bus drivers in this metropolitan transit agency resulted in millions of dollars of losses over the period covered by this study, a result that provides support for investments in engineering controls and the exploration of administrative controls, such as job rotation and extended rest breaks throughout the workday. Prior research on bus drivers reported that the minimization of MMH tasks – by, for example, the installation of remotely operated retracting access ramps, mandatory breaks from sitting throughout the workday, and the installation of manual transmissions – can help reduce LBP injuries [20]. Prolonged sitting has been identified as a leading cause of LBP development among bus drivers [22]. However, this study found that drivers, even when compared to the referent group of administrative jobholders – a population that is also exposed to long periods of sitting – were are at an elevated risk of developing back injuries. This finding suggests that sitting is not the sole cause of the observed increase in risk of back injuries in the driver population.

Application to future occupational injury studies

The findings of this study suggest that the proportional hazards model is appropriate for the evaluation of occupational injuries among similar work groups employed by the same agency. The methods applied are appropriate for the evaluation of an administrative injury database that was not specifically designed or maintained for the purpose of epidemiologic study. An expansion to include additional categorical variables that capture personal factors outside the workplace would provide further insight into the specific causes of low back injuries and their possible contribution to adverse health outcomes. However, absent the inclusion of detailed personal factors, this study was able to use a long-term administrative injury database (as opposed to the self-reported occupational injury experiences that had been explored in prior research) to minimize the effect of recall bias and misreporting associated with asking drivers to report past injury experiences. Future applications of the proportional hazards model would enhance occupational injury research, particularly if the research included interviews with claimants to capture underlying medical conditions, personal demographic factors, physical characteristics, and assessments of workplace stress experiences.

Finally, an interesting finding of this study was that bus drivers were not found to be at elevated risk of upper extremity or head and neck injuries, relative to those working in administrative positions at the same agency. This finding does not align with previous research, which found that professional drivers are at an elevated risk of developing upper extremity injuries (e.g., shoulder pain), compared to other sedentary occupations [23-26]. However, ergonomic research on extended computer use agrees with the results of this study, insofar as such research suggests that long-term work in administrative positions can lead to an elevated risk of upper extremity and head and neck pain [27, 28].

Field-based WBV Exposure Assessment (Chapter 3)

Extensive research has been conducted on WBV exposures among professional drivers to investigate the link between extended WBV exposure and the development of LBP. In the United States, there are no regulations governing WBV exposure, although the American Conference of Governmental Industrial Hygienists (ACGIH) has adopted measurement and exposure guidelines outlined in the international standards for WBV [29-31]. Given the established high occupational injury rates among professional drivers (along with the high number of days injured drivers spend away from work), the lack of regulatory guidance in the United States over such an expensive problem remains a source of debate among occupational health professionals [32]. The EU has established 8-hour action and exposure limits for WBV exposure in an attempt to force employers to address the problem of chronic WBV exposure [33]. However, whether this directive has reduced occupational injury rates has yet to be assessed. Despite the fact that work-related injuries cause a very significant drain on individual companies and the national economy, ergonomics regulations in the United States have yet to be established. In order to address MSD injuries among the U.S. workforce, the Occupational Safety and Health Administration (OSHA) planned to institute an ergonomics standard in 2001. However, the standard was repealed by Congress in a move that was largely viewed as a victory for business and a defeat for the health of workers. The only existing enforcement for the ergonomic hazards referenced by OSHA is the general duty clause that states, "Each employer shall furnish to each of his employees employment and a place of employment which are free from recognized hazards that are causing or are likely to cause death or serious physical harm to his employees." Two states, California and Washington, have passed regulations addressing ergonomic exposures; however, the Washington regulation was repealed by voter initiative.

Despite political considerations, one of the challenges facing the passage of regulations to reduce WBV exposure is the fact that many occupational health and safety professionals have little knowledge of the phenomenon and its link to injury outcomes [34]. Until recently, measurement of WBV in a field setting was cumbersome, requiring a significant investment in data collection equipment and an advanced knowledge of signal processing technology to accurately measure and process vibration data. However, several self-contained systems for the quantification of WBV exposures are now commercially available. Significant advancements in computer processing power, battery life, and GPS equipment have increased the accuracy and ease of field-based WBV exposure assessment.

WBV data collection systems are now capable of accurately measuring exposure differences between vehicles, seats, and road types. As data collection technology has advanced, sampling speed has increased, thus expanding the ability of researchers to quantify time-weighted average vibration exposures, as well as exposures to violent shocks that have been linked to acute back injury [31]. This advancement has afforded researchers the ability to evaluate engineering controls and recommend administrative controls to reduce WBV exposures among professional bus and truck drivers [10, 35-37], heavy equipment operators [8, 38-40], forklift operators [41], train conductors [42-44], subway operators [45, 46], taxi drivers [47, 48], professional pilots [49-51], and other occupations exposed to WBV [52-54].

Complicating the quantification of WBV exposures is the fact that the dominant axis of exposure is not universal across work tasks or exposure scenarios. In general, the axis of concern is the vertical vibration exposure (z-axis), which has been shown biomechanically to exert compression and tensioning forces on vertebrae and intervertebral discs, ultimately increasing the likelihood of a back injury. The ISO vector sum approach that accounts for vibration exposures in the fore-and-aft (x-axis) and lateral (y-axis) directions may be more accurate, depending on the exposure scenario and vehicle. Recent research indicates that highly repetitive fore-and-aft shear forces could result in an increased risk of damage to the disc and facet joints [55]. This exposure would be ignored with strict reliance on the dominant axis in the vertical direction. The vector sum approach is particularly valuable when comparing WBV exposures across occupations (e.g., comparing heavy equipment operator exposures to those of professional drivers). The EU directive does not subscribe to the vector sum approach, since the directive requires one dominant axis of exposure for the assessment and enforcement of WBV standards. A key finding of this research is that reliance on a single dominant axis of exposure may underestimate both the true exposure and the need for an intervention to prevent injuries.

Application to future field-based WBV exposure assessments

The findings presented in Chapter 3 relied on the normalization of WBV exposures to a standard 8-hour workday, an approach that is common in occupational exposure assessments. However, professional drivers, particularly truck drivers, are regularly required to work schedules that require extended hours in the seat. This extended exposure has been linked to increased fatigue and ultimately to weakness in the back, which can produce a large increase in injury risk. Laboratory-based research has shown an increase in electromyography (EMG) magnitude in the muscles of the back after prolonged exposure to WBV. This effect may ultimately lead to muscle fatigue and mechanical damage of vertebral tissues (due to the continuous loading of spinal structures), as well as to long-term mechanical creep in the spine [56]. Reliance on 8-hour estimates of WBV exposures may underestimate the actual exposure duration that professional driver populations experience. To quantify real world exposures more accurately, future field studies of WBV exposures should take advantage of increased battery life, data storage capacity, and data processing power to collect full-shift measurements of WBV exposures.

The results of this study suggest that there is a need for additional analysis of long-term WBV exposures among chronically exposed populations. Prior to expanding the WBV data collection effort, training programs should be developed to inform occupational health specialists and safety professionals about the injury risks associated with chronic WBV exposure. In order for feasible interventions to be identified in an effort to reduce back injuries, accurate measurement techniques need to be shared and made readily available to employers. Recalling the popular management philosophy espoused by W. Edwards Deming, “manage what you can measure,” it is vitally important that employers understand how to measure physical occupational exposures and how to interpret the exposures, particularly relative to adverse health outcomes. Employers must also be given feasible intervention options to reduce occupational injuries. Once this takes place, longitudinal studies should be performed to determine whether interventions result in the long-term prevention of injuries.

Laboratory-based WBV Exposure Assessment (Chapter 4)

The vibration simulation techniques that have previously been applied to test seat suspensions generally focused on the vertical (z) axis of exposure [57]. The majority of prior laboratory-based WBV research focused on operator-controlled variables, such as the presence of foot supports, seat back inclination, or other strictly controlled test conditions designed to parse out the effect of operator adjustments to the seat or personal characteristics [58-61]. Drawing on experience gained from a field-based WBV exposure assessment, Chapter 4 of this study applied real world vibration signals in a laboratory setting to test the ability of a newly developed seat suspension to attenuate vibration measured at the floor. This novel study design was the first of its kind to apply field-based data to the laboratory through the use of a 6 degree-of-freedom electric motion platform (hexapod). The hexapod allowed tri-axial vibration simulation, applying signals measured at the floor of a semi-truck and a transit bus to compare the performance of an air-ride suspension seat to that of an EM-active seat. This method provided an advantage in reducing variability between trips associated with field-based data collection.

Additionally, playing real world data through a hexapod eliminated the need for coordinating vehicles and drivers for exposure testing when evaluating seat suspension designs.

This study found significant vertical vibration attenuation potential through the application of the EM-active seat suspension technology. The study also measured the transmission of vibration through the torso of subjects with a sternum-mounted accelerometer. Previous research measuring spinal vibration transmission relied on the instrumentation of cadavers [62, 63]. WBV cadaver research found that there was some frequency-dependent amplification from the seat pan to the sternum of the subjects. Other research targeting vibration transmission through the spinal column recruited subjects to have vibration transducers instrumented in vivo into the lumbar vertebrae, a highly invasive procedure [64-66]. The use of cadavers or in vivo transducers was beyond the scope of this research, given ethical considerations and the development of alternative methods of acquiring spinal transmission data. Analysis of the sternum-mounted accelerometer data found amplification of vibration measured at the sternum that was weight class dependent.

Air-ride seats currently dominate the market for controlling WBV exposures among professional bus and truck drivers. The air-ride technology is passive and relies on a compressed air bladder to attenuate WBV exposure. Air-ride seats are considered a significant advancement in vibration attenuation, when compared to a strictly mechanical (scissor and spring) design [41, 67]. However, a problem with air-ride seats is that they are slow to react to impulsive shocks. Such shocks have been identified as a significant cause of driver discomfort and degeneration leading to disc injuries [31, 68].

The newly developed EM-active seat suspension technology relies on a high-power, linear, electromagnetic actuator that is designed to counteract forces at the floor of the vehicle caused by road disturbances [69]. A built-in microprocessor continuously and instantaneously controls vertical (z-axis) vibration-induced seat motion, which results in lower WBV exposures reaching the seat pan of the driver. Based on laboratory measurements, this new technology has the potential to significantly reduce vertical WBV exposures experienced by drivers. Application of the vector sum approach to the EM-active seat reduced A(8) WBV exposures by 30-46% relative to the air-ride truck seat, depending upon subject weight and road type (Table 13). There is a significant reduction in injury risk, considering the fact that EM-active seat exposure is nearly half that of an air-ride seat evaluated in a repeated measures design over the same pool of subjects (Table 14).

The EM-active seat reduced A(8) WBV exposures by 39-44% relative to the air-ride bus seat, depending upon subject weight and road type. Two key findings of this study are (1) the EM-active seat has the potential to significantly reduce WBV exposures relative to air-ride technology and (2) the seat technology designed for truck drivers performed well in reducing bus exposures in a laboratory setting. The EM-active seat did not perform well at attenuating high frequency WBV exposures (as measured at the sternum), relative to the air-ride seat on the truck simulation signal. This may be improved through additional testing and adjustments to the algorithm used by the seat manufacturer. Additional field research is needed to install and evaluate the EM-active seat technology in a real-world bus environment.

Application to future laboratory-based WBV exposure assessments

Previous WBV laboratory research has relied on a combination of controlled vibration intensity or randomly applied vibration across frequencies known to cause resonance in the structure of the spine [70, 71]. However, this is the first study to combine field-based vibration signals with tri-axial WBV measurements at the seat pan and sternum to quantify WBV transmission through the trunk to the sternum of subjects. Further laboratory investigations should take advantage of the field-based technologies to evaluate real world exposures in a laboratory setting. Evaluation of WBV exposures in a laboratory setting has the potential to significantly advance the science of MSD prevention, in large part by reducing the variability associated with driving style, traffic, and driver skill that affect field-based studies.

Recommendations for Future Research

Future field-based studies should take advantage of increased battery power to measure full-shift WBV exposures among professional drivers, accounting for speed and road type to accurately catalogue exposures by vehicle type. Full-shift measurements have the potential to accurately quantify WBV exposures beyond the 8-hour workday. This advancement would be particularly advantageous to measuring WBV exposures among truck drivers, who are regularly tasked with driving for the DOT-specified maximum of 11 hours per day [72], although some drivers exceed that limit [73].

Cost-intensive cab isolation technologies – commonly referred to as “ride control” – have been developed and tested for the heavy equipment market, and they have shown promise in reducing WBV exposures [74]. However, this technology has yet to be adapted for use in the professional driver market, largely due to cost. The recently developed seat technology advancements have shown promise in attenuating vertical vibration, ultimately leading to lower vector sum WBV exposures. Longitudinal studies measuring prevention after the installation of engineering controls described by NIOSH have the potential to quantify the effect on injury rates over time after the application of new engineering controls.

Finally, research has shown that risk assessments based on the current standards governing WBV (i.e., ISO 2631 Parts 1 and 5) may not fully capture the risk of injury associated with chronic exposure. Evidence has shown that the application of an average exposure-effect relationship may not necessarily be generalized to the individual case, due to the lack of consideration of anthropometric features and age during exposure [55]. High injury risks have been identified despite exposure measures below the health guidance caution zone outlined in the ISO standard [30, 75, 76]. This finding may assist in explaining the high injury rates among populations that are measured to have low-magnitude WBV exposures according to the standard. A large-sample longitudinal study measuring pre- and post-intervention WBV exposures, combined with long-term injury risk outcomes, would provide a significant advancement in this field of research. Such a study would allow for the measurement of injury prevention, while providing an evaluation of the long-term application of ISO-recommended exposure limits to adverse health outcomes.

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VITA

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