Evaluating the Effects of Altering Whole-Body Vibration Exposures on Truck Drivers' Vigilance

Fangfang Wang

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Reading Committee:
Peter Johnson, Chair
Linda Boyle
Shan Liu

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Abstract

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Fangfang Wang

Chair of the Supervisory Committee:
Professor Peter Johnson
Department of Environmental and Occupational Health Sciences

Whole-body vibration (WBV) may contribute to truck driver fatigue and increase the potential for vehicular accidents. Previous studies of truck induced WBV exposures have mostly focused on physical discomfort, whereas there is little quantitative research on how WBV affects drivers' alertness levels. The goal of this study is to explore whether there is an association between exposures to WBV and truck drivers' vigilance, the fundamental aspect of attention. Truck driver's vigilance was measured using Psychomotor Vigilance Task (PVT). Furthermore, a laboratory-based study and a field study were conducted to assess drivers' vigilance performance with different levels of exposure to WBV created by using seats with different vibration damping performance. The results indicated that the changes of drivers' vigilance were dependent on the WBV exposure levels. Less decline in vigilance performance was found after drivers sat in the truck seats that exposed them to lower levels of vibration, which may be due to seat-related differences in the vibration attenuation performance, and in particular, the attenuation of low frequency energy (1 – 4 Hz) in these seats. This dissertation provides evidence that truck seats, and ultimately different levels of exposure to WBV, may influence driver fatigue and the truck driver's vigilance.

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DEDICATION

I dedicate this work to my family, including my husband, Shuhan, who is always there backing me up; my son, Darren; my parents, Baoping and Yuling; my grandfather, Yuzhao; and my parents in-law, Hongde and Lin. I could not have completed this work without their constant love and support when faced with challenges in my study and life.

Chapter 1 Introduction

According to the National Highway Transportation and Safety Administration (NHTSA, 2017), in 2015, over 72,000 police-reported crashes involved drowsy drivers. These crashes led to 41,000 injuries and more than 800 deaths. Drowsy driving is thought to be substantially under-reported in police crash investigations (Lyznicki 1998).

Fatigue or drowsiness refers to the cognitive, or physical state of tiredness or weariness caused by physical or mental exertion. Sleepiness, a related but distinct term, refers to the physiological propensity to fall asleep. Fatigue has been widely recognized as a major risk factor for road accidents, and professional drivers are more at risk for fatigue-related accidents than private drivers (Sagberg, 2004).

Fatigue and sleepiness-related accidents can lead to property damage and fatalities, the US NHTSA estimates that drowsy driving accounted for 396,000 (1.4 percent) out of 29,000,000 total police-reported motor vehicle crashes (including fatalities, injuries, and property damage only), between 2011 and 2015, with 2.5 percent of fatigue-related crashes resulting in fatalities (NHTSA, 2017).

Factors contributing to truck driver fatigue include shiftwork, nighttime driving, extended working hours, prolonged sitting, sleep disorders, and alcohol consumption (McCartt Rohrbaugh, Hammer, Mark & Fuller, 2000; Howard et al., 2004; Heaton, 2005; Girotto et al., 2013; Sieber et al., 2014). Among these factors, obstructive sleep apnea (OSA) is a prevalent and potentially dangerous condition among commercial motor vehicle (CMV) drivers, and individuals with OSA are clearly at increased risk for fatigue-related vehicle accidents (Tregear et al., 2009).

Researchers and decision makers have been developing a greater interest in operational factors related to vehicle crashes, which are the environmental factors that drivers experience or are exposed to while driving. Whole-Body Vibration (WBV) is one of such operational factors. For truck drivers, WBV conveys road and vehicle-related energy to the body of the human operator. WBV is typically measured and evaluated using the methods outlined in the International Organization for Standardization (ISO) standards 2631-1 (ISO, 1997) and 2631-5 (ISO, 2004). To reduce WBV exposures and mitigate potential adverse health outcomes, trucks are increasingly fitted with higher quality vibration-damping seat technologies (Blood & Johnson, 2011).

It is believed that exposure to WBV is associated with several adverse health outcomes including low-back pain and driver fatigue. The fatigue-related components are thought to contribute to vehicle-related accidents (Conway, 2007). Most studies have been focused on the musculoskeletal disorders induced by WBV, and the indirect effects of poor sleep quality on driver fatigue (Du, 2015). The mechanisms of how WBV affects, and influences driver fatigue still merit further investigation; however, in the interim, it is important to explore the effects that WBV may have on truck driver drowsiness, fatigue and vigilance, especially in real-world scenarios. Further elucidating potential associations with exposure to WBV may provide evidence and methods for reducing the risks of potential fatigue and vigilance-related truck accidents. Vibration reduction technologies in truck seats may be one means for reducing the risks for fatigue and vigilance-related truck accidents. If the truck seats reduce vibration and the vibration attenuation feature reduces the risks for fatigue and vigilance-related truck accidents, then it may be beneficial to develop and provide vibration reduction recommendations and/or guidelines to seat manufacturers, trucking industries, truck drivers and employers.

The purpose of this dissertation is to explore whether there is an association between WBV and truck drivers' vigilance though both laboratory and field-based studies. Chapter 2 contains a literature review of truck driver working conditions, the factors affecting drivers' vigilance, with an emphasis on the potential effects that WBV may have on driver vigilance. Chapter 3 describes a laboratory-based study conducted to understand the effects that two different levels of WBV exposure have on truck drivers' vigilance in a simulated setting using a lower performing passive, air-suspension seat, and a higher performing active suspension seat. Chapter 4 introduces a field study that was conducted to determine whether there were differences in WBV attenuation performance and self-reported discomfort across four different commercially available truck seats, including three passive air-suspension seats and an active suspension seat. Chapter 5, using a field-based PVT task, explored the practical implications of using the four different truck seats and whether reducing a truck driver's exposure to WBV had any association and effect on truck driver's reaction time and lapses. Finally, Chapter 6 describes the overall findings and conclusions of this dissertation, discusses the contributions and potential areas for future work.

Chapter 2 Background

2.1 Background of Trucking Industry

There were 3,802 trucks associated with deadly crashes (FMCSA, 2014). Large trucks are trucks with gross weight more than 453.6 kg (NHTSA, 2013). In US, 2012, 4,183 individuals were killed in 3,702 crashes including large trucks or buses. This fact represented 12.5% of the 33,561 total vehicular crash fatalities for the year.

Commercial vehicle collisions have a significant human and economic toll. Zaloshnja and Miller (2007) estimate that the average total cost of a police-reported collision involving a large truck is $91,112. These costs have a negative social impact on the trucking industry, including increased costs for medical and emergency services, property damage, lost productivity, and increased workers' compensation premiums for the trucking company.

2.1.1 Job Description of Operating CMV

Operating a truck is more demanding compared to passenger vehicles. The stopping distance is approximately 50% greater in CMV's (NHTSA, 2013). Lane changes are harder due to the vehicle mass, length, and visibility, and turning around the corner also requires larger radius. Truck drivers must be more cautious planning the drive and need to maintain higher vigilance level than passenger vehicles drivers. Aside from driving a truck for up to thirteen hours per day, truck drivers have many additional duties including loading and unloading the trailers, brake checks and basic maintenance of the truck (Van Der Beek, 2012).

2.1.2 Health and Well-Being

Truck drivers are at high risk of serious health problems. There is an increasing prevalence of chronic stress, obesity, cancer, cardiovascular disease, musculoskeletal disorders in truck drivers compared to the general population (Apostolopoulos, 2010), with a life expectancy of 12-20 years less than the average worker in the United States (Saltzman & Belzer, 2007). In addition, truck drivers tend to have an unhealthy diet, consume alcohol, and smoke more than the average US worker (Apostolopoulos, 2010).

2.1.3 Role of Driver Drowsiness in Large Truck Crashes

The Federal Motor Carrier Safety Administration (FMCSA) reported that 78,000 large trucks were involved in crashes between April 2001 and December 2003, and critical reasons for the crashes included driver, vehicle, and environmental factors (FMCSA, 2007). According to Table 1, 87% of crashes were human factor related. The critical reasons including recognition, decision, and performance were all related with degraded sustained attention. Therefore, driver fatigue is a key factor in large vehicle crashes.

Table 1 Factors associated with large truck crashes, by major categories

Factors	**Number of Trucks**	**Percent of Total**
Driver	**68,000**	**87%**
Non-Performance	9,000	12%
Recognition	22,000	28%
Decision	30,000	38%
Performance	7,000	9%
Vehicle	**8,000**	**10%**
Environment	**2,000**	**3%**
Total Number of Large Trucks	**78,000**	**100%**

2.2 Driver Fatigue

Fatigue is defined as a state of tiredness or weariness caused by exertion on a cognitive, affective, or physical level. Sleepiness has been recognized as an important factor for fatigue, leading to vehicle related accidents, and most studies on driver fatigue have focused on shift scheduling and sleep regulation aspects, aiming to guarantee a driver's sleep time and reduce tiredness (Dawson & McCulloch, 2005). In the United States, drivers can work up to 14 hours a day and drive up to 11 hours every 24 hours. They are allowed to drive for 60/70 hours for 7 or 8 consecutive days, after which they need to rest for 34 hours (FMCSA, 2014). In Canada, the maximum on-duty time per 24-hour period is 14 hours and the maximum driving time is 13 hours. They can drive up to 70 hours a week and then must rest for 36 hours (Government of Canada, 2016).

As can be seen in Table 1, approximately 90% large truck crashes are resulted from human factors. Driver fatigue has been identified as a key factor (Thiffault, 2011). In this dissertation, driver fatigue and driver drowsiness will be used interchangeably. Driver fatigue is defined as an increased propensity to sleep or the process by which the state of wakefulness moves toward the sleepy end of the sleep-wake continuum, while further decreasing the driver's alertness (Thiffault, 2011).

In one study, almost half of truck drivers admitted to falling asleep while driving at least once in their careers (McCartt & Rohrbaugh, 2000). Although the hour of service regulations has helped to reduce the amount of overtime and the propensity for these drivers to fall asleep at the wheel, degraded vigilance remains an issue.

2.2.1 Vigilance

Mental fatigue can modulate high level cognitive processes, in terms of less attentional resources being allocated to stimuli, which then leads to a decrease in information processing and the speed with which decisions are made (Guo, Chen, Zhang, Pan, & Wu, 2016). Reduction in vigilance (alertness, attentiveness) and performance is often observed during drowsiness, the transient state between wakefulness and sleep (Corsi-Cabrera, Arce, Ramos, Lorenzo, & Guevara, 1996). The term vigilance has a variety of definitions, but the most common is sustained attention or tonic alertness (Oken, Salinsky, & Elsas, 2006).

Sustained attention is a critical component of attention; it refers to the brain's ability to retain attention and remain vigilant in the face of important stimuli that occur at unpredictable situations and over extended periods of time. (Parasuraman, 1976; Warm, 2008). These time points are random in nature. While focused attention, divided attention, shifting attention, and executive control of attention are all critical, sustained attention is the aspect that is most closely associated with alertness (Oken et al., 2006). Sustained attention is a basic attentional function that governs the efficiency of 'higher' forms of attention (selective attention, split attention) and cognitive capacity in general (Sarter, Givens &, Bruno, 2001). Sustained attention performance, such as driving, requires the subject to anticipate what type or modality of signal to expect (traffic lights, signs, and other vehicles), and how to respond in accordance with previously established response norms. Furthermore, the subject develops expectations for the likelihood of signals and reporting strategies for signals versus false alarms (Kastner & Ungerleider, 2000).

Numerous occupations, like driving, radar monitoring, and aircraft operation, demand operators to keep sustained attention on diverse items for extended periods of time. The reduction of sustained attention is an important factor that may have a negative impact on task performance and operational safety. (Bonnefond, 2010). Driving in a highly predictable or repetitive environment can be considered as a vigilance task and the impaired performance caused by decreased vigilance may contribute to vehicular accidents (O'Hanlon & Kelly, 1977; Chisvert, & Monteagudo, 2004; Lal & Craig, 2001; Thiffault & Bergeron, 2003; Straussberger, Schaefer, & Kallus, 2004). Truck drivers, especially long-haul truck drivers, experience long periods of monotony, which negatively impact driver alertness, vigilance, and driving performance (Harris, 1977).

2.2.2 Measuring Vigilance

Common drowsiness assessment methods include both subjective and objective assessments. Fatigue can be measured subjectively using the self-reported fatigue scales such as the Karolinska Sleepiness Scale, which has been adopted to assess driver sleepiness (Forsman, Vila, Short, Mott, & Van Dongen, 2013). Objectively, physiological assessments including electro-encephalography (EEG) have been used to measure fatigue directly by recording and analyzing brain wave patterns (Lal & Craig, 2001). Performance measures are also objective measures that track the performance degradation after performing sustained attention-requiring tasks, including Stimulus-response tasks, and more complex tasks utilizing driving simulators (Baulk, 2008). It has been suggested that drowsiness detection methods should be validated according to the gold-standard measures, including Karolinska Sleepiness Scale (KSS), Psychomotor Vigilance Task (PVT), lane deviation, and EEG (Golz & Sommer, 2010; Sunde et al., 2020). According to a comprehensive review, all fatigue monitors should be verified using PVT (May & Baldwin, 2009). In some testing environments, physiological measures like EEG might not be possible and efficient in detecting driver drowsiness. The Psychomotor Vigilance

Task (PVT) is easy to perform in the field study to detect the change in vigilance through different interventions (Du, 2015).

2.2.3 Psychomotor Vigilance Task (PVT)

The PVT is a sustained reaction time test that assesses subjects' alertness state and cognitive performance by measuring their response times to a visual stimulus (Dinges & Powell, 1985). The subject is told to press the button immediately after observing the number or dot on the screen. Within 5-10 minutes, the stimulus appears randomly every 2-10 seconds, for a total of 40-80 trials (Basner & Dinges, 2012).

2.2.3.1. Validity of PVT

Validity refers to an assessment tool's ability to accurately assess what it proposes to measure. As for PVT, the original purpose was to check the level of alertness throughout the day. The PVT is a neurocognitive test designed to monitor the temporally dynamic changes generated by interactions between the homeostatic urge for sleep and the circadian rhythm by assessing an individual's ability to maintain attention and respond promptly to salient cues (Dorrian, Rogers, & Dinges, 2005). PVT sensitively evaluates the sleep model, various variables that affect wakefulness, and the performance of daily activities (Du, 2015).

2.2.3.2 Application of PVT

PVT is advantageous because it is easy to manage, non-invasive, and provides direct measurement with a high degree of validity and reliability (Dorrian et al., 2005). The PVT has been extensively used to assess the effects of sleep deprivation, circadian rhythm disruption, duration on tasks, and sleep treatments on subjects' level of alertness (Van Dongen & Dinges, 2001). The PVT has also been used to assess truck drivers', airline pilots', and astronauts' vigilance (Dorrian et al., 2005).

Lopez et al. (2011) investigated the impact of 35 hours of continuous sleep deprivation on the PVT and flight operation of 10 US Air Force pilots in a flight simulator. The performance of PVT was compared with the performance of another cognitive task, the Operational Span Task (OSPAN). They found that PVT and OSPAN accurately predicted the performance and variance of the best performance during simulated flight. Another study using 40-hour sleep deprivation demonstrated that when the homeostatic pressure to sleep (or time awake) rose, PVT performance declined (lapses and reaction time increased) (Graw, Krauchi, Knoblauch, Wirz, & Cajochen, 2004).

Environmental effects on PVT performance have been studied. Morris and Pilcher (2016) conducted a PVT study to determine the effect of cold stress on simulated driving behavior. When approaching a stop sign during the car-following task, participants in the cold condition followed the lead car 22 percent (0.82 s) closer and began braking 20 percent later. However, there was no change in attention or psychomotor alertness.

PVT has been compared with other cognitive and sleepiness measures. Shattuck and Mastsangas (2015) evaluated the Epworth Sleepiness Scale's utility to predict deteriorated psychomotor vigilance performance in an operational context with active-duty crew members of a US Navy cruiser. It was found that there was a correlation between the Epworth Sleepiness Scale score and the average reaction time, reaction speed, the slowest 10% reaction speed, and errors. Compared with crew members with normal Epworth Sleepiness Scale scores, crew members with higher scores on the Epworth Sleepiness Scale (Epworth Sleepiness Scale> 10) had an average of 60% longer response time, and at least a 60% increase in lapses and false starts.

Lee and colleagues (2010) used the Multidimensional Fatigue Symptom Scale to study the relationship between PVT and subjective measures of fatigue in people with varying degrees of obstructive sleep apnea (OSA). They found that after controlling for age, BMI, degree of depression, and apnea severity, PVT lapses were still related with physical fatigue.

Lee (2011) also explored the relationship between sustained attention and health-related quality of life as measured by SF-36 in OSA patients with varying degrees of apnea. The study discovered that impairments in sustained attention may underline the limitations in physical health-related quality of life experienced by patients with OSA, even when demographic characteristics, apnea severity, and depression were controlled for.

Dostálová and Šonka (2011) suggested that the PVT test is a more sensitive tool than the Multiple Sleep Latency Test (MSLT) for evaluating psychomotor performance and indirectly measuring drowsiness. PVT reaction times were significantly higher, and the number of lapses increased in the group with pathologically shortened sleep latency in MSLT compared to the controlled group with normal sleep latency.

Molina and colleagues (2013) examined the correlation between the EEG spectrum and changes in the PVT reaction time (RT) on a trial-by-trial basis to assess the vigilance decrement. They discovered that frontal beta and occipital alpha power increased as the RTs lengthened, corroborating that the PVT may be a good candidate for predicting vigilance decrements in daily life tasks.

Furthermore, PVT has been used to assess the accuracy of ocular measurements. Wilkinson et al. (2013) discovered that the average duration of eyelid closure, the inter-event duration (IED), and the ratio of the amplitude to the velocity of eyelid closure were reliable indicators of PVT lapses (two or three more in a minute) with high sensitivity and specificity.

PERCLOS is an effective measure of driver drowsiness. PERCLOS considers the percentage of slow eyelid closure over a period (1-3 minutes) where an eyelid closure is defined as the eyelids being greater than 80% shut. When the eyelids are closed for over 13% of the time, it is a vigilance lapse (Wierwille, 1994).

PERCLOS is one of the most effective in-vehicle measurements of driver drowsiness (Ji, Zhu, & Lan, 2004) and has shown a high correlation with PVT. The PERCLOS measure has also been shown to be correlated to lane departures and subjective sleepiness (Morris, Pilcher, & Switzer, 2015), and has been used as a dependent measure in many other naturalistic studies of drivers (Wiegand, Hanowski, & McDonald, 2009; Dingus et al., 2006).

Although research results indicate that eye measurements may be a good predictor of drowsiness during driving, it cannot be extended to road driving without caution, because variables such as head and vehicle movement may change eyelid measurements. However, there are some eyeglasses with built in cameras that get around some of the limitations with dash mounted cameras, but literature on their use is limited. What's more, the physiological measurements obtained from eye-tracking and EEG are often difficult and expensive, making it difficult to incorporate them into real-world driving tasks (Caldwell, 2005). Hence, for research purposes, PVT may be a less invasive and low-cost method to assess driver drowsiness in practical situations, such as pre- and post- shift, or roadside testing during breaks. However, PVT is not suitable for continuous monitoring of drowsiness, which can be achieved through ocular measurements (Wilkinson et al., 2013).

2.2.3.3. PVT Metrics

The PVT has been used to assess perception, cognitive interpretation, and motor reactions. The PVT has been shown to be free of aptitude and learning effects and is reliable and sensitive to performance variations due to sleepiness and/or fatigue (Basner, Mollicone, & Dinges, 2011). Mean reaction time (RT), the number of lapses (reaction time >500 ms), lapse probability (lapses divided by total trials), reciprocal of reaction times (1/RT), and fastest 10% are obtained as performance metrics (Doran et al., 2001). Fatigue due to partial or total sleep loss causes reliable and quantifiable alterations in PVT performance, resulting in a general increase in response times and the number of lapses. Attentional lapses can occur because of either internal factor, such as sleep loss, or task-related factors including time on task. The 1/RT metric has been found to be sensitive to total and partial sleep loss (Dinges, 1987). 1/RT emphasizes slowing down in the optimum and intermediate response domains and, unlike mean reaction time (RT), it greatly reduces the impacts of long lapses (Banser & Dinges, 2011). Besides, since the duration of the PVT is fixed, the total number of stimuli including lapses depends on the reaction time of all the trials. Calculating the lapse probability normalizes the variance in the total number of trials.

2.2.4 Driver Drowsiness Factors

Falling asleep at the wheel is the greatest fatigue-related risk for crashing. Driver fatigue includes decreased vigilance, decreased performance, decreased motivation, impaired judgment, and feelings of drowsiness. Physiological and task-related factors are the two main categories of fatigue causations (Thiffault, 2011).

2.2.4.1. Internal physiological factors

Individual differences in age, fatigue susceptibility, circadian rhythms, sleep inertia, hours awake, caffeine intake, medication, and general health status are the most prominent physiological factors affecting alertness levels (May, 2009). Three major classes of factors impact drivers' sleepiness: recent sleep, time awake, and circadian status (Balkin et al., 2000; Dorrian, Baulk, & Dawson, 2011).

Acute sleep loss and cumulative sleep debt, result in decreased vigilance. Circadian rhythm, time of day effects also critically affect sleep, alertness, and driver performance. Past research showed that a great proportion of fatigue-related crashes happened in the early morning between 2:00 to 6:00 and during the afternoon between 14:00 to 16:00, because of internal circadian time of day (Thiffault, 2011). Health and wellness status affects the alertness of drivers. Health issues including sleep disorders and lower back pain also negatively impair drivers' neurocognitive performance (Karimi et al., 2012).

Previous research shows that untreated OSA is a critical factor for vehicle accidents (Tregear et al., 2009), and the prevalence of mild to severe OSA is higher among commercial truck drivers compared with the general population (Pack et al., 2006; Huhta, Hirvonen, & Partinen, 2021). Howard et al. (2004) conducted a study involving 3268 Australian commercial vehicle drivers and found 59% of the drivers were at risk for a different severity of sleep-disordered breathing and 15.8% had OSA. Pack and colleagues (2006) found that among 406 commercial drivers in Pennsylvania, 28.2% had more than mild sleep apnea, and 4.7% had severe sleep apnea based on the Apnea-Hypopnea Index (AHI) values.

While OSA has been linked to the increased risk of motor vehicle accidents, it was found to be unrelated to the PVT performance (Terán-Santos, Jiménez-Gómez, & Cordero-Guevara, 1999; Pack et al., 2006). As vehicle crashes are rare events and likely to be multifactorial. As suggested by Batool-Anwar (2014), no significant association was found between OSA severity as measured by AHI and vigilance-related PVT performance. In a review by Tregear et al. (2009), among drivers with OSA, the characteristics associated with vehicle crashes include BMI, AHI, oxygen saturation, and possibly daytime sleepiness.

Individuals with high levels of extraversion and a desire for excitement are more likely to suffer from boredom-related drowsiness, as they exert less effort when driving on monotonous roads (Thiffault & Bergeron, 2003). In addition, it has been found that as age increases vigilance gets more impaired, but older workers near or above retirement age (~60 years old) are less susceptible to circadian and wake-dependent PVT performance decrements (Blatter & Cajochen, 2007). Also, compared to mid-aged drivers, younger drivers tend to feel less vigilant when driving in monotonous road conditions (Otmani, Roge, & Muzet, 2005). Because they are more sensation seeking and easier to get bored.

2.2.4.2. External task-related and environment factors

Time on task (such as hours driving), task complexity, and monotony are all task-related elements that contribute to driver drowsiness (Thiffault, 2011). While task-related performance degradation is most noticeable with highly demanding jobs, it can also occur with less demanding tasks such as driving. Besides internal factors that determine the baseline status of a driver’s alertness, there are task-related external factors that affect drivers' drowsiness levels. Moreover, there exist environmental factors that also contribute to the impairment of driving drowsiness. Prolonged hours on the task also negatively affect alertness, which will impair sustained attention and cause a slowing in reaction times, and increasing drowsiness (McDonald, 1984). In almost any driving schedule where the driver’s shift rotates or periodically changes, there is a high degree of co-variation with time awake, driving hours, and work hours. Previous research shows that being awake for more than 16 hours is associated with significant performance decrements (Van Dongen, Maislin, Mullington, & Dinges, 2003). Multitasking driving, for example, texting and conversation on the phone, and direction searching needs additional mental capacity and may result in decreased alertness (Vearrier & McKeever, 2011; Nijboer, Borst, Van Rijn, & Taatgen, 2016). Different job complexity levels might result in either active or passive task-related drowsiness. For instance, driving in a complex environment, such as an urban region, needs more vehicle operation and is more challenging than driving in rural areas with a monotonous environment (Du, 2015).

Task-monotony-related fatigue factors have been shown to contribute to performance decrements over time. Monotony is an inherent characteristic in the transportation industries including road transport. Monotony can have an adverse impact on safety, reliability, and efficiency (Dunn, 2011). Driving with little traffic and other stimuli, especially on a specific route driven every day may be a cause of decreased alertness, contributing to passive task-related fatigue. These results suggest that solutions to monotony rely on increasing cognitive demand and task-directed effort. Conversely, over-engaging in mentally demanding tasks may induce an equally dangerous component of active task-related fatigue.

According to the Yerkes-Dodson Law, the relationship between arousal level and performance can be visualized as an inverted-U-shaped curve, as shown in Figure 1 (Yerkes & Dodson, 1908). This finding suggests that both low arousal (fatigue) and excessive arousal (stress) are related to performance declines (Coughlin, Reimer, & Mehler 2009). The Yerkes-Dodson findings also show that strong emotionality can improve performance under "simple" learning conditions, such as when learning requires a concentrated attention on a limited range of cues but impairs performance under more complex or challenging learning conditions, such as divided attention, multitasking, and working memory tasks (Diamond et al., 2007). The optimal range of performance lies between these two extremes, when the amount of arousal and attention is well matched for the task demands (Hanoch & Vitouch, 2004).

Hence, monotonous driving conditions low in complexity can be quite challenging to handle because drivers may find it hard to focus on the important aspects of the driving task due to the lack of arousal and stimuli (Unal, 2013).

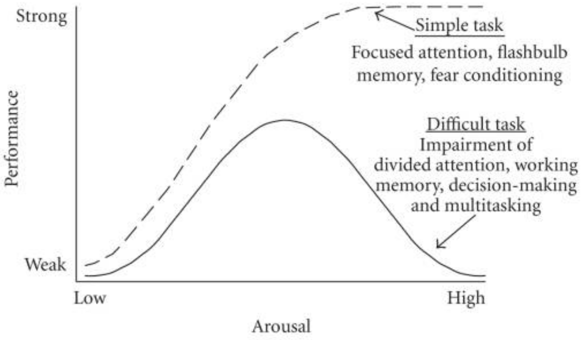


Figure 1 Yerkes-Dodson Law (Diamond, 2007)

Furthermore, the environment in which the operating task is performed also influences driver vigilance. Whole-body vibration is one important environmental component that drivers are continually exposed to (WBV) during operating vehicles. WBV is the oscillation of the human body generated by the truck engine's vibration and the road (ISO 2631-1, 1997). Previous study employing EEG as an objective measure of wakefulness discovered that following a 20-minute exposure to WBV, wakefulness level decreased (Satou, 2006). Other studies utilizing self-reports of alertness discovered comparable findings following acute WBV exposure (Ljungberg, 2007). A thorough description of WBV will be included in the following sections.

2.2.5 Managing Driver Drowsiness

Different fatigue management methods may be used to assess different factors that may be associated with driver fatigue. If sleep deprivation is the source of drowsiness, caffeinated product consumption, taking a rest break, and altering or improving the driving shift schedule are methods that can be employed to reduce sleep related drowsiness (Du, 2015).

For active task-related fatigue, technologies including adaptive cruise control (ACC), lane tracking and warning systems all help reduce drivers' mental workload and allow drivers to re-allocate their attention. Indeed, these strategies and assistive devices have limited effectiveness for reducing accident risk (Ting, Hwang, Doong, & Jeng, 2008). ACC reduces the workload, but it also slows the driver's response time. Such outcomes may be attributed to misconceived effort regulation; drivers attempted to adapt to changing workloads dynamically, but do not always allocate resources optimally (Hancock & Verwey, 1997). Recent studies revealed that ACC may change driving patterns and perceptions over time. One study found that drivers who reported higher overall use of ACC also used the system in distracted or impaired situations, which can negate the overall benefits of ACC, whereas older drivers were less likely to use ACC while distracted (Wu & Bolye, 2015). A survey-based study discovered that users' trust with ACC seemed to be formed in the initial interactions with ACC, and users tended to over trust ACC if they were male, misused the system, lacked the awareness of ACC limitations (Dickie, 2010).

What's more, stimulating activities such as listening to music, talking to someone will help relieve passive task-related drowsiness, which can also lead to cognitive distraction (Barr, Howarth, Popkin, & Carroll, 2009; vearrier et al., 2016).

2.3 Whole-Body Vibration Exposures to Drivers

The International Organization for Standardization (ISO) defines WBV as the vibrations transmitted from the supporting surface to the human body through the buttocks of an operator (ISO 2631-1, 1997). Previous studies have shown that long-term exposure to occupational WBV may damage the cardiovascular, cardiopulmonary, metabolic, endocrine, nerve, gastrointestinal, and musculoskeletal systems of the operator (Thalheimer, 1996).

2.3.1 Features of Whole-Body Vibration

There are three main features of WBV: vibration frequency, magnitude, and duration. The typical range of excitation in ground vehicle is 4 to 10 Hz (Wang & Rakheja, 2008). According to previous studies, the natural frequency of human body parts ranges from 3 Hz to 17 Hz, and the dominant frequency transmitted from the seat to the operator's body in the vertical director is mainly 4–6 Hz (ISO 2631-1, 1997; Ren, Peng, Shen, Li, & Yu, 2018). Human body was most sensitive with the vibration ranges 2 - 6 Hz in the vertical and fore-and- aft direction, and 1 - 2 Hz for the lateral direction (Arnold & Griffin, 2018).

The magnitude of WBV is an important aspect that affects human health. Exposure to WBV below 0.01 m/s^2 is rarely felt, and exposure above 10 m/s^2 is considered hazardous (Griffin, 1990). When the average weighted WBV amplitude exceeds 2.0 m/s^2, people will feel very uncomfortable (ISO 2631-1, 1997).

The duration of WBV exposure also influences the human body's response to vibration (Seidel & Heide, 1986). ISO 2631-1 states that increasing the magnitude and duration of vibrations increases the health concerns associated with WBV exposure. A long-term acceleration with a smaller amplitude can be compared to a shorter period acceleration with a larger amplitude (ISO 2631-1, 1997).

WBV exposure is described in terms of the frequency-weighted root-mean-square (RMS) acceleration (Aw), and the vibration dose value (VDV) calculated through root-mean-quad (RMQ), which is more sensitive to jolts and shocks (Dong, 2013). The predominant axis, the z-axis in the vertical direction is often used to calculate the two measures for the seated WBV. Aw and VDV are always expressed by the equivalence over and 8-hour referenced period as A(8) and VDV(8) (Bovenzi, 2009). The action and exposure limit values recommended by the European Union Vibration Directive 2002/44/EC (EU, 2002) are in Table 2.

Table 2 European Limits for whole-body vibration exposure

European Union	**A(8) (m/s^2)**	**VDV(8) ($m/s^{1.75}$)**
Action Limit	0.5	9.1
Exposure Limit	0.8	14.8

2.3.2 Reducing Whole-Body Exposure to Drivers

WBV is associated with many adverse health effects, including low back pain, muscle fatigue, headaches, gastrointestinal problems, hearing loss, sleep problems, and driver drowsiness, all of which can contribute to vehicle-related accidents. According to Bovenzi (1996), the Council of the European Union produced a directive prior to the revised 1997 ISO standards advising investigators to use their daily 8-hour action level A (8) of 0.25 m/s^2 as the threshold for which no adverse health effects will occur (Cann, Salmoni & Eger, 2004). WBV is particularly hazardous to truck drivers due to the chronic exposures to resonant frequencies which the human body is sensitive to. Additionally, there is a large body of literature on the use of WBV to prevent muscular dystrophy and bone loss in spinal cord patients, osteoporosis patients, and astronauts. However, these WBV bouts are usually administered in a standing or lying position at a higher frequency (20 to 50 Hz) with a short duration less than 30 minutes (Cardinale & Pope, 2003).

Drivers' exposures to WBV can be affected by multiple factors including vehicle characteristics, vehicle speed, road conditions, seats, and driving characteristics. (Village et al., 2012). Cab suspension, seat suspension, weight of driver, and the posture of the driver have been recognized as factors that can influence the levels of WBV experienced by drivers (Tiemessen, 2007). Vehicle speed was found to have a great influence on the ride comfort experienced by heavy duty truck drivers. The ride comfort in heavy duty trucks was shown to decrease with increasing speed (Jie, Wang, Gao, & Zhang, 2016). Rougher roads are associated with greater levels of WBV in all three axes because of the increased jostling caused by potholes and irregularities of the road surface. In contrast, more of the WBV experienced when travelling on smoother road profile is predominantly in the vertical direction and these vibrations are from the engine, tires, and suspension of the vehicle (Cann et al, 2004; Li, Wang, Gao, & Zhang, 2016).

Low frequency vibration around 3.2 Hz has been shown to linked to extremely uncomfortable driving and riding experiences of commercial heavy trucks (Yang, Lu, Sun, Liu, & Hou, 2016), and it has been found that poor isolation of the rear tandem suspension system in the semi-truck cab is the root cause of these low-frequency vibrations. For vertical vibration, research also found that the loaded trucks attenuate higher frequency vibration (> 20 Hz) and amplify the lower frequency vibration (1 – 20 Hz), whereas for the translational x- and y-axes, the opposite is the case. With unloaded trucks having empty trailers, the vibrations in the translational axes increase relative to loaded trucks. (Maheras, Lahti, & Ross, 2013).

In engineering interventions, seat suspension design has always been a promising area for reducing WBV (Griffin, 1990). It has been advocated to compare various seats and suspension systems for reducing exposures to vibration (Cann et al., 2004). Some studies have shown that there is a significant difference in vibration attenuation between laboratory research and field research; this may be because laboratory and field research have different vibration characteristics. For instance, a defective or worn seat may amplify the driver's exposure to low-frequency vibration (Dentoni & Massacci, 2013). What's more, laboratory-based vibration simulators cannot capture low-frequency components below 1 Hz, such as changes in vehicle suspension and road terrain.

Almost all commercial industrial seats use a passive mechanism that consists of a damper and spring element. Usually, the spring element is a steel spring or cylinder, which is used to minimize the vibration transmitted to the operator (Padden & Griffin, 2002; Ji, 2015). However, previous studies have shown that these mechanisms of the seat often amplify rather than reduce vibration exposure (Paddan & Griffin, 2002; Donati, 2002; Cation, Oliver, Jack, Dickey, & Lee, 2008; Dentoni & Massacci, 2013). What's more, due to the complexity of the seat's frequent-dependent performance, heavy-duty vehicle seats should be chosen and adjusted appropriately for the vehicles and vibration environment in which they will be used (Ji, 2015).

Recently, electromagnetically active seat suspension has been introduced as a countermeasure to reduce the vibration experienced by the truck drivers (Johnson, Zigman, Ibbotson, Dennerlein, & Kim, 2018). These active suspension seats have been shown to reduce the floor transmitted z-axis WBV exposure by 50% compared to the conventional passive air suspension seats (Blood, Dennerlein, Lewis, Rynell, & Johnson, 2011).

2.4 WBV and Vigilance

Very few studies have examined the effect of WBV on cognitive performance in real, field-based trucking scenarios, and the testing conditions in lab-based studies are not representative because of the variation in the cab suspensions, vehicle suspensions, road terrain, and speed (Troxel, 2015).

In 1985, the relation between WBV and wakefulness was examined by electroencephalography (EEG) with a vibration simulation platform. Random vibration ranges from 2 to 20 Hz and 3 Hz sinusoidal vibration exposures were simulated with a magnitude of 0.3 m/s^2. Both types of vibration exposure resulted in a significant decrease in wakefulness when compared to a resting period without vibration (Landström & Lundström, 1985). In this study, the ratio between EEG alpha and theta activity was used as the measure of wakefulness; an increased theta and decreased alpha activity indicated decreased wakefulness. In another study, Satou and colleagues discovered a significant decrease in EEG's alpha attenuation coefficients after participants were exposed to a 12-minute WBV of 10 Hz and 0.6 m/s^2 (Satou, 2007). Usually, the z-axis WBV exposures of heavy vehicles range from 0.4 to 2.0 m/s^2, with an average of 0.7 m/s^2 (Mabbott, Foster, & McPhee, 2001). Various studies aiming to mimic the WBV exposures of operating different types of vehicles have been conducted in both laboratory studies and field studies.

In the laboratory studies, vibration exposures have been replicated using vibration platforms, where participants sat on a truck seat or car seat placed and accelerometers mounted on the seat top to measure the vibration. The vibration exposures in many studies are constant or with small variations such as sinusoidal waveforms (Mozell & White, 1958; Webb et al., 1981;

Landström & Lundström, 1985). For example, a study by Ljungberg and Neely (2007) simulated the vertical operating vibration of a forwarder with amplitude 1.1 m/s^2 at 4Hz.

Some recent studies have focused on keeping the frequency and amplitude more representative of the real world or even collecting real on-road vibration as the exposure for the simulation. There is one study simulating vibration exposures with amplitude and frequency consistent with the trucking environment, where 3 dimensional random/sinusoidal vibration exposures were controlled at the magnitudes of 0.53, 0.81, and 1.12 m/s^2 with the frequency ranges from 3 to 7 Hz (Zamanian, Nikravesh, Monazzam, Hassanzadeh, & Fararouei, 2014).

Very few field studies have studied the effect of WBV on alertness. The duration of many of the previous studies was significantly shorter than truck drivers' working hours. In most of the studies, WBV exposures were less than 30 minutes. Moreover, some studies exposed the participants with accelerations less than 3-minute duration (Newell & Mansfield, 2008; Zamanian et al., 2014). Short term exposures were less representative of the prolonged exposure suffered by professional truck drivers, which limited these studies.

A few studies have explored the effect of prolonged WBV through observation instead of quantitative measurements, self-reported methods were used instead of objective measures (Lindberg, Carter, Gislason, & Janson, 2001; Abbate et al., 2004). Lindberg et al. aimed to build the link between WBV and occupational accidents including both driving-related and non-driving-related accidents, and thus have limited generalizability on fatigue-related accidents induced by WBV. Abbate et al. (2004) found that there was more self-reported fatigue from the mechanical trolley drivers compared with non-drivers, which was believed to be associated with long term WBV exposures.

In summary, most controlled laboratory studies have indicated that there are negative effects of WBV on alertness using both subjective and objective measures. There do not appear to be any published field studies that examine the decline in drivers' vigilance performance as a direct result of WBV exposures. Rather than that, much of the research on WBV prevention has been motivated to establish the relationship between WBV and low back pain (Tiemessen, 2007; Burström, Nilsson, & Wahlström, 2014). Most data on driver drowsiness come from self-reports or accident reports based on collision analysis. Rather than studying earlier signs of sleepiness such as hypovigilance, many of these studies focus on extreme cases of sleepiness, such as drivers with chronic fatigue or sleep disorders, who have a high likelihood of falling asleep behind the wheel (Thiffault, 2011). Therefore, a study that measures the changes of vigilance due to long-term laboratory and actual field environment WBV exposure is needed to fill some of the existing gaps in the study.

Thus, the primary goal of this research is to establish whether seat suspensions that reduce WBV levels have any influence on vigilance when measured via a sustained reaction time task.

2.5 Study Objectives and Specific Aims

The objectives of this thesis, in both simulated, lab-based; and occupational, field-based settings; is to determine whether there are differences in PVT performance (including the mean reaction times, mean reciprocal of reaction times, mean fastest reaction times, and lapse probability) when sitting (lab-based) or operating vehicles (field-based) in seats with different WBV attenuation characteristics.

Aim 1

Compare the WBV exposures and PVT responses in a lab-based setting using an industry standard passive truck seat and an active suspension truck seat.

Aim 2

In a real world, field setting, compare the WBV exposures across four industry standard truck seats to determine whether there are differences in vibration attenuation characteristics across the four seats. If there are differences in attenuation characteristics, then it is hypothesized there may be differences in PVT responses.

Aim 3

In a real world, field setting, determine whether prolonged exposure to WBV affects drivers' sustained attention over the course of a normal work shift through PVT. In addition, compare the PVT performance outcomes across four truck seats to determine whether different levels of WBV exposures affect drivers' vigilance differentially.

This dissertation will consist of two main parts, Chapter 3 contains and covers results form a repeated measure laboratory-based simulated vibration study and Chapters 4 and 5 consists of a crossover field study characterizing WBV exposures and comparing PVT performance across four different commercially available truck seats.

In the laboratory study, eight experienced truck drivers were recruited. To create a WBV exposure contrast, the drivers were instructed to seat on an active and a passive suspension seat installed on a vibration simulating platform for two hours while being exposed to real-world WBV exposures previously collected from a freeway. In this study, a PVT task was administered before and after the WBV exposures and WBV attenuation performance and PVT outcomes were compared with respect to time and between the two seats.

In the field study, twenty-four truck drivers from a transportation company, were recruited. WBV exposures were collected over drivers' 10-hour regular shifts as they all drove across the same standardized route while using four different commercially available truck seats: the truck's original fitted, industrial standard passive suspension seat, an active suspension seat, and two other passive suspension seats. The WBV exposures across the whole shift were measured and the drivers took the PVT and a discomfort survey before and after their regular shift with the four seats. WBV attenuation performance and PVT outcomes were compared with respect to time and across the four seats.

Chapter 3 A Laboratory-Based Study

3.1 Introduction

The goal of this laboratory-based study was to determine whether there were differences in PVT performance when subjects were exposed to different levels of WBV. Two seats, an active and a passive-suspension seat were compared to explore if there were differences in the PVT outcomes with the expected differences in WBV exposures. According to prior research, it was anticipated that the two seats would exhibit a roughly 50% difference in WBV attenuation performance (Blood & Johnson, 2011). A three-dimensional vibrating platform (hexapod system) was configured in a laboratory setting using field-collected WBV exposures from the floor of a truck cab to expose eight truck drivers to two hours of simulated truck driving (Halverson, 2013). The aim of this study was to determine whether changes in drivers' vigilance performance occurred with prolonged exposures to WBV and whether there were vigilance differences based on the expected WBV exposure differences between the two seats.

3.2 Methods

3.2.1 Study Participants

Eight male subjects agreed to participate in this study and their informed consent was obtained. The demographics for the subjects are shown in Table 3.

Table 3 Description of study participants, N=8, SD=standard deviation

Characteristics	Mean	SD	Range
Age	43.25	9.91	(25, 55)
BMI	33.96	5.16	(25.79, 42.17)
Weight (kg)	107.27	19.92	(83.9, 141.1)
Height (cm)	177.48	6.71	(167.6,187.9)
Years as Trucker	21.75	11.47	(3,40)

3.2.2 Study Design

The laboratory study used a repeated measures design to determine the effects of seated vibration exposure on truck drivers' cognitive function and whether different magnitudes of WBV had a differential effect on measures of vigilance. As shown in Figure 2, a six degree of freedom vibrating platform named hexapod (Moog Inc., Kirkland, WA) was used to replay the field collected vibration data. Mock steering wheels and pedals were installed on the hexapod to better simulate the driving experience during the simulated truck driving. Subjects were exposed to simulated WBV exposures for two hours collected from a semi-truck. Two different truck seats were used to create two different levels of WBV exposures. The experiment was conducted on two consecutive days. The truck drivers were exposed to WBV on one day while sitting in an active suspension truck seat (BoseRide; Bose Inc.; Framingham, MA), and on the subsequent day sitting in an industry standard passive air-suspension truck seat. The passive suspension seat was simply the active suspension seat with the active suspension turned off, so the two seats looked the same. When truck drivers sat in the passive-suspension seats, WBV exposures were expected to be approximately 50% higher (Blood et al., 2011; Wang, Davies, Du, & Johnson, 2016; Johnson et al., 2018). Seating arrangements were randomly assigned and counterbalanced.

Subjects were asked to complete a 5-minute Psychomotor Vigilance Task on a laptop immediately before and after two hours of WBV exposure (PVT).

3.2.3 Vibration Simulating System

The Hexapod system has previously been successfully used to simulate various occupational vibration exposures related to the use and operation of heavy vehicles (Cation, Oliver, Jack, Dickey, & Lee 2011). An 8-minute segment of tri-axial truck floor vibration data collected from a freeway in Washington State was continuously repeated for two hours to serve as the input of the hexapod (Halverson, 2013). The daily averaged weighted vibration [A(8)] and the daily vibration dose value [VDV(8)] WBV exposures were equivalent 0.48 $m/s^2$and 9.3 $m/s^{1.75}$, respectively.

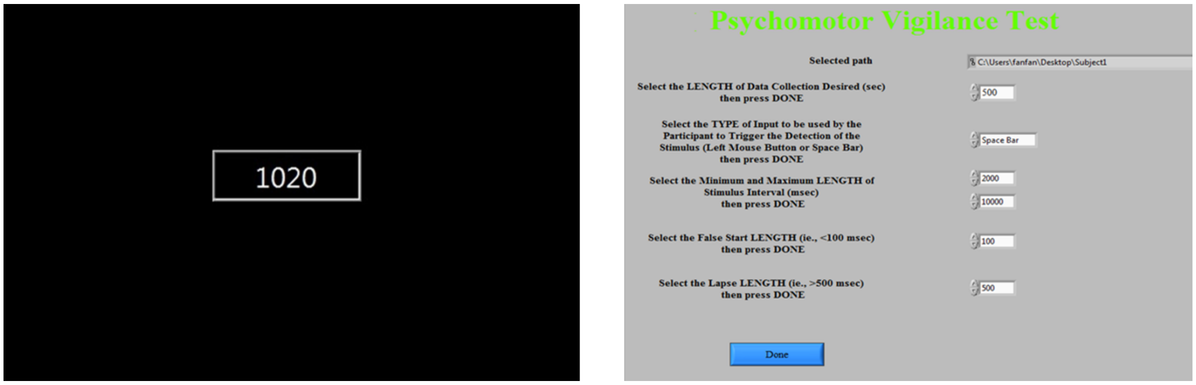
Figure 2 Hexapod mounted with the two truck seats, the active suspension seat is in the background and the passive suspension seat in the foreground

According to ISO 2631-1 WBV standards, WBV exposures were collected at 1280 Hz from the top of the truck seat and the hexapod floor using tri-axial accelerometers (Model 356B40; PCB Piezotronics; Depew, NY) (Wang, Davies, Du, & Johnson, 2017). The data acquisition system that was used to collect WBV exposure was an eight-channel data recorder (model DA-40, Rion Co., LTD., Tokyo, Japan) where raw unweighted triaxial WBV measurements were taken. (Blood & Johnson, 2011). The WBV exposures when the subject sat in the active and passive suspension seat were compared to determine if the two seating conditions resulted in different exposures. Subjects adjusted their seats to their desired height and back rest position prior to the experiment; armrests were used in all cases. As illustrated in Figure 2, subjects were asked to simulate driving conditions and were instructed to watch a large screen television in front of the hexapod. (Halverson, 2013).

3.2.4 PVT Measurement

Most previous studies have adopted the standard 10- minute PVT. However, the standard 10-min PVT was often considered impractical for operational settings due to its duration. This study used the 5 minute PVT since it had been validated in other applications and settings (Roach, Dawson, & Lamond, 2006) . Immediately before and after the two-hour WBV exposure, a 5-minute, laptop-based psychomotor vigilance task (PVT) was used to measure subjects' reaction time (RT). The PVT program was written in LabVIEW (LabVIEW, Version 2013, National Instruments, Austin, TX). As shown in Figure 3, during the task, subjects saw a blank box in the middle of the screen. At random intervals (2-10s), a millisecond counter started to scroll, and subjects were instructed to stop the counter by pressing the space bar using the index finger of their dominant hand as soon as they could (Dinges & Powell, 1985). The RT of each trial was displayed and recorded. Subjects completed training trials until they got familiar with the task.

PVT performance was evaluated pre- and post-WBV exposure and compared between the two different WBV exposure conditions (the two seating conditions) to assess the potential influence of WBV exposures on subjects' PVT performance and examine the effect of different levels of WBV exposures on vigilance performance impairment (Wang & Johnson, 2014).



Selected path: C:\Users\fanfan\Desktop\Subject1
Select the LENGTH of Data Collection Desired (sec) then press DONE: 500
Select the TYPE of Input to be used by the Participant to Trigger the Detection of the Stimulus (Left Mouse Button or Space Bar) then press DONE: Space Bar
Select the Minimum and Maximum LENGTH of Stimulus Interval (msec) then press DONE: 2000, 10000
Select the False Start LENGTH (ie., <100 msec) then press DONE: 100
Select the Lapse LENGTH (ie., >500 msec) then press DONE: 500

Figure 3 The left part shows the laptop screen with number scrolling during the PVT, and the right part shows the parameter settings of PVT

3.2.5 Data Analysis

From the 5-minute PVT, four outcome metrics: mean reaction time (RT), mean reciprocal of RT (1/RT), the mean fastest 10% RT, and the lapse probability were selected and calculated in the subsequent data analysis. To minimize the learning effect, the first two trials of the PVT were omitted (Doran, Van Dongen, & Dinges, 2001). In each PVT, the total number of lapses (RT>500 ms) were counted, and lapse probability was calculated by dividing the total number of lapses by the total number of stimuli (Anderson, Wales, & Horne, 2010). 1/RT was calculated by reciprocally transforming each RT, multiplied by 1,000, and then the average of the 1/RT values for the entire test was obtained as mean 1/RT (Basner & Dinges, 2011). Mean 1/RT is a measure that is similar to the mean RT as it takes into account all RT, but by the nature of the inverse function, the fastest (smallest) reaction times are weighted more heavily than the slowest (largest) RT (Du, 2015). The fastest 10% RTs for each PVT were identified and averaged. In each PVT test, outliers of more than three standard deviations above the mean RT of that test were excluded for calculating mean RT and mean 1/RT (Jackson et al., 2013; Wilson, Dollman, Lushington, & Olds, 2010). Consequently, 2% of all reaction times were excluded as outliers in the 32 PVT tasks. There were on average 44 (SD = 3.69) reaction time trials in each PVT task, and 1419 reaction times in total.

The main effects responsible for changes in the PVT metrics were test time (pre- or post-exposure) and seat type (passive suspension or active suspension). Statistical software R (R Core Team, 2021) was used to perform these analyses. PVT performance differences between the two WBV exposure conditions and pre- /post- WBV exposure were expected.

Power and sample size methods exist only for a small class of mixed models analyzing repeated measure data sets, most of these methods are based on approximations (Guo, Chen, Zhang, Pan, & Wu, 2013). Hence, validated computer software has been recommended, and GPower has been one of those software applications for calculating power and sample size (Prajapati, Dunn, & Armstrong, 2010).

This study can be described as a two-by-two repeated measure design, given two vibration levels and test times. Setting type I error α to 0.05, type II error β to 0.2, and effect size of lapse probability to 1.59, GPower (Version 3.1.9.2) calculated the sample size as 7. As a result, a sample size of at least 7 participants per study group was required to conclusively demonstrate that there is a difference in PVT scores between seats, as shown in Appendix A . Since the effect size used was based on acute sleep deprivation, the sample size may need to be larger than 7 because of the difference of the exposures. While an 8-person sample size is not optimal, it was chosen due to the constraints of cost and time (access to hexapod).

Because of the potential small sample size obtained, nonparametric Wilcoxon signed-rank tests were used to evaluate the main effects test time and seat type on the PVT outcome metrics. The median differences in the four PVT outcome metrics between vibration levels and pre- and post-WBV exposure were used for hypothesis tests. One test was performed to determine whether there was a significant difference in PVT performance after a two-hour WBV exposure. A second test was conducted to determine whether there was a statistical difference in PVT performance between the active suspension and passive suspension seat, based on the anticipated 50% difference in WBV exposure. Finally, to control for potential individual differences in the pre-shift, baseline PVT outcome measures, the changes in PVT outcome measures (Post-Shift – Pre-Shift) were compared.

3.3 Results

3.3.1 WBV Exposure Data

There were significant differences in WBV exposures between the two seat types. Only the z-axis WBV exposures were reported because the hexapod was programmed to only provide vibration in the z-axis. As can be seen in Table 4, the 8-hour average weighted vibration, A(8) for the active and passive suspension seats was 0.25 (±0.014) and 0.51 (±0.009) m/s^2, respectively. The average hexapod floor-measured z-axis A(8) vibration was 0.41 (±0.002) m/s^2 (Halverson, 2013). With the active suspension turned off, the active suspension seat behaved identically to a passive air-suspension seat, amplifying WBV exposures measured on the hexapod floor by 20.8% (± 20%), whereas the active suspension seat reduced WBV exposures by 33.6% (±10%).

Table 4 The mean and standard error of z-axis WBV exposures measured from the seats and at the floor of the hexapod. SEAT stands for Seat Effective Amplitude Transmission and is the percentage of the floor measured vibration transmitted to the seat of the operator

A(8) (m/s^2)	Active Suspension	SE	Passive Suspension	SE	p-value
Seat	0.25	0.014	0.51	0.009	<0.0001**
Floor	0.41	0.002	0.41	0.002	1.00
SEAT	67%	10%	120.80%	20%	<0.0001**

3.3.2 Main Effects

Pre- vs. Post-Exposure

The effects of the test time (pre- or -post) on PVT performance across both seats are shown in Table 5. Although the differences were not significant, higher mean RT, lower mean 1/RT, and higher lapse probability occurred after the exposure to the WBV.

Table 5 Median and interquartile range (IQR) of the four PVT outcome metrics presented by test time. (n =16)

PVT Outcome Metrics	Pre-Exposure	Post-Exposure	p-value
Mean RT (ms)	327.91 (322.40, 355.18)	346.81 (329.64, 359.54)	0.26
Mean 1/RT (1/s)[1]	3.09 (2.89, 3.17)	2.98 (2.85, 3.07)	0.24
Fastest 10% RT (ms)	277.89 (265.83, 285.32)	277.79 (266.63, 290.60)	0.73
Lapse Probability (%)	2.44% (0, 7.05%)	3.16% (0.52%, 6.36%)	0.86

[1] For Mean 1/RT higher values indicate superior performance.

Active suspension vs. Passive suspension

Table 6 and 7 show the effect of seat type on PVT performance before and after the WBV exposures. No significant differences of the PVT measures were found between the two seats before and after the exposures. From Table 7, although the PVT outcome metrics were not significantly different between the two seating conditions, the trend continues to show that PVT performance was better with the active suspension seat after the exposure.

Table 6 Median and IQR of the four PVT outcome metrics before exposures presented by seat type. (n=8)

PVT Outcome Metrics	Active Suspension	Passive Suspension	p-value
Mean RT (ms)	322.90 (319.99, 352.33)	337.31 (322.99, 367.44)	0.29
Mean 1/RT (1/s) [1]	3.14 (2.92, 3.20)	3.05 (2.80, 3.14)	0.17
Fastest 10% RT (ms)	276.77 (262.08, 284.72)	280.14 (266.52, 289.37)	0.46
Lapse Probability (%)	3.31% (0, 7.02%)	2.44% (0, 8.60%)	0.87

[1] For Mean 1/RT higher values indicate superior performance.

Table 7 Median and IQR of the four PVT outcome metrics after exposures presented by seat type (n=8)

PVT Outcome Metrics	Active Suspension	Passive Suspension	p-value
Mean RT (ms)	346.81 (320.03, 357.33)	348.39 (332.75, 388.29)	0.60
Mean 1/RT (1/s) [1]	3.00 (2.85, 3.17)	2.92 (2.84, 3.07)	0.53
Fastest 10% RT (ms)	274.92 (264.67, 292.52)	279.77 (271.05, 290.60)	0.60
Lapse Probability (%)	2.3% (0, 4.33%)	5.00% (2.09%, 8.98%)	0.20

[1] For Mean 1/RT higher values indicate superior performance.

3.3.3 The Change of PVT Outcome Metrics

From Table 6 and 7, although not significant, lower pre- exposure while higher post-exposure lapse probability was found with the passive suspension seat compared to the active suspension seat. After the WBV exposure, potentially less degradation in PVT performance was found in the active suspension seat than in the passive suspension seat.

As shown in Table 8, the changes in PVT outcome metrics were obtained by subtracting the pre-exposure metrics from the post-exposure metrics for each measurement. Wilcoxon signed-rank tests were conducted to compare the difference in PVT outcome metrics between pre- and post- exposures by seat types. A significant post-exposure increase in lapse probability was found for the passive suspension seat, while the lapse probability decreased with the active suspension seat. Also, potentially larger degradation of mean RT and mean 1/R were found with the passive suspension seat.

Table 8 Median (IQR) of the changes in the four PVT outcome metrics after the WBV exposures by seat type; **=p<0.05. (n = 8)

Changes in PVT Outcome Metrics	Active Suspension	Passive Suspension	p-value
Mean RT (ms)	4.26 (-10.85, 22.43)	14.84 (-18.32, 22.03)	0.83
Mean 1/RT (1/s)[1]	-0.06 (-0.23, 0.08)	-0.09 (-0.19, 0.13)	0.75
Fastest 10% RT (ms)	9.30 (-11.83, 20.49)	4.05 (-14.48, 10.69)	0.60
Lapse Probability	-0.50% (-2.00%, 0)	3.66% (-0.23%, 4.58%)	0.046**

[1] For Mean 1/RT higher values indicate superior performance.

3.4 Discussion

This laboratory study partially supported the hypothesis that WBV exposures appeared to affect drivers' vigilance, and reduced WBV exposure was associated with less degradation in vigilance. In comparison to the conventional passive air suspension seats, there was a trend toward truck drivers using the active suspension seats maintaining a higher level of vigilance. The changes in vigilance were found under these study conditions using the PVT, with the lapse probability being the most sensitive outcome metric.

The BMI (mean ± SD) of the study participants was 34.0 ± 9.9, which was higher than the average for truck driver populations, with four out of every eight drivers having a BMI of 35 or greater (obese status). However, studies have shown that truck drivers are more likely to be obese, up to 69% (Sieber et al., 2014; Du, 2015). As a result, the sample used in this study was representative of the truck driver population.

The active suspension seats were effective to lower truck driver's WBV exposures. Consistent with the results from previous studies (Blood et al., 2011), the z-axis A(8) of seat top WBV of the active suspension seats was found to be 49% lower than the passive air suspension seats.

The changes in PVT performance had a greater degradation after the WBV exposures when subject sat in the passive suspension seat. Newell and Mansfield (2007) discovered a significant increase in visual motor choice reaction times of approximately 50ms after exposure to WBV in a laboratory study. Our study adds to the body of evidence that lowering WBV exposure may improve performance in reaction time tasks. Also, we found the lapse probability decreased after the two- hour WBV exposure in the active suspension seat, which indicated there was actually a slight improvement in lapse performance with the active suspension seat.

According to the results in Table 6 and 7, not all PVT outcome metrics reacted the same way to the main effects, test time (pre- and post-WBV exposure) or seat type. In general, the mean RT and lapse probability metrics were more sensitive to detect differences than the fastest 10% RT and mean 1/RT (Du, 2015). Consistent with the Basner and Dinges (2011) study, the most frequently used PVT outcome metric was lapses, which was also used to validate driver drowsiness detection devices.

Furthermore, different PVT outcome metrics detect different aspects of driver vigilance. For instance, the mean RT considers all reaction time trials and evaluates the overall performance, but it disregards performance variability. As with mean RT, mean 1/RT also accounts for all reaction times; however, the reciprocals of reaction times were heavily weighted due to the nature of the inverse function, which mitigates the effect of outliers with extremely slow reaction times. Besides, the fastest 10% provides the limit of how fast a subject can respond, perhaps characterizing the upper limit cognitive capability of the subject.

3.5 Conclusions

The passive, air-suspension seat had substantially higher WBV exposures than the active-suspension seat and the responses to the PVT appeared to be affected by the magnitude of the WBV exposure levels (Wang & Johnson, 2014). When the subjects sat in the passive-suspension seat, post-WBV exposure, they tended to have longer reaction times and more lapses per trial. In the real driving scenario, more complex situations will be encountered by the drivers compared with the simple button-pressing task in PVT. Reaction times will increase greatly when there are multiple stimuli and response options (Hick, 1952), indicating higher risk of accidents. This laboratory study provided evidence that truck seats, and ultimately WBV, influence driver drowsiness and performance as evaluated by the PVT. This study showed that driver vigilance can potentially be improved with the control of WBV levels through the ergonomic intervention, the active suspension seat technology.

3.6 Limitations and Bias

The primary limitation of this study involved its small sample size of 8 subjects. Though nonparametric approach was applied, stronger relationships could be discovered with larger subjects. Besides, a larger sample size may have the potential to reduce the possibility of type 2 error. In addition, neither subjects nor researchers were blinded to the type of seat, and it was possible that this lack of blinding may have biased results away from null if subjects expected faster reaction time after the exposure to the WBV when sitting in the active suspension seat.

Another limitation was that the steering wheels and the pedals did not work, which will not simulate the driving environment and the operations to drive the trucks. Also, the drivers were watching a movie played on a screen placed approximately 3 meters in front of them to help simulate keeping their eyes in front of them on the road, which was not representative of real-world driving, and this may have affected the mental load and thus could have biased the PVT performance towards not detecting differences.

Finally, although the two-hour WBV exposure was created from real on road vibrations, the duration may not accurately reflect truck drivers' work shift exposures, which usually last for 10 hours. To gain better understanding of the effects of WBV exposures on drivers' vigilance, a study with larger sample size and longer duration of exposure may merit investigation.

Chapter 4 A Field Study Comparing WBV Exposures and Discomfort across Four Seats

4.1 Introduction

Based on results in the last chapter, a study of larger sample size, with prolonged WBV exposures under real trucking scenarios was identified as one means to further assess the utility of the PVT for characterizing vigilance. The goal of this crossover field study was to evaluate the shift-long WBV exposures and driver discomfort over a wider variety of seats; three passive air-suspension seats and one active suspension seat, in occupational settings, to determine whether the same WBV exposure contrasts identified in the lab study could be recreated in the field.

Twenty-four heavy truck drivers from British Columbia, Canada participated in this field study during their regular shifts. Daily continuous cyclical vibration exposures A(8), and daily cumulative impulsive, VDV(8), WBV exposures were evaluated and compared across four different commercially available truck seats and under two different road conditions (on-road and off-road driving). A power spectral density (PSD) analysis of the vibration exposures was also used to further explore the differences in the frequency content of the WBV exposures across the seats. PSDs can be used to identify the frequency ranges where the seats achieve the best vibration attenuation performance.

Truck driving, which is second only to retail sales, is a common occupation in North America, employing 1 in 35 adult men (Stats Canada, 2014). In this study, which was conducted in British Columbia (BC), Canada, there are about 26,000 registered trucking companies. Approximately four out of five workers in the trucking industry in BC are employed as professional truck drivers (Statistics Canada, 2014). According to the Conference Board of Canada, the average professional truck driver age is 46 years compared to the national average for all workers of 41.5 years. In 2013, close to half (47 percent) of the professional truck drivers in BC were between the ages of 45 and 64. Trucking is a male-dominated industry; in BC, only 4 percent of professional truck drivers were female (Workbc.ca, 2014; bctrucking.com, 2018). According to Transport Canada's (1999) Annual Review, highway drivers compose 24.9% of the transport services industry in Canada.

Studies have found that drivers' discomfort increases with exposures to WBV (Mansfield, Sammonds, Nguyen, 2015; Bovenzi, 1996). Previous studies have also indicated that reduction in truck drivers' exposure to WBV through seating intervention can lead to improvements in low back pain and other health outcomes (Kim et al., 2016). In this study, truck drivers' self-reported discomfort ratings in eight body regions, collected using a Standardized Nordic questionnaire, were collected before and after a full shift using each of the four different seats.

The goal of this study was to determine whether there were differences in on-road and off-road WBV exposures across the four different commercially available truck seats. The second goals of this study were to determine whether there were differences in driver discomfort after a full, 10-hour shift after using each seat and whether discomfort levels were associated with WBV exposure levels.

4.2 Methods

4.2.1 Study Site

The study was conducted in collaboration with Arrow Transportation Systems Inc., Chilliwack, BC. Arrow Transportation specializes in bulk commodity transportation, reload operations, and freight management in Canada and the United States. For this study, as shown in Figure 4, regional line-haul trucking routes were selected such that trucks left and returned to the

Chilliwack fleet base each day after loading aggregate material from the copper mines in the mountain area east to Chilliwack and then unloading their payload in the North Vancouver Port. Arrow Transportation provided the 9 axle semi-trucks used in this study, of the same model and manufacturer (Model 4900XD Tri-drive; Western Star; Portland, OR) as shown in Figure 5.

Figure 4 Typical route of a 10-hour shift. The route starts from the base in Chilliwack, BC, the trailers are loaded with aggregate in the mine, the aggregate gets unloaded at the port, and then the trucks return to the base in Chilliwack, BC.

Figure 5 9-axle truck with trailer

4.2.2 Study Participants

A convenience sample of 24 male truck drivers with regular routes and schedules were recruited from the Arrow Transportation Systems Inc., in Chilliwack, BC. Demographic information of the truck drivers is shown in Table 9. Eligible participants had a minimum of one-year experience on the truck type and the routes we tested. Subjects received written and in-person description of the study, and informed consent was obtained.

Table 9 Description of the field study participants, N=24, SD=standard deviation

Characteristics	Mean	SD	Range
Age	50.2	7.8	(35, 64)
BMI	30.4	4.7	(23.0, 42.6)
Weight (kg)	98.1	19.8	(72.6, 158.8)
Height (cm)	179.1	7.9	(162.6,193.0)
Years as Trucker	24.2	10.8	(5, 46)

4.2.3 Four Seats Tested

Four seats were evaluated and compared in this study, one seat was the trucking company's original-fitted seat, which was tested in 9 different trucks, and on average, the seats tested in these trucks were 12 months old (Seat 1 – Model National Premium; Commercial Vehicle Group; Columbus OH). The other three seats were brand new and serially installed and tested in the same truck on three separate occasions (Seat 2 – Model Elite, Sears Seating, Davenport, IA; Seat 3 – Model 5080, Isringhausen, Detroit, MI; Seat 4 – BoseRide, Bose Corporation, Framingham, MA). Seat 2 and Seat 3 are both aftermarket truck seat available in North America. Seat 4 is an active suspension seat (BoseRide, Framingham, MA), a newer model of the seat used in the previous laboratory-based study in Chapter 3.

Seat 1 National Premium

Seat 2 Sears Elite 80

Seat 3 Isringhausen 6860

Seat 4 Bose Ride

Passive-suspension seats

Active-suspension Seat

Figure 6 The four seats evaluated in this study: three passive suspension seats, one active suspension seat

4.2.4 Study Design

This study used a crossover design, where the same set of measures were taken with each of the four seats to determine whether there were differences in WBV exposures across the four seats and whether there were significant changes in driver discomfort ratings over the course of their 10-hour shift.

Data collection was undertaken between the months of May and December and sampling was avoided in winter months when the roads potentially snow-covered and the trucks were using chains. As shown in Table 10, on the data collection days, WBV measurement equipment was set up in the driver's seats to collect acceleration for the entire 10-hour shift. Participants were asked to arrive to the terminal 15 minutes before their shift to complete a health-related questionnaire.

Table 10 Field study Protocol

Work Schedule	Data Collection
15 min Pre-shift	Pre-shift questionnaire
Work Shift	Driving with Vibration measurement equipment
15 min Post shift	Post shift questionnaire

4.2.5 Whole-Body Vibration Exposure

WBV exposures for the 4 different seating interventions were collected compared over the eleven-hour, 280 km route. Following ISO 2631-1 WBV standards, a tri-axial seat-pad accelerometer (Model 356B40; PCB Piezotronics; Depew, NY) was taped on the driver's seat, and either an identical tri-axial or single axis (z-axis) accelerometer (Model 352C33; PCB Piezotronics; Depew, NY) was mounted magnetically to the floor of the truck cab beneath the driver's seat (Kim et al., 2016). WBV exposures were collected at 1,280 Hz using either a four or eight channel data logger (Model DA-20 or DA-40; Rion Co. LTD; Tokyo, Japan) over the whole route (Figure 7) (Wang et al., 2016). In addition, truck speed and location data were collected every second using a GPS tracking device (Model CR Q1100P; Qstarz; Taipei, Taiwan).

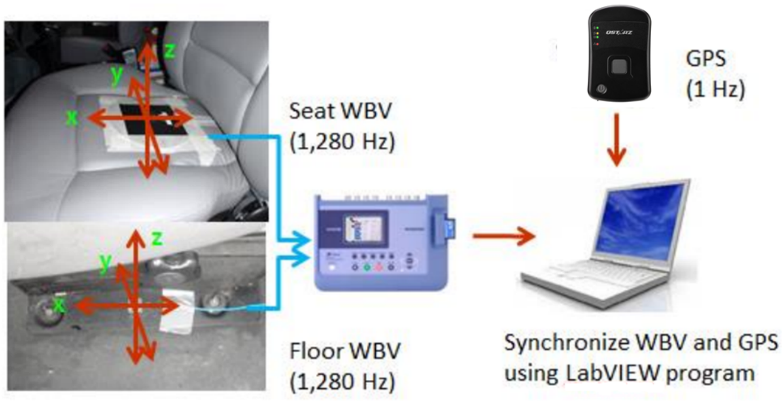


Figure 7 Typical WBV data acquisition set up for this study showing both floor and on-seat mounting of accelerometers

The ISO 2631-1 has provided guidelines to calculate average weighted vibration (A_w) and Vibration Dose Values (VDV).

A_w were calculated at the floor and seat top (units m/s^2) according to equation (1):

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

Where $a_w(t)$ represents the acceleration as a function of time with unit m/s^{2}and T is the duration of the exposure in second (Dietze, 2020).

The cumulative-impulsive VDV WBV exposures (units m/s$^{1.75}$), which are more sensitive to jolts and shocks, were calculated using the following formula according to equation (2):

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

To evaluate the health effects of vibration, A_w and VDV are normalized to an 8-hour work day of exposures as A(8) and VDV(8) to facilitate comparisons by seat and by road type (Wang et al., 2017).

In addition, the “Seat Effective Amplitude Transmissibility” (SEAT) was calculated as the ratio of the seat-measured vibration divided by the floor-measured vibration, which gives a measure of how much of the floor measured vibration is transmitted by the seat to the seated truck driver.

Finally, using the exposures normalized to represent 8 hours of driving, A(8) and VDV(8), the truck operation time to reach the ISO 2631-1 daily vibration action limits (DVAL) were derived using equation (3):

$$\boldsymbol{Time\ to\ reach\ DVAL} = \left(\frac{\boldsymbol{Action\ limit}}{\boldsymbol{Exposure(8)}}\right)^{\boldsymbol{n}} \times \mathbf{8} \qquad (3)$$

When Exposure (8) = A(8), Action Limit = 0.5 m/s^2 and n = 2. When Exposure (8) = VDV(8), Action Limit = 9.1 m/s$^{1.75}$ and n = 4.

A LabVIEW program (Version 2015; National Instruments; Austin, TX) was used to align the acceleration data with the GPS data, and then calculate the A(8), VDV(8), and SEAT values over the whole route and by the different road types (on-road and off-road). In addition, Power Spectral Densities (PSDs) were also calculated for each driver and seat condition, based on identical 60 second segments from each road type which were selected and identified using the GPS data. A PSD is a measure of a the WBV’s power intensity in the frequency domain. In practice, the PSD is computed from the Fast Fourier Transform (FFT) spectrum of a signal (Semmlow, 2012). The PSD provides a useful way to characterize the amplitude versus frequency content of a random WBV signal. PSDs were used to better understand the vibration content of the four seats across the different vibration frequencies the drivers were exposed to (Oppenheim & Verghese, 2015).

Fast Fourier Transform (FFT):

$$X(f) = \frac{1}{N}\sum_{n=1}^{N-1} x[n]e^{-i2\pi\frac{f}{N}} \text{ }, f = 0,1,2,\ldots,N-1 \qquad (4)$$

For vibration testing, the amplitude values of a PSD are normally expressed in g^2/Hz (m^2/g^3). The g^2 units result from the way that the spectrum is calculated, and Hz (frequency) is a normalizing quantity. It has been demonstrated that the PSD is the most complete and concise representation of a random process (Rahman et al., 2013). If the FFT of vibration signal is used, then the PSD may be calculated directly in the frequency domain (Howard, 2003) using equation:

$$PSD = \frac{a_{RMS}^2}{f} \qquad (5)$$

PSDs for the seat and floor accelerations were calculated using the Welch method with a window size of 2048 points, an overlap of 512 points (256 points at each tail), and 2048 frequency bins (Johnson & Aulck, 2012). Energy transmission for each seat across the vibration frequency spectrum (0 – 30 Hz) was calculated by dividing the PSD values of the seat at each frequency by values from the floor.

Linear-mixed models were used to determine whether there were differences in WBV exposures across the four seats. Each WBV exposure outcome was the dependent variable for the linear-mixed model and the fixed effect was the seat type while the random effect was subject ID. All statistical analyses were performed with R.

4.2.6 Health-Related Questionnaire

Drivers were instructed to complete health related questionnaires before the shift started and after they returned to the terminal upon completing their 10-hour shift. Questions were adapted from the Standardized Nordic questionnaires (Crawford, 2007) assessing pain/discomfort in 8 regions of their body, including: the shoulder(s), wrist(s)/forearm(s), knee(s), ankle(s)/feet, neck, upper back, lower back, and buttocks/leg(s). The drivers were instructed to select a number from 0 to 10 that best represented the pain/discomfort that they felt at the time of filling out the questionnaires, where 0 was no pain/discomfort, and 10 was the worst pain/discomfort that could be imagined. The ratings from the 8 body regions were added together to create a sum metric, which was derived as and overall measure of the pain/discomfort the subject was experiencing. A list of dependent variables of the WBV and discomfort outcomes is listed in Table 11.

Table 11 Dependent Variables including WBV and Discomfort scales

Dependent Variables	Variable Name	Variable Type	Description
WBV Levels	A(8)	Continuous	Average weighted vibration normalized to 8 hours
	VDV(8)	Continuous	Cumulative impulsive vibration normalized to 8 hours
Discomfort	Shoulder Pain	Integer	Self-rated discomfort scale, range from 0 to 10, 0 (No pain), 10 (worst pain)
	Wrist(s)/Forearm(s) Pain	Integer	
	Knee(s) Pain	Integer	
	Ankle(s) Pain	Integer	
	Neck Pain	Integer	
	Upper back Pain	Integer	
	Lower back Pain	Integer	
	Buttocks Pain	Integer	

4.3 WBV Results

4.3.1 A(8) and VDV(8)

From the field study, 17, 13, 12 and 7 WBV measurements were obtained from Seat 1, Seat 2, Seat3 and Seat 4 respectively. Figure 8 shows the seat-measured A(8) and VDV(8) WBV exposures by axis over the whole route. Since there was not a significant seat by axis interaction, the results by axis were averaged across all seats. As can be seen in Figure 8, the z-axis was the predominant axis of exposure. Since ISO standards recommend reporting of the predominant axis exposures, only z-axis analysis will be reported in the subsequent results of this chapter.

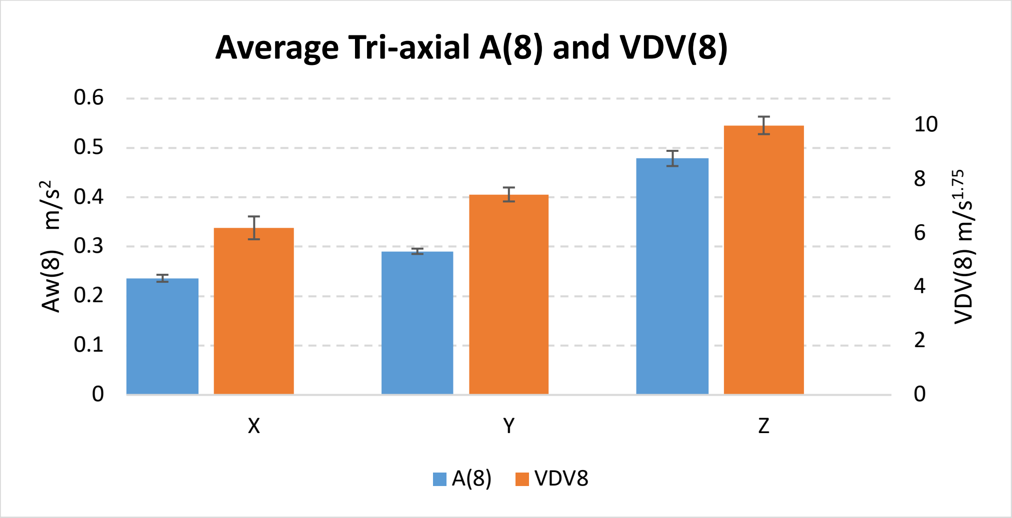


Figure 8 Mean (±SE) tri-axial seat-measured A(8) and VDV(8) WBV exposures over the whole route (n =49)

Table 12 shows the mean z-axis floor and seat WBV exposures over the entire 10-hour shift. As shown in Table 12, the A(8) seat-measured WBV exposures from Seat 4 were the lowest, Seats 2 and 3 had intermediate exposures and Seat 1 had the highest exposures. With respect to the VDV(8) seat-measured WBV exposures, Seat 1 had significantly higher exposures than the other three seats.

Small but significant differences were found between the floor measured WBV exposures across the four seats. Seat 4 had the highest A(8) floor-measured WBV exposures, Seat 1 had intermediate exposures, and Seats 2 and 3 had the lowest floor measured exposures. When the VDV(8) floor-measured WBV exposures were compared across the seats, Seat 1 had the highest VDV(8) exposures when compared with the other three seats.

Table 12 Mean (± SE) z-axis seat- and floor-measured WBV exposures over the whole route. The ISO Daily Vibration Action Limits are in parenthesis in the first column of the table. Values with different superscripts across rows are significantly different

		(n = 17)	(n = 13)	(n = 12)	(n = 7)	
Parameter	**Location**	**Seat 1**	**Seat 2**	**Seat 3**	**Seat 4**	**p-value**
A(8) **$(0.5\ m/s^2)$**	Seat	0.54^{a} (0.02)	0.43^{b} (0.03)	0.44^{b} (0.01)	0.27^{c} (0.04)	<0.0001**
	Floor	0.57^{a} (0.01)	0.52^{b} (0.01)	0.53^{b} (0.01)	0.65^{a} (0.05)	0.0005**
VDV(8) **$(9.1 m/s^{1.75})$**	Seat	11.1^{a} (0.4)	9.1^{b} (0.7)	9.3^{b} (0.4)	6.6^{c} (0.85)	<0.0001**
	Floor	13.0^{a} (0.2)	11.9^{b} (0.3)	12.0^{b} (0.2)	13.7^{a} (0.74)	0.0007**

Table 13 shows the WBV exposures from the 148.9 km on-road highway and 2.56 km off-road unpaved segments encountered by the truck drivers when the truck was fully loaded. Driving on highways was the predominant WBV exposure for shift and route.

As can be seen in Table 13, there were significant differences across seats in the z-axis A(8) and VDV(8) measures on the highways where the trucks travelled at moderate to high speed, with Seat 4 subjecting the truck drivers to the lowest WBV exposures. The WBV exposures on the highway segments of Seat 1 were significantly higher than the other three seats.

No significant differences in seat measured A(8) WBV exposures on the lower-speed, off-road segments were found between Seat 1, 2, and 3, but of-road WBV exposures were lower with Seat 4 and approached significance.

Table 13 Mean (± SE) z-axis seat-measured A(8) and VDV(8) WBV exposures and speed of the on-road and off-road segments . The ISO Daily Vibration Action Limits are in parenthesis in the first column of the table. Values with different superscripts across rows are different.

Road Type	Exposures	(n = 17) Seat 1	(n = 13) Seat 2	(n = 12) Seat 3	(n = 7) Seat 4	p-value
On-Road	A(8) (0.5 m/s^2)	0.61^a (0.03)	0.51^b (0.03)	0.50^b (0.02)	0.34^c (0.08)	0.0012**
	VDV(8) (9.1m/s$^{1.75}$)	11.6^a (0.6)	9.7^b (0.7)	9.3^b (0.4)	6.5^c (1.5)	0.0003**
	Speed (km/h)	86.8 (0.9)	85.4 (2.1)	86.1 (1.8)	87.7 (1.2)	0.83
Off-Road	A(8) (0.5 m/s^2)	0.65 (0.07)	0.69 (0.07)	0.65 (0.05)	0.34 (0.07)	0.1
	VDV(8) (9.1m/s$^{1.75}$)	12.3 (1.1)	13.3 (1.5)	13.1 (0.8)	9.5 (1.5)	0.51
	Speed (km/h)	23.0 (2.1)	23.8 (1.4)	20.8 (2.6)	22.0 (0.5)	0.91

4.3.2 SEAT Values

The SEAT ratios of the four seats were also calculated, the SEAT ratio measures the percentage of the truck cab floor WBV exposure transmitted through the seat to the driver. The highest WBV attenuation performance was observed from Seat 4, and the poorest attenuation performance was found in Seat 1. No significant differences between the attenuation performance existed between Seats 2 and 3 in both A(8) and VDV(8) WBV exposure measures. As shown in Table 14, the SEAT values of the whole routes based on A(8) indicated that Seat 1 reduced the average floor-transmitted WBV exposures by 5.8%, Seat 2 by 18.3%, Seat 3 by 16.4%, and Seat 4 by 63.8%. SEAT values based on VDV(8) demonstrated that Seat 1 reduced the cumulative-impulsive WBV exposures by 14.4%, Seat 2 by 22.9%, Seat 3 by 23%, and Seat 4 by 57.3%.

Table 14 Mean (± SE) z-axis SEAT values based on A(8) and VDV(8) over the whole route. Values with different superscripts across rows are significantly different

SEAT Values	(n = 17) **Seat 1**	(n = 13) **Seat 2**	(n = 12) **Seat 3**	(n = 7) **Seat 4**	**p-value**
A(8)	94.2% ^{a} (4.0%)	81.7% ^{b} (4.6%)	83.6% ^{b} (2.1%)	36.2% ^{c} (3.0%)	<0.0001*
VDV(8)	85.6% ^{a} (3.4%)	77.1% ^{b} (5.1%)	77.0% ^{b} (2.8%)	42.7% ^{c} (3.9%)	<0.0001*

As shown in Figure 9, mean A(8) SEAT values of Seat 4 were significantly lower than Seat 1, 2 and 3 on both paved highways and unpaved roads (p=0.0007 for on-road measures; p=0.014 for off-road measures). The A(8) SEAT ratio of Seat 1 was significantly higher than those of Seat 2 and 3 on both on- and off-road segments (p=0.024 for on-road measures; p=0.040 for off-road measures). Also, the A(8) SEAT ratios of Seat 3 was significantly lower than those of Seat 1 for the on- road, paved highway segment (p=0.048), indicating better WBV attenuation performance.

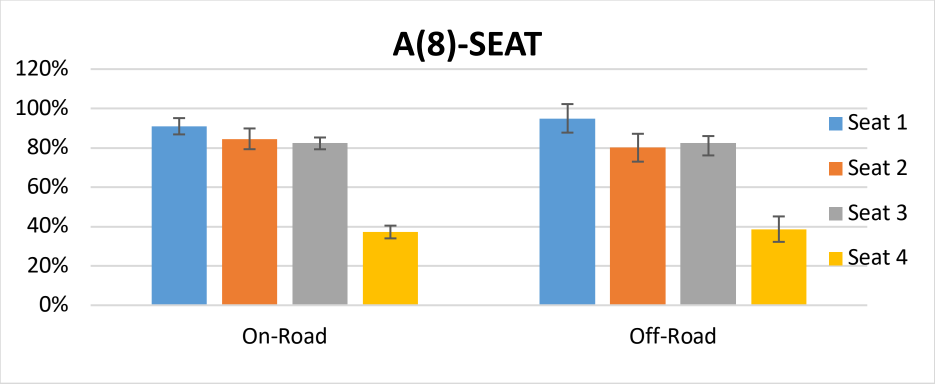


Figure 9 Mean (± SE) z-axis A(8) SEAT values by road type. Seat 1 n= 17, Seat 2 n = 13, Seat 3 n=12, Seat 4 n=7

As shown in Figure 10, mean VDV(8) SEAT values of Seat 4 were significantly lower than Seats 1,2, 3 on paved highways (p=0.0035). No significant difference was found between the four seats from the off-road segments. VDV(8) SEAT ratios of Seat 1 was nearly significantly higher than those of Seat 4 with p value 0.067. Besides, the VDV(8) SEAT ratios of Seat 4 was nearly significantly lower than those of Seat 3 for off-road segments, indicating better WBV attenuation performance.

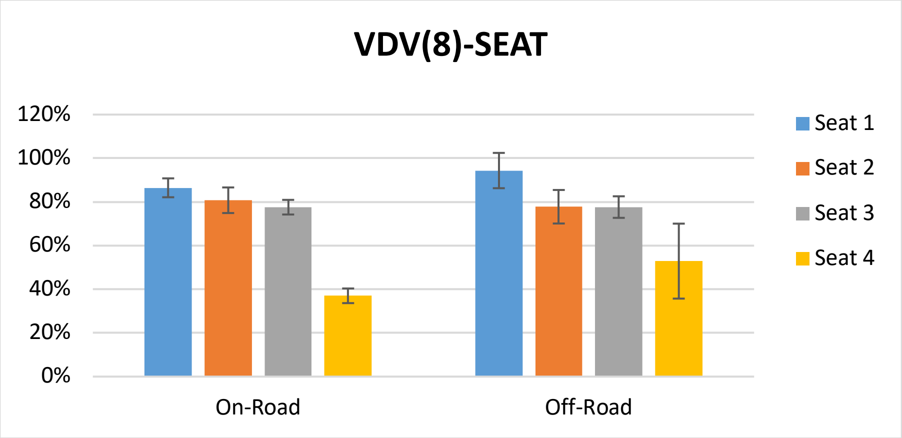


Figure 10 Mean (± SE) z-axis VDV(8) SEAT values by road type. Seat 1 n= 17, Seat 2 n = 13, Seat 3 n =12, Seat 4 n = 7.

Figure 11 illustrates the truck operation hours until reaching the ISO 2631-1 daily vibration action limits (DVALs) based on operating the trucks over the whole route. The operation times of Seat 4 were significantly longer than the other three seats (p<0.0001 for A(8) and VDV(8)). Based on the operation time derived from A(8), the median operation time sitting on Seat 4 reaching the DVAL almost was 37.0 hours compared with that of Seat 1, 6.3 hours, increasing the allowable operation time by 6-fold. The median allowable truck operation time with Seat 2 and 3 also exceeded the operational time with Seat 1 by 2-fold on average.

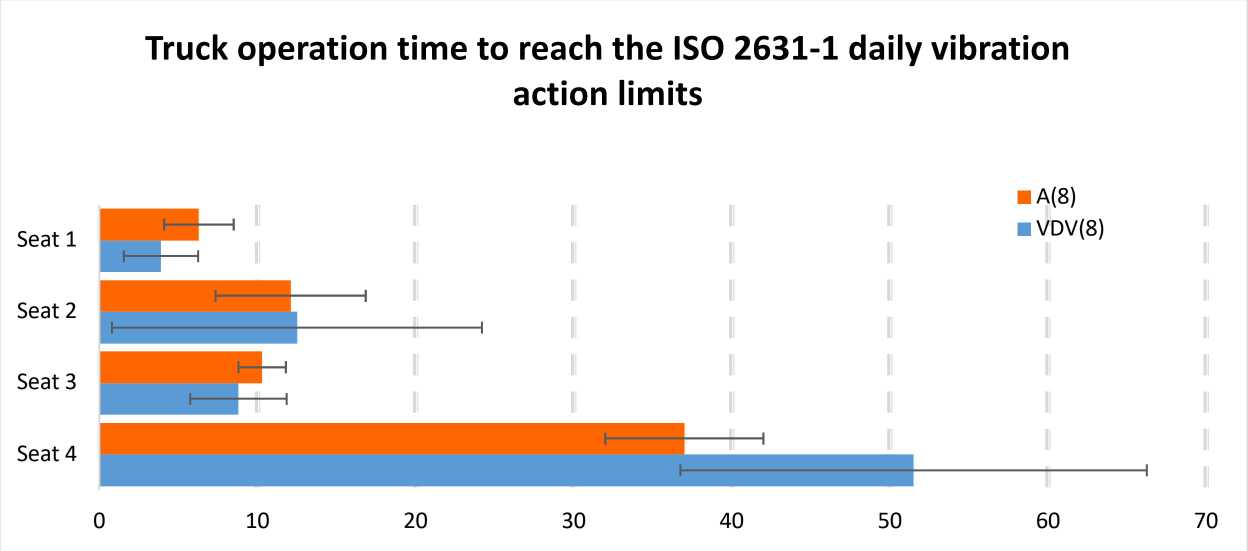


Figure 11 Median (± IQR) time in hours, grouped by type of WBV exposure, that trucks could be operated until reaching the ISO Daily Vibration Action Limits. Time limits were based on the whole route exposures. Seat 1 n= 17, Seat 2 n = 13, Seat 3 n =12, Seat 4 n=7

4.3.3 Power Spectral Density Analysis

Using the GPS data, identical 60 second road segments for both on-road (Figure 12) and off-road segments (Figure 13) were selected from each shift to compare the Power Spectral Densities (PSDs) and energy transmission. As shown in Figure 12, for the on-road highway segment, between 0.5 to 5 Hz, highest amount of vibration energy was measured from Seat 1, and lowest amount of vibration energy was measured from Seat 4. The PSDs from Seat 2 and Seat 3 were intermediate with respect to the low, 0.5 to 5Hz vibration energy. With respect to the vibration energy between 5 to 15 Hz, Seat 4 has the lowest amount of vibration energy and Seats 1, 2 and 3 had similar levels of energy. The most vibration energy from the truck floor occurred between 7 to 15 Hz, which overlapped with the resonance frequency of the vehicle's engine, tire rotation frequency, and the modal/resonant frequency of the truck cab, which is typically most prominent between 6 to 10 Hz (Gagliardi & Utt, 1993), and all four seats attenuated the vibration energy within this range. In contrast, the low frequency energy between 0.5 to 5 Hz was transmitted by Seats 1, 2 and 3 with a transmission peak between 2 to 3 Hz.

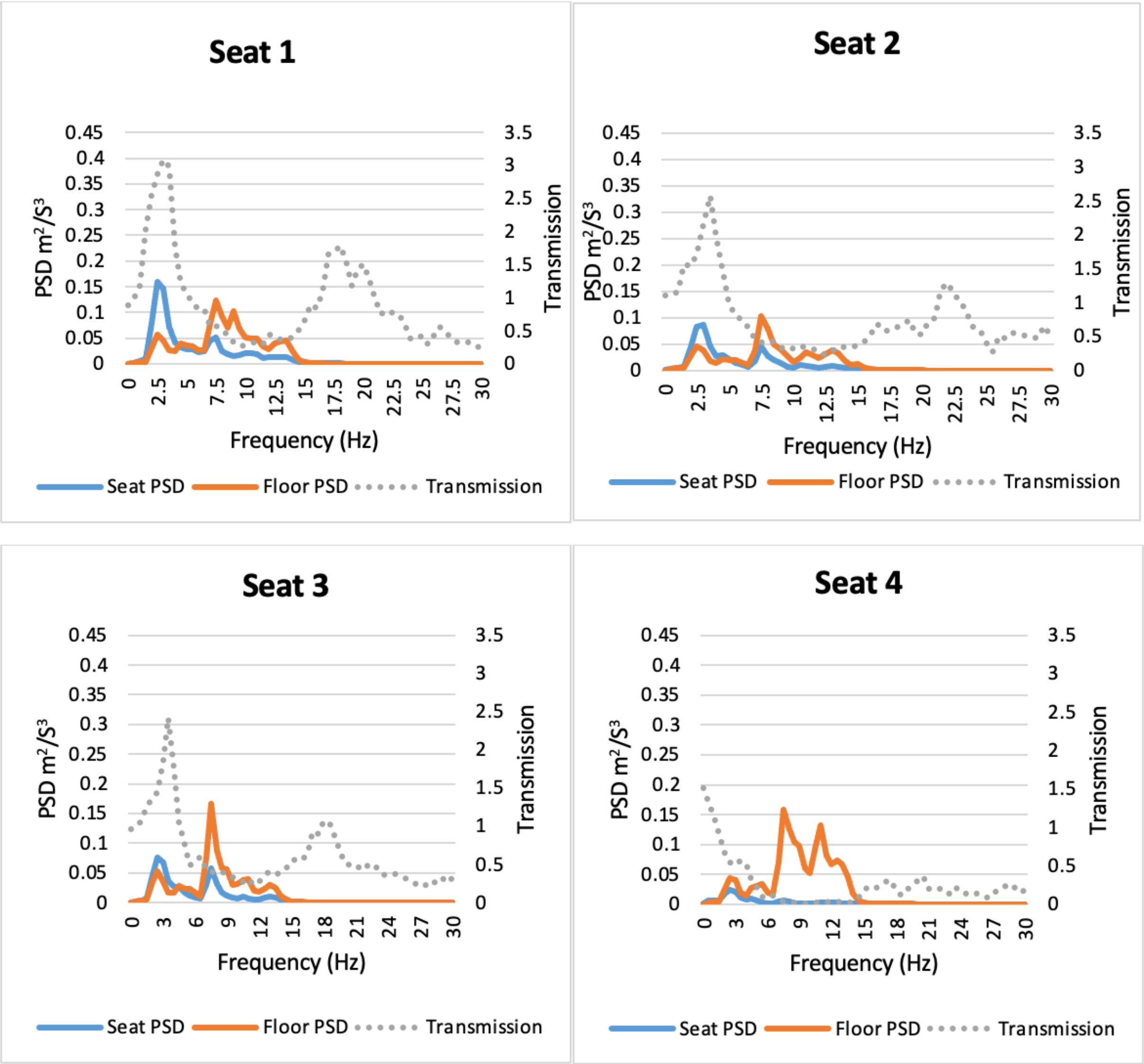


Figure 12 Median z-axis seat and floor PSDs and transmission of the on-road segment by seat types. Seat 1 n= 17, Seat 2 n = 13, Seat 3 n =12, Seat 4 n = 7

For the off-road segments, as shown in Figure 13, the lowest PSDs occurred with Seat 4. No significant difference in the PSDs were found between Seat 1, Seat 2, and Seat 3. Similar to the on-road segment, all PSDs from the off-road segments reached their peak between 2.5 and 3.5Hz.

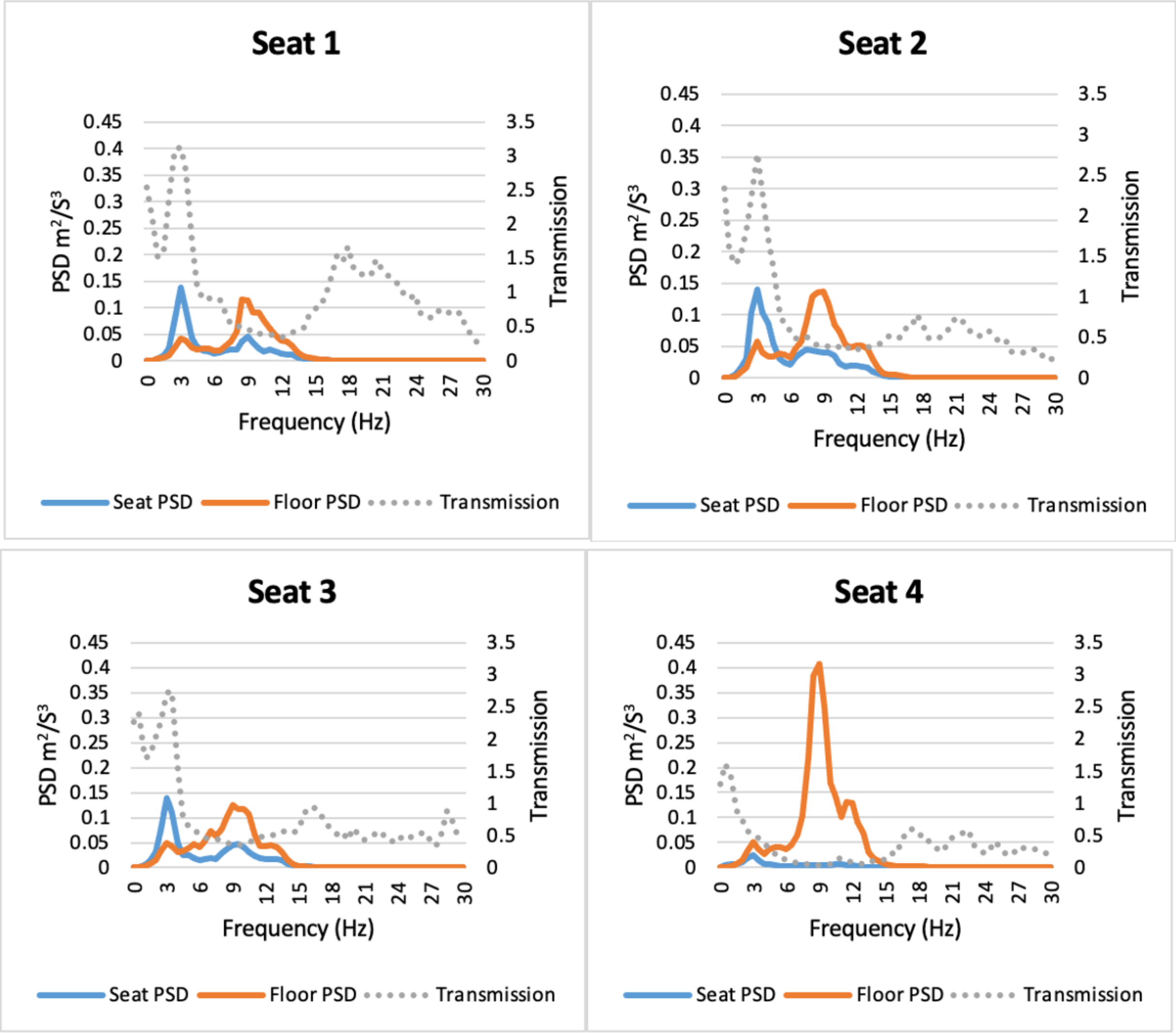


Figure 13 Median z-axis seat and floor PSDs and transmission of the off-road segment by seat types. Seat 1 n= 17, Seat 2 n = 13, Seat 3 n =12, Seat 4 n = 7

Transmission represents ratio of the seat PSD divided by the floor PSD across the frequency spectrum (0 to 30 Hz). Transmission values less than 1 indicates the seat is attenuating the floor-transmitted energy, and transmission values greater than 1 indicate that the seat is amplifying the floor-transmitted vibration. According to the energy transmission curves in Figure 12 and Figure 13, Seat 4, the active suspension seat, attenuated the vehicle transmitted vibration energy above 1.5 Hz for both the on- and off-road segments and Seat 1, Seat 2 and Seat 3 amplified the vibration energy between 0.5 to 4.5 Hz for both road types. For the on-road segment, the average z-axis energy transmission of Seat 1 was highest among the four seats, and Seat 4 had the lowest transmission, with Seat 2 and Seat 3 having intermediate levels of vibration transmission. The highest energy transmission occurred at the lower frequencies between 2 to 3 Hz and were thought to be associated with the resonant frequency of the seat suspension.

In summary, all four seats attenuated the higher frequency vibration energy between 4.5 and 15 Hz; but, compared to Seat 4, Seat 1, Seat 2, and Seat 3 didn't damp much of the lower frequency vibration energy between 0.5 to 4.5 Hz. The PSDs and energy transmission results complement the WBV exposure measures and demonstrate the superior performance of Seat 4, the active suspension seat, for reducing truck drivers' exposure to WBV. Especially for low-frequency vibration energy between 1 and 4 Hz. Vibration damping at intermediate frequencies is critical because the resonant frequency of the lumbar vertebrae and spine has been estimated to be in a range between 4 to 12 Hz (Panjabi, Andersson, Jorneus, Hult, & Mattsson, 1986), and the lower frequency vibration, at or below 3.2 Hz, has been linked to extremely uncomfortable driving and riding experiences due to the exaggerated movement of the seat relative to the truck cab (Yang et al., 2016).

4.4 Discomfort Ratings Results

Previous research has shown that adverse health outcomes are expected to increase as WBV exposures increase (Kim et al., 2016). The main effects of seat type, test time, and their interactions were studied for the self-rated discomfort scales in the eight body regions evaluated, and in addition, the cumulative discomfort was evaluated as the sum of the discomfort over all body regions. The sum of the pain ratings of 8 body regions were used as the metric to characterize the overall pain/discomfort the subject experienced (Kuorinka et al., 1987).

Differences in discomfort were expected across the four seat types and pre- /post- shift. Linear-mixed models were used to analyze the discomfort ratings.

From the field study, 24, 13, 12 and 11 health-related questionnaires, as shown in Appendix F, were obtained from Seat 1, Seat 2, Seat3 and Seat 4. As shown in Table 15, significantly higher discomfort ratings were measured after the shift in neck, upper back, and the sum metric. Nonetheless, no significant differences in discomfort ratings were found across the four seat types and the seat by time interaction as in Figure 14 and 15.

Table 15 Mean values and standard errors of the discomfort scales of eight body parts and their sum metric presented by test time. (n = 60)

Discomforts	Pre-shift	SE	Post-shift	SE	p-value
Shoulder(s)	0.72	0.16	1.17	0.20	0.07
Wrist(s)/forearm(s)	0.60	0.17	0.50	0.13	0.63
Knee(s)	0.72	0.15	0.90	0.16	0.40
Ankle(s)/Feet	0.47	0.11	0.61	0.14	0.43
Neck	0.63	0.14	1.22	0.23	0.04**
Upper back	0.58	0.14	1.15	0.20	0.02**
Lower back	1.28	0.25	1.97	0.29	0.08
Buttocks/Leg(s)	0.92	0.20	1.50	0.22	0.06
Sum metric	5.92	0.96	9.01	1.20	0.04**

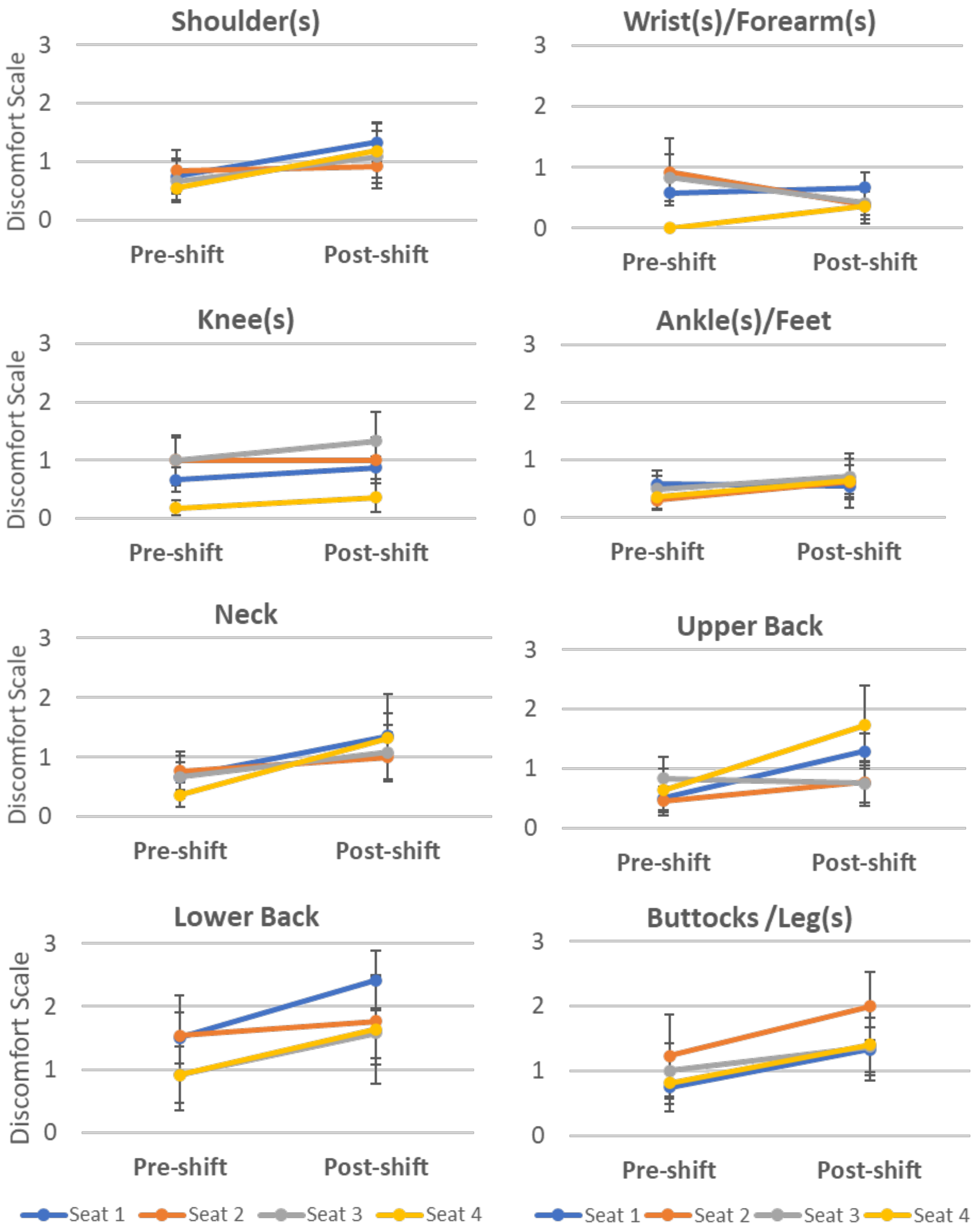


Figure 14 Mean (± SE) pre- and post-shift discomfort scales of the eight body parts by seat types. Seat 1 n= 24, Seat 2 n = 13, Seat 3 n=12, Seat 4 n = 11

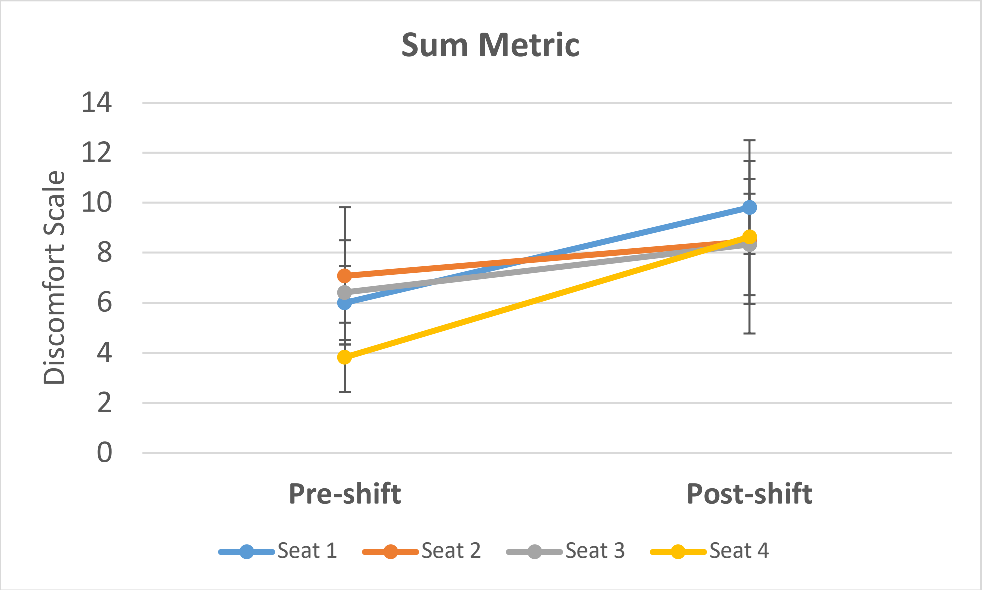


Figure 15 Mean (± SE) pre- and post-shift pain sum metric of the four seat types. Seat 1 n= 24, Seat 2 n = 13, Seat 3 n = 12, Seat 4 n = 11

Considering the different baseline of the pre- shift discomfort ratings in Figure 14 and 15, the changes in discomfort ratings were obtained by subtracting the pre-shift ratings from the post-shift ratings. As shown in Table 16, the changes were compared, but no significant differences were found across the four seats, which indicates that the changes in discomfort ratings were not dependent on the seat type. Potential seat-dependent differences were still found in wrist(s)/forearm(s) and upper back, and Seat 4 tended to have higher changes in overall sum metric of discomfort ratings, which could be due to drivers' unfamiliarity with the seat.

Table 16 Mean values and standard errors of the post-shift changes in the discomfort ratings across the four seat types. (n = 60)

Changes in Discomfort Ratings	Seat 1 (n=24)	Seat 2 (n=13)	Seat 3 (n=12)	Seat 4 (n=11)	p-value
Shoulder(s)	0.58 (0.3)	0.08 (0.14)	0.42 (0.19)	0.64 (0.36)	0.57
Wrist(s)/forearm(s)	0.08 (0.21)	-0.54 (0.31)	-0.42 (0.19)	0.36 (0.28)	0.07
Knee(s)	0.21 (0.25)	0.00 (0.16)	0.33 (0.31)	0.18 (0.23)	0.87
Ankle(s)/Feet	-0.04 (0.23)	0.31 (0.17)	0.21 (0.17)	0.27 (0.47)	0.74
Neck	0.69 (0.34)	0.23 (0.12)	0.42 (0.40)	0.95 (0.56)	0.64
Upper back	0.79 (0.29)	0.31 (0.33)	-0.08 (0.19)	1.09 (0.37)	0.09
Lower back	0.92 (0.38)	0.23 (0.20)	0.67 (0.28)	0.73 (0.38)	0.57
Buttocks/Leg(s)	0.58 (0.25)	0.77 (0.52)	0.38 (0.30)	0.59 (0.55)	0.93
Sum metric	3.81 (1.68)	1.38 (0.94)	1.92 (1.21)	4.82 (2.67)	0.56

4.5 Discussion

One potential concern with the WBV measurement could be the small sample size obtained from Seat 4. But as demonstrated in the previous studies, Seat 4, the active suspension seat, has repeatedly been shown to reduce the vibration exposures by up to 50% (Blood et al., 2011; Kim et al., 2015). The PSD results were also consistent with another study, where an active suspension seat, an older model of Seat 4, attenuated the vehicle transmitted vibration energy above 1 Hz whereas the passive seat, Seat 1, amplified vehicle transmitted vibration energy between 1 - 7 Hz on the freeway (Johnson & Aulck, 2012).

Another concern with the current comparisons may be the older age of Seat 1 which on average, was 12-month-old in the trucks tested, but in a Randomized Controlled Trial (RCT) which measured WBV exposures in new seats over a one-year period, no decline in seat performance was observed over the 12-month period (Kim et al, 2015).

For the three passive suspension seats, the results indicated the suspension of Seat 1 had some design difference that exposed drivers to more vibration with lower frequency content (0.5 to 4 Hz) compared with Seat 2 and Seat 3. The PSD analysis also indicated that Seat 1 exposed drivers to significantly more lower frequency energy compared to Seat 4, The lower frequency vibration had been shown to be related with uncomfortable driving experiences due to the exaggerated movement of the seat relative to the truck cab.

With this reduction in WBV exposures when operating the trucks with the active suspension seat, as shown in Figure 11, the time it took truck drivers to reach daily vibration action limits (DVALs) ranged between 30 to 50 hours, which was beyond realistic work periods. Seat 1 had the highest WBV exposures that resulted in a time to reach DVALs that was half of that of Seats 2 and 3. The study results indicate that there are some higher performing passive air suspension seats that can reduce WBV exposures and double the allowable truck operating time a truck before reaching DVALs. It’s not advocated that truck drivers operate their trucks for such long durations, but rather the longer vehicle operation time indicates how much lower and acceptable the WBV exposures are with the better performing seats.

Significantly higher ratings in discomfort were observed after the shift, but no significant difference was found for the changes of discomfort ratings after sitting in the four seats over the shift. In a previous study, where five drivers were measured in the active suspension seat and the conventional passive suspension seat each for a week, decrements in discomfort in the lower back and wrist(s)/forearm(s) were found to be substantially less with the active suspension seat, compared to the conventional passive-suspension seat (Du, 2015). Because this field study only measured the discomfort in each seat for only one full shift, self-reported discomfort ratings may not reflex their actual discomfort over the long term. Further, these findings indicated that there were small differences on overall seat preference regarding drivers' discomfort.

4.6 Conclusion

This part of the field study compared the WBV attenuation performance and driver discomfort ratings between the three passive suspension seats and one active suspension seat. The results demonstrated that the WBV attenuation performance of the four seats differed. Seat 4, the active suspension seat, was found to have significantly lower WBV exposures and better WBV attenuation performance when compared to the other seats on both paved highways and unpaved roads. Also, poorer WBV attenuation performance was observed in Seat 1, the original-fitted passive, air-suspension seat used by the participating trucking company. In addition, Seat 1 had poorer WBV attenuation performance when compared to the other passive suspension seats, Seat 2 and Seat 3. This is similar to a previous study where Seat 1 and Seat 2 were tested across a non-standardized set of predominantly paved roads and Seat 2 outperformed Seat 1 (Kim et al, 2015).

The results also indicated that besides Seat 4, the active suspension seat, there were two commercially- available passive air-suspension seats, Seat 2 and Seat 3, which were found to reduce truck driver WBV exposures by over 20%. This contrasted with the other passive suspension seat, Seat 1, which only reduced truck driver WBV exposures by 10% or less. Power Spectrum Density analysis showed that all the four seats attenuated higher frequency vibration energy between 5 to 15 Hz, but Seat 2, 3 and 4 attenuated more lower frequency vibration energy (less than 5 Hz) compared with Seat 1, which is important for the drivers' comfort, health, and well-being. The results also suggest that that proper matching of seat attenuation features to vehicle vibration characteristics is important in the attenuation of WBV exposure (Cann et al.,2004), because 94% of trucks may have been installed with seats that haven't provided the optimal vibration attenuation matching the trucks' characteristics (Padden & Griffin, 2002).

In addition, more deterioration in discomfort ratings was observed after the shift, but no significant differences in driver discomfort were found across the four seats over the shift, which implies a future study may be merited to evaluate the long-term impacts on the health outcomes with different seating interventions.

4.7 Limitations

The primary limitation is the low sample sizes from the crossover study due to the operational difficulties and personnel challenges. The sample size of WBV exposure measurements from the active suspension seat (n=7) was small. Although previous studies have demonstrated the superior vibration attenuation performance of the active suspension seat, a larger sample size may have the potential to reduce the possibility of type 2 error. Besides, relationships between discomfort ratings and seat types might also be potentially discovered with more subjects.

In addition, the subjects were not blinded to the type of seat, and it was possible that this lack of blinding may have biased results away from null if subjects expected better discomfort ratings after the WBV exposures sitting in the seats other than the original fitted seat, even though this expectation effect wasn't shown in the results.

Finally, the time span of the data collection was over several months because of the constraints in the drives' schedules, during which the drivers' health condition could have changed. The discomfort surveys conducted on consecutive shifts are suggested to counter this problem.

Chapter 5 A Field Study Comparing PVT Results across Four Seats

5.1 Introduction

Based on results in Chapter 3, a study was conducted on a larger sample of truck drivers with prolonged exposures to WBV under real trucking scenarios to further assess the utility of the PVT for detecting changes in vigilance.

Twenty-four heavy truck drivers from British Columbia, Canada participated in this field study during their regular shifts. Drivers drove across standardized routes while using four different commercially available truck seats: the truck's original fitted; a standard passive suspension seat; an active suspension seat; and two other passive suspension seats. With each seat, the drivers performed the PVT before and after operating their truck over their regular shift. As demonstrated in Chapter 4, the lowest WBV exposures resulted from operating the trucks with the active suspension seat, the original fitted seat had the highest exposures, and intermediate exposures occurred when operating the trucks with the other two passive suspensions seats.

The aim of this study, using the PVT in an actual field setting, was to determine whether prolonged exposure to WBV affects the sustained attention of truck drivers over the course of their normal 10-hour work shift. The second aim of this study was to compare the PVT performance and the changes of PVT performance over the shift across four truck seats to determine whether different levels of WBV exposures, because of WBV attenuation differences between the seats, affected the truck drivers' vigilance differentially.

5.2 Methods

5.2.1 Study Participants

The study site has been described in Section 4.2.1. A convenience sample of 24 truck drivers with regular routes and schedules were recruited from Arrow Transportation Systems Inc., in Chilliwack, BC. Demographic information from the truck drivers is shown in Table 17. Eligible participants had a minimum of one-year experience operating the trucks on the routes we used to evaluate seat WBV attenuation and PVT performance. Subjects received written description of the study, and informed consent was obtained.

Table 17 Description of the field study participants, N=24, SD=standard deviation

Characteristics	**Mean**	**SD**	**Range**
Age	50.9	8.1	(35, 64)
BMI	30.1	4.6	(23.0, 42.6)
Weight (kg)	96.4	18.7	(73, 159)
Height (cm)	178.4	7.8	(163,193)
Years as Trucker	24.1	11.4	(5,46)

5.2.2 Four Seats Tested

Four seats were evaluated and compared in this study, one seat was the trucking company's original-fitted seat, which was tested in 9 different trucks of the same make and model, and on average, the seats tested in these trucks were 12 months old (Seat 1 – Model National Premium; Commercial Vehicle Group; Columbus OH). The other three seats were brand new and serially installed and tested in the same truck (Model 4900XD Tri-drive; Western Star; Portland, OR) on three separate occasions (Seat 2 – Model Elite, Sears Seating, Davenport, IA; Seat 3 – Model 5080, Isringhausen, Detroit, MI; Seat 4 – BoseRide, Bose Corporation, Framingham, MA). Seat 2 and Seat 3 are both aftermarket truck seats available in North

America. Seat 4 was an active suspension seat, a newer model of the seat that was used in the previous laboratory-based study in Chapter 3.

Figure 16 The four seats evaluated in this study: three passive suspension seats and one active suspension seat

5.2.3 Study Design

This study employed methods where the same set of vibration exposures were collected over the truck drivers' regular 10-hour shift. Data collection was undertaken between the months of May and December and sampling was avoided in winter months when the roads had the potential to be snow-covered and the trucks would have to use chains, resulting in different frequency and higher vibration exposures.

As shown in Table 18, on the data collection days, participants were asked to arrive at the terminal 15 minutes before their shift to complete a 5-minute PVT. During this time, WBV measurement equipment was set up in the truck driver's cab to collect the WBV exposures from the truck seat and floor for the entire 10-hour shift. Finally, when the truck drivers returned to the terminal after their 10-hour shift, a post-shift PVT task was performed and the WBV measurement equipment was removed from the truck cab.

Table 18 Field study Protocol

Work Schedule	Data Collection
15 min Pre-shift	5 min PVT
Work Shift	Driving with Vibration measurement equipment
15 min Post shift	5 min PVT

Before their shift started, the drivers were asked about their sleep history, and sleep quality was rated using a four-point scale from the Pittsburg Sleep Quality Index (PSQI): very good, fairly good, fairly bad and very bad (Buysse et al., 1989). After the shift, drivers reported their experience with the seat tested during the shift. As shown in Table 19, some additional variables that may have influence on drivers' vigilance performance were also recorded. These variables included the shift starting time, shift duration, total rest duration, and the amount of caffeine products the driver had consumed during the shift.

Table 19 Shift-related variables

Variable Name	Variable Type	Description
Seat type	Categorical	Four seat types
Test Time	Categorical	Pre-shift or post shift
Sleep Quality	Categorical	Very bad, Fairly bad, Fairly good, Very Good
Shift Starting Time (hour)	Integer	12 pm to 19 pm
Shift Duration	Continuous	0 to 14 hours
Total Rest Duration	Categorical	0-10 mins, 10-20 mins, 20-30 mins, 30-40 mins, >40 mins
Caffeine Intake	Continuous	Number of cups of caffeine product during the shift

5.2.4 PVT Data Collection

The PVT was collected and performed using a PVT application built in LabVIEW running on a tablet (ASUS Transformer 10.1" Notebook, Beitou District, Taipei, Taiwan). Although the original PVT was 10 minutes in durations, a 5-minute PVT was used due to time constraints associated with truck drivers having to maintain their tight shift schedules. The 5-minute PVT has been shown to have adequate sensitivity to detect changes in vigilance (Loh, Lamond, Dorrian, Roach, & Dawson, 2003).

Based on the use of the PVT metrics in the previous literature (Basner & Dinges, 2011), four outcome metrics were selected and calculated from the 5-minute PVT: mean reaction time (RT), mean reciprocal of RT (1/RT), the mean fastest 10% RT, and the lapse probability. With all the PVT results, the first two responses were excluded to minimize the effects that could be associated with learning (Dinges, 2001). With each PVT test, in order to calculate mean RT and mean 1/RT, outliers of more than three standard deviations above the mean RT of that test were excluded (Jackson et al., 2013; Wilson et al., 2010).

The main effects evaluated for influencing PVT metrics were test time (pre- or post-shift) and the four seat types. The difference between post- and pre- shift PVT metrics were obtained and compared across the different seat types to determine whether the differences in PVT response metrics were associated with the differential WBV exposure levels across the four seats.

To minimize the effect of circadian rhythm on PVT, only the PVT measurements that were collected when the subjects started their shifts in the afternoon with daylight and ended their shifts in darkness were analyzed. PVT measurements that started in darkness and ended in daylight were excluded as these measurements opposed natural circadian rhythm and sleep cycles. A total of 41 pairs of pre- and post- shift PVT measures were included and 19 pairs of PVT data were excluded where the truck drivers shift started in darkness and ended in daylight.

5.2.5 Data Analysis

To achieve a power of 0.8 with the alpha value set to 0.05, a minimum requirement of 11 subjects was calculated by GPower as shown in Appendix A.

Because of the potential small sample size obtained, nonparametric Kruskal Wallis tests were used to evaluate the main effect seat on the PVT outcome metrics. One test was performed to determine whether there were differences in pre-shift PVT outcome measures across seats, ideally subject would be in the same or similar physiological state at the start of their shift and there would be no difference in PVT outcome measures. A second test was performed to determine whether there were differences in post-shift PVT outcome measures across seats. Due to the known differences in WBV exposures between seats, subjects may be in different physiological states and the tests were performed to determine whether there were significant differences in PVT outcome measures across seats. Finally, to account for the shift-related changes and control for any potential individual differences in the pre-shift, baseline PVT outcome measures, the changes in PVT outcome measures (Post-Shift – Pre-Shift) were also compared.

In addition, the relationship between the changes in each PVT outcome metrics were evaluated against the daily WBV exposures of the A(8) and VDV(8) measures the driver experienced during their entire shift in Appendix B.

Demographic and shift- related variables were also examined using multiple univariate ANOVAs to select the potential confounding variables that could affect the PVT metrics significantly. The results are presented in Appendix C. All statistical analyses were performed with statistical software R.

5.3 Results

5.3.1 Demographic and Shift-Related Variables

Of the 60 pairs of pre-shift and post-shift PVT data that were collected (Seat 1, n=24; Seat 2, n=13; Seat 3, n=12; Seat 4, n=11), 41 pairs of measurements, where drivers' shift started in the daylight, were included in the final analysis (Seat 1, n=19; Seat 2, n=5; Seat 3, n=6; Seat 4, n=11).

Demographic and shift-related variables associated with the four seats and PVT outcome measures are summarized in Table 20, the demographic information including age, BMI, weight, and height was compared across the four seats and no significant differences were found with these variables. Also, no significant differences were seen in the shift-related information including shift duration and the cups of caffeine taken across the four seats.

Table 20 Median (IQR) of demographic and shift-related variables and p-values comparing the differences across the four seats

Demographic and Shift-Related Variables	Seat 1 (n=19)	Seat 2 (n=5)	Seat 3 (n=6)	Seat 4 (n=11)	p-value
Age	52 (35, 55.5)	53 (42, 56)	53 (36, 54.5)	52 (42, 55.5)	0.95
BMI	30.4 (25.1, 31.2)	30.5 (23.0, 31.57)	29.4 (25.1, 31.1)	30.5 (26.5, 32.0)	0.97
Weight (kg)	97.1 (72.6, 100.92)	99.8 (72.6, 102.1)	82.8 (72.6, 96.4)	99.8 (72.6, 102.1)	0.44
Height (cm)	178.0 (170.2, 182.9)	177.8 (171.5, 188.0)	170.2 (164.5, 177.9)	180.3 (170.2, 182.9)	0.23
Years as Truck Driver	24 (5, 31.5)	25 (10, 26)	29.5 (7, 36)	25 (5, 31.5)	0.85
Shift Starting Time	15:00 (12, 17)	17:00 (12, 19)	18:00 (14, 18.75)	15:00 (14, 15.5)	0.37
Shift Duration	10 (9.5, 11)	11 (10, 11)	11 (10, 11.75)	11 (9.5, 11)	0.45
Cups of Caffeine	2 (0, 4)	6 (0, 6)	4 (0, 5.5)	2 (0, 3)	0.50

Table 21 shows the distribution of the driver's self-reported sleep quality before their shift started. None of the drivers reported having very bad sleep quality prior to their shift. Most of the drivers reported they had fairly good or very good sleep, except one driver who reported having fairly bad sleep before operating the truck with Seat 4.

Table 21 Distribution of participants' pre-shift sleep quality by four seats

Sleep Quality	Seat 1 (n = 19)	Seat 2 (n = 5)	Seat 3 (n = 6)	Seat 4 (n = 11)
Very Bad	0.0%	0.0%	0.0%	0.0%
Fairly bad	0.0%	0.0%	0.0%	9.1%
Fairly good	52.6%	40.0%	66.7%	63.6%
Very good	47.4%	60.0%	33.3%	27.3%

Table 22 presents the distribution of drivers' total rest duration categories. This observation indicates that the majority part of the drivers' rest time fell below 20 minutes during the entire shift for all seat types.

Table 22 Distribution of participants' total rest duration during a shift by four seats

Total Rest Duration	Seat 1 (n = 19)	Seat 2 (n = 5)	Seat 3 (n = 6)	Seat 4 (n = 11)
0-10 min	57.9%	80.0%	50.0%	45.5%
10-20 min	31.6%	20.0%	16.7%	36.4%
20-30 min	5.6%	0.0%	16.7%	18.2%
30-40 min	5.3%	0.0%	16.7%	0.0%
>40 min	0.0%	0.0%	0.0%	0.0%

In summary, no apparent differences were found in the numeric self-reported demographic and shift-related information across the four seating conditions, which lowered the potential for confounding effects associated with the main effects, seat types and test time. Regarding the categorical variables total rest duration, there still appeared to be imbalance in the distribution of each category.

5.3.1 Whole-Body Vibration Exposures by Seat Type

The WBV exposures of the four seats were characterized, compared, and summarized in Chapter 4, and the WBV attenuation performance of the four seats differed. Seat 4, the active suspension seat, attenuated the WBV exposures by over 50%, and was found to have significantly lower WBV exposures and better WBV attenuation performance when compared to the other three passive suspension seats. Also, the poorest WBV attenuation performance occurred with Seat 1, the original-fitted, passive suspension seat, which only reduced truck driver WBV exposures by 10% or less. Besides Seat 4, the other two passive air-suspension seats, Seat 2 and Seat 3, had intermediate WBV attenuation performance and were found to reduce truck driver WBV exposures by roughly 20%. Based on the documented differences in seat WBV exposures, the PVT outcome metrics were evaluated to determine whether there were performance differences across the four seats.

5.3.2 PVT Performance by Seat Type

Table 23 and 24 show the pre- and post-shift PVT outcome measures. Table 23 indicates that none of pre-shift PVT measures were significantly different but the differences in Mean RT and Fastest 10% RT approached significance. This indicates that, based on the pre-shift PVT outcome metrics, the drivers appeared to be in the same physiological condition across all four seats at the start of their shift. The post-shift PVT measures by seat are presented in Table 24. The results indicated that there were significant differences across seats in the post-shift PVT outcome metrics. PVT performance was the poorest with Seat 1, intermediate with Seats 3 and 4, and the best performance was recorded with Seat 2.

Table 23 Median (IQR) of the pre-shift PVT outcome metrics and p-values comparing the differences across the four seats. Values with different superscripts across rows are significantly different

PVT Outcome Metrics	**Seat 1 (n=19)**	**Seat 2 (n=5)**	**Seat 3 (n=6)**	**Seat 4 (n=11)**	**p-value**
Mean RT (ms)	299.77 (284.16, 333.93)	301.73 (275.70, 337.82)	308.07 (285.56, 334.63)	343.06 (306.55, 347.93)	0.10
Mean 1/RT (1/s) [1]	3.38 (3.02, 3.56)	3.35 (3.06, 3.68)	3.28 (3.07, 3.54)	2.99 (2.92, 3.32)	0.07
Fastest 10% RT (ms)	242.11 (231.34, 250.12)	248.62 (233.34, 255.38)	257.38 (242.48, 278.91)	256.88 (245.86, 265.65)	0.16
Lapse Probability (%)	0 (0, 2.5%)	0 (0, 0)	1.3% (0, 4.9%)	0 (0, 2.4%)	0.20

[1] For Mean 1/RT higher values indicate superior performance.

Table 24 Median (IQR) of the post-shift PVT outcome metrics and p-values comparing the differences across the four seats. Values with different superscripts across rows are significantly different

PVT Outcome Metrics	**Seat 1 (n=19)**	**Seat 2 (n=5)**	**Seat 3 (n=6)**	**Seat 4 (n=11)**	**p-value**
Mean RT (ms)	333.43^a (292.94, 357.95)	288.74^b (273.52, 298.81)	304.68^a (295.76, 320.16)	324.36^a (308.58, 349.78)	**0.03****
Mean 1/RT (1/s) [1]	3.05^a (2.86, 3.46)	3.52^b (3.41, 3.70)	3.32^a (3.17, 3.43)	3.16^a (2.91, 3.31)	**0.045****
Fastest 10% RT (ms)	262.43 (251.87, 287.92)	239.1 (231.84, 251.62)	256.75 (244.92, 273.59)	245.41 (227.30, 269.20)	0.051
Lapse Probability (%)	0 (0, 2.7%)	0 (0, 2.6%)	0 (0, 3.2%)	0 (0, 2.7%)	0.069

[1] For Mean 1/RT higher values indicate superior performance.

5.3.3 The Change of PVT Outcome Metrics

Similar to the methods in Chapter 3, the changes in PVT outcome metrics were obtained by subtracting the pre-shift metrics from the post-shift metrics for each PVT outcome measure. As shown in Table 25, these changes were compared across the four seat types.

Table 25 Median (IQR) of the post-shift changes in the PVT outcome metrics across the four seat types; P-values were based on the Kruskal Wallis test. Values with different superscripts across rows are significantly different

Changes in PVT Outcome Metrics	Seat 1 (n=19)	Seat 2 (n=5)	Seat 3 (n=6)	Seat 4 (n=11)	p-value
Mean RT (ms)	18.84 [a] (-1.14, 51.46)	-5.57 [b] (-45.98, 1.08)	1.08 [b] (-12.65, 11.82)	-0.5 [b] (-16.78, 36.76)	**0.03****
Mean 1/RT (1/s)[1]	-0.25 [a] (-0.41, 0.02)	0.1 [b] (-0.01, 0.42)	-0.03 [b] (-0.14, 0.14)	0.06 [b] (-0.29, 0.13)	**0.02****
Fastest 10% RT (ms)	15.27 [a] (5.51, 37.05)	-2.5 [b] (-15.52, 6.76)	-1.25 [b] (-14.27, 10.83)	-4.51 [b] (-19.03, 9.31)	**0.02****
Lapse Probability (%)	0 (0, 2.7%)	0 (0, 2.6%)	-0.07% (-2.3%, 0)	0 (0, 2.7%)	0.15

[1] For Mean 1/RT higher values indicate superior performance.

As shown in Table 25, significant differences across seats in the changes over the shift occurred with mean RT, mean 1/RT, and mean fastest 10% RT. Many of the largest changes in the PVT performance outcomes in the direction of vigilance degradation were found with Seat 1. The large magnitude changes with Seat 1 contrasted with the smaller magnitude changes observed with the other three seats.

The changes in the four PVT outcome metrics for Seat 1 were predominantly different from the other three seats. In contrast, no significant differences in the four metrics were found between Seat 2, Seat 3, and Seat 4. Given the enhanced vibration attenuation performance of Seats 2, 3 and 4, and the similarity in PVT metrics across the three seats, final exploration was made for comparing the PVT performance between the original seat, to the three seats with the enhanced vibration attenuation performance.

5.3.4 Comparing the Original Seat and the Pooled-Enhanced Seats

After dividing the four seats into the original seat group (Seat 1) and the enhanced seat group (Seats 2, 3 and 4), there were 19 pre- and post-shift PVT measurements from the original seat group and 22 measurements from the enhanced seat group. The changes in the four PVT outcome metrics between the two groups were compared

As shown in Table 26, significantly longer mean RT, shorter mean 1/RT, and longer mean fastest 10% RT were found with the original seat after the shift. The lapse percentage was not significantly different between the two groups.

Table 26 Median (IQR) of the post-shift changes in the PVT outcome metrics across the four seat types; Difference between the enhanced and original seats were obtained. P-values were based on the Kruskal Wallis test. Values with different superscripts across rows are significantly different

Changes in PVT Outcome Metrics	Original (n=19)	Enhanced (n=22)	Difference	p-value
Mean RT (ms)	18.84 (-1.14, 51.46)	-2.8 (-19.66, 7.53)	-21.64	0.0065**
Mean 1/RT (1/s)[1]	-0.25 (-0.41, 0.02)	0.05 (-0.12, 0.16)	0.3	0.0029**
Fastest 10% RT (ms)	15.27 (5.51, 37.05)	-3.25 (-15.72, 8.53)	-18.52	0.0014**
Lapse Probability (%)	0 (0, 2.7%)	0 (-0.03%, 0.6%)	0	0.13

[1] For Mean 1/RT higher values indicate superior performance.

5.3.5 PVT Performance and WBV Exposure Levels

In Appendix B, as shown in Table 27 and 28, the relationship between the changes in each PVT outcome metrics and the WBV exposures A(8) and VDV(8) were examined respectively. Positive association was found between A(8) and VDV(8) and the change in mean RT and mean fastest 10% RT. Also, WBV exposure levels were found to have negative association with mean 1/RT. These results suggested that WBV exposures appeared to be related with the degradation of PVT outcome metrics, and higher magnitude of WBV exposures was associated with poorer PVT performance.

5.4 Discussion

From the analysis of this chapter, the results of this field study indicate that WBV exposures may have affected truck drivers' PVT performance during their regular shift, and the effects appeared to be dependent on seat type. Similar results were found in a study conducted by Du et al., (2017) where the PVT outcome measures were compared between two seats that had different vibration attenuation properties. In Du's 2017 study, they measured PVT performance when truck drivers operated their trucks over standardized routes with their standard passive seats and then compared their PVT when driving over their same standardized routes with a higher performing active suspension which substantially reduced WBV exposures. With the passive seat, which attenuated less of the WBV exposures, the fastest 10% RT lengthened significantly when compared to the PVT performance of the active seat.

The subsequent analysis indicated potential differential effects where the PVT outcome metrics of the original truck seat (Seat 1) were different than the PVT performance of the other three truck seats (Seat 2, 3 and 4). To eliminate the effects from the pre-shift baseline measurements, the changes in the PVT outcome metrics over the shift were evaluated. Besides the main effect seat type, demographic and shift-related variables were also analyzed to determine whether there were potential confounding effects as shown in Appendix C, but even after introducing the potential confounders, seat type was still dominant to the PVT outcome metrics, as shown in Appendix D.

Based on the results of Chapter 4, the major difference between Seat 1 and the other three seats appeared to be the WBV attenuation performance and the amount of lower frequency vibration energy content between 0.5 and 4.5 Hz. Substantial vigilance degradations were observed in many of the PVT outcome metrics occurred after operating the trucks with Seat 1, the seat which had the poorest WBV attenuation performance and the greatest amount of vibration energy between 0.5 – 4.5 Hz. This contrasted with the WBV exposure results obtained with the other three seats.

Given the similarity in the PVT performance across the three seats with enhanced vibration attenuation performance, further analysis was performed comparing PVT performance between the original seat and the other seats with enhanced vibration attenuation performance. The results demonstrated that significant differences in PVT performance existed between the two classes of seats. There were larger changes in the direction of vigilance deterioration for the original seat PVT performance when compared to the enhanced seats' which had lower WBV exposures. The original seat had a significantly greater changes in mean RT (18.84ms, p = 0.0065), mean 1/RT (-0.25s^{-1}, p = 0.0029), and fastest 10% RT (15.27ms, p = 0.0014).

Related results were found in a recent lab-based study conducted by Yung et al., (2018) investigating the acute effect of WBV from an agricultural all-terrain vehicle (ATV) on eighteen college students (age 26.1 ± 5.3 years). Significant lengthening in mean RT (17.15ms, p=0.005) and an increase in lapse probability (1.4%, p=0.02) of PVT were found after 60-minute acute WBV exposures simulated by a hexapod, with z-axis WBV averaged at 2.13 m/ s^{-2}. While no significant changes in vigilance were found after the relatively lower level WBV exposure at 0.94 m/ s^{-2}. Though this study demonstrated the negative effects of being exposed to acute WBV, the exposures in this simulated study far exceeded the WBV action limit proposed by ISO guideline, and the participants didn't represent the workforce population of truck driver either. In contrast, the field study provided realistic WBV intensities and durations and thus supported that WBV exposures impacted driver's vigilance in the real trucking scenarios.

Most of the studies using PVT to evaluate vigilance performance were focused on the impacts of total and partial sleep deprivation (Van Dongen et al., 2003; Basner & Dinges, 2011; Wilkinson et al, 2013). This study also attempted to explore the association between the WBV exposures and approximated prior night sleep duration, and approximate one hour longer sleep duration was found with Seat 2, 3, and 4 compared with Seat 1 as shown in Appendix E. The results potentially reveal that the effects of WBV exposures on vigilance decrements might be equivalent to individual experiencing a certain duration of sleep deprivation.

Difference in WBV exposures may be one explanatory factor for the differences in PVT performance between the two classes of seats. The distinguishing characteristic of the seats may be the larger amount of lower frequency energy between 0.5 and 4.5 Hz in the PSDs with Seat 1 compared to Seats 2, 3 and 4. Perhaps this lower frequency energy and greater amounts of low frequency vibration transmissibility, which was important for the drivers' comfort, health and well-being contributed to degraded PVT performance with Seat 1.

5.5 Conclusion

This study investigated how different truck seats influence drivers' vigilance performance in a naturalistic setting, and it supports the hypothesis that driving a truck for a 11-hour shift affected drivers' vigilance, and a reduction in WBV exposure appeared to be associated with smaller decrements in vigilance. The results demonstrated that drivers were able to maintain vigilance better after sitting in the truck seats with enhanced vibration attenuation performance as indicated by the changes in mean reaction time, response speed, and optimum reaction time over the entire shift. When the drivers operated their trucks with the rougher-riding, original-fitted seat, greater degradations in PVT performance were found compared to the three seats which had enhanced vibration attenuation.

In summary, this study provides evidence that truck seats, and ultimately WBV, may influence drivers' vigilance during their regular shift. Since very few studies have explored the cognitive effects of WBV in a field setting, this study contributes to the literature of the link between the environmental factors WBV and drivers' mental fatigue specially in sustained attention.

5.6 Limitations

The primary limitation of this study were the small sample sizes obtained from some of the seats evaluated, and thus nonparametric approaches were used. Although the power analysis suggested adequate power after pooling the seats into two groups, a larger sample size would have the potential to reduce the possibility of type 2 error. Some other limitations included that the seats had to be tested serially, rather than randomizing due to operational difficulties. The subjects were not blinded to the type of seat either.

Also, it was hard to control the exact shift start time, driving hours, traffic conditions, and the drivers' behavior during the shift, as this was a naturalistic study. These factors could affect the vigilance performance and mask the actual responses between WBV and vigilance. Fortunately, the drivers selected all started their shift in the afternoon, which reduced potential confounders of daylight and circadian effects.

5.7 Future Work

First, a study with a larger sample size and repeated PVT measures is preferred to provide adequate power with randomization of subjects and the seat order. The measurements collected during a short period of time with shifts starting in a relatively smaller time window is desirable.

Secondly, besides assessing drivers' vigilance before and after the shift, obtaining vigilance measurements during the shift would aid to the understanding of the change of vigilance performance over the time of WBV exposures. Possible extra vigilance measures could be taken at a roadside stop, or when the driver is waiting for the truck to get loaded/unloaded.

Thirdly, fatigue monitoring technologies can be used in the future research. These fatigue monitoring systems track drivers' drowsiness level through analyzing a driver's face and eye state in real time and can help to detect the early stage of drowsiness over a driver's shift (Lenne & Jacobs, 2016; Verma, Girdhar & Jha, 2018). These on-board devices could also help to record the drivers' behavior during their shift without interrupting them from the driving task.

Chapter 6 General Conclusion

This chapter concludes the overall findings of the dissertation, summarizes the contribution to the current field of research, discusses the limitation, and presents possible future research that may impact and potentially improve the working environment of truck drivers.

The overall purpose of this dissertation is to explore the association between WBV and commercial truck drivers' vigilance. Decreased vigilance contributes to accidents involving trucks. Truck driver's vigilance was measured using Psychomotor Vigilance Task. Furthermore, a laboratory-based study and a field study were conducted to assess drivers' vigilance performance with different levels of exposure to WBV.

The association between WBV exposures and operators' physical discomfort has been studied intensively. Whereas very few studies have been conducted that have focused on the cognitive effects of exposure to WBV. Although some studies have shown a possible link between vehicle vibration and driver drowsiness, there is little quantitative research on how WBV affects alertness levels.

Summary of Research Gaps

Most of previous studies have been laboratory-based, short-term studies exploring the association between WBV exposures and driver fatigue (Newell & Mansfield, 2008; Zamanian et al., 2014; Costa, Arezes, & Melo, 2014). Although some studies have observed increased drowsiness after exposure to WBV, due to the short duration exposures, it's uncertain whether the results translate to real-occupational situations. With longer duration exposures, levels of driver drowsiness may not follow or match the short-term exposures, since over time, the driver accommodate and get used to the vibration. Also, the intensity and frequency of vibration in some of the lab-based studies may not be representative of the actual vibration experienced in trucks (Ljungberg & Neely, 2007; Yung et al., 2017). Some studies exposed subjects to sinusoidal vibration, which may result in more drowsiness because sinusoidal signals provided more monotony compared to random vibration (Landström & Lundström, 1985; Zamanian et al., 2014).

There is still insufficient quantitative research on WBV and occupants' drowsiness because fatigue occurred with multiple mechanisms. Additionally, whether current WBV vibration standards and guidelines can protect occupants from cognitive fatigue hasn't been investigated. Therefore, the findings from these studies, the prolonged effects of WBV on changes in driver alertness in the real setting merit further investigation.

Major Findings

Through a laboratory simulation study and a field study applying using different truck seats to create vibration contrasts, we observed changes in drivers' drowsiness level-based differences in the PVT performance metrics. The results suggested that various truck seats could expose the drivers with different levels of WBV exposures, which appeared to be related with the changes in drivers' vigilance. Drivers were able to maintain vigilance better after sitting in the truck seats which exposed drivers to lower vibration levels, whereas decrements in vigilance was observed after sitting in truck seats which exposed drivers to higher levels of WBV. The results of this dissertation support the hypothesis that shift-long exposures to higher levels of WBV may negatively affected truck drivers' vigilance as measured by the PVT reaction time measures.

This study provides evidence that truck seats, and ultimately different levels of exposure to WBV, may influence driver fatigue and the truck driver's vigilance. Since very few studies have explored the cognitive effects of WBV in a field setting, this study revealed that exposure to higher levels of exposure to WBV may adversely impact drivers' sustained attention.

The major findings are:

1. High levels of whole-body vibration can occur even in modern trucks fitted with industry standard air-suspension seating technology.
2. Significant improvements in whole-body vibration attenuation are achievable with active suspension seats. However, attenuation performance improvements are also possible with lower-cost, passive suspension seats.
3. Truck seats appear to have different frequency-related vibration properties. The original-fitted, passive suspension seat had the poorest WBV attenuation performance and the greatest amount of vibration energy between 0.5 – 4.5 Hz.
4. In the lab-based study in Chapter 4, there were trends indicating that, when sitting in an industry standard passive, air suspension seat, as little as two hours of exposure may decrease the level of drivers' vigilance. Similar trends were not seen when the same drivers sat in an active suspension seat which reduced WBV exposures by 50% on average.
5. The changes of drivers' vigilance were dependent on the WBV exposures during the drivers' regular shift. Less decline in vigilance performance was found after drivers sat in the truck seats which exposed them to lower levels of vibration over their shift. Based on the differences in the Power Spectral Densities between seats, which express vibration energy as a function of frequency content, the vigilance differences may be due to the differences in the vibration attenuation performance of low frequency energy in these seats.

Contribution

The results demonstrate that WBV may have adverse effects on seated drivers' vigilance. Drowsy driving has been one of the major causes of road accidents involving commercial trucks. Truck drivers' sleep management and driving schedules aspects have been studied intensively previously. However, limited research has been done so far on truck driver drowsiness induced by whole-body vibration, an important environmental factor. Although ISO-2631 has been widely used for assessing human physical discomfort, there is no guideline for vehicle vibration on drivers' mental fatigue.

This dissertation demonstrated that exposure to WBV may possibly cause decline in wakefulness of commercial truck drivers, resulting in lengthened reaction times to visual stimuli. Performance metrics of PVT also demonstrated sensitivity to the changes in vigilance induced by different levels of WBV exposures. In the laboratory-based study in Chapter 3, unlike previous simulation studies; which have either used non-random, sinusoidal vibrations, unrealistically high exposure levels, and/or short duration exposures; the WBV exposure the drivers experienced in our lab study was of longer duration (two-hours) and was actual field-measured vibration from a semi-truck travelling over a freeway. The longer duration, two-hour exposure, and using actual, field-measured truck vibration added to the validity of the study outcomes. The naturalistic, field study measuring PVT outcomes with truck drivers driving during their regular shifts was also unique, which contributed to the understanding of the cognitive effects of WBV. This is the first study that demonstrated the potential impacts of WBV on truck drivers' vigilance.

This dissertation also investigated intensively the WBV features that Canadian truck drivers in mining industry experienced. The WBV exposures on different road conditions were compared with four different truck seats. Higher WBV was found on the rough, unpaved road compared with the highway. Also, the power spectral density analysis revealed the vibration energy contents at different frequency. More low frequency energy less than 3 Hz was observed with the truck's original-fitted air suspension seat, while the active suspension seat and two other passive suspension seats were found to have less low frequency energy. Consistent with previous studies, low frequency vibration contents below 3 Hz were strongly related with mental fatigue and were critical to rider's comfort (Yang et al., 2016). This may explain why greater decrease in vigilance was found after sitting in the original-fitted seat. Additionally, in the field study, the changes in PVT performance metrics, mean RT, mean 1/RT, and fastest 10% RT over drivers' regular shift appeared to be associated with the magnitudes of WBV. This is the first study attempting to explore the dose-response of WBV on driver cognitive vigilance.

In summary, this dissertation contributes to characterizing the WBV exposures truck drivers are exposed to in the real occupational settings. More importantly, this study explores the association between WBV exposures and the impairment of drivers' vigilance, which will expedite the understanding of the effects of WBV in the mental domain, extending the current literature. In practice, these findings have the potential to provide additional guidelines for reducing whole-body vibration in truck drivers, and thus affect the use of vibration-reducing seats in current and future trucks. Since the impaired vigilance among truck drivers increases the risk of accidents, accounting for truck drivers' whole-body vibration exposures will help improve the public road safety as well.

Limitation

Like all research studies, there are some limitations associated with this dissertation. The primary limitation is the small sample size in both laboratory and field study. Since no previous study with similar exposure has been done, power of the study was roughly obtained through the effect size from a study that assessed PVT performance under sleep-deprivation, which may result in the sample size obtained to be different from the actual sample size needed with WBV exposures.

There may also be some limitations to the generalizability of our field-study results. The findings from the field study are more related with the long-haul truck drivers that stay most of their shift on the highway, so the WBV exposures and vigilance may be different from the delivery truckers or bus drivers that drive in the urban area and stop frequently due to different task requirements and mental loads.

In the field study, it was also hard to control the exact shift start time, driving hours, and traffic conditions. These factors could have impacts on the PVT performance and vigilance. But fortunately, the drivers selected all started their shift in the afternoon, which reduced potential confounders of daylight and the effect of circadian rhythm.

Finally, in the field study, PVT performance was measured before and after drivers' WBV exposures, which could not measure or reflect how drivers' vigilance changed while they were driving. Additionally, though effective in detecting changes in vigilance, the simple reaction time task as PVT is still different from the real truck driving, which involves several processes including information encoding, executive function, and cognition.

Future Research

With respect to potential future research, a laboratory based- study that exposes the drivers with WBV at various frequencies could be conducted. The study could be designed to evaluate truck seats which pass different frequencies of vibration to the drivers. Truck seats could be select that pass low frequency vibration content through to the driver, like Seat 1; pass intermediate vibration frequency content though to the drivers, like Seat 2 and 3; and pass very little vibration energy content to the drivers, like Seat 4. Then this study could identify whether changes in reaction times were with the differences in vibration frequency composition from the various seats.

To overcome the operational difficulties faced during the field study, future studies could recruit the drivers remotely and let the drivers conducted the PVT using a smart phone-based application, with the test results uploaded to the cloud automatically (Grant et al., 2017). The WBV exposures can also be measured using an iOS application (McGlothlin, Burgess-Limerick, & Lynas, 2015), which may increase the efficiency of data collection.

Although PVT performance metrics have demonstrated its sensitivity towards assessing vigilance performance under vibration exposures, a comprehensive test battery may be merited to facilitate measuring drivers' cognitive performance at different aspects (Matthews, 2012). Karolinska Sleepiness Scale (KSS), selective attention and divided attention task, and executive function could all be included along with PVT, when the test environment allows. An on-board motion tracking device can be used to record and detect drivers' drowsiness, where the percentage of slow eyelid closures is obtained in real time, and this method has been validated against PVT.

Future research should take control of the potential confounders encountered during the naturalistic study, ensuring the drivers start their shift at the same time. Having the same subject participates in both field and laboratory-based study is strongly desired to reduce study variation. Besides, in the field study, the test battery should not only be performed before and after the shift, but also during drivers' shift when the driver is taking a break to evaluate how drivers' vigilance changes over their shift.

Future research should determine if there is a dose-response relation between the degradation of vigilance and WBV exposures. In the field study, even though lower WBV magnitudes were found from the active suspension seat compared with the other two better performing passive suspension seats, there wasn't considerable difference in the change of PVT metrics. Therefore, further quantification is necessary to characterize the pattern of this relationship.

Currently there are no guidelines that clearly define and regulate the cognitive effects of WBV on drivers. In the field study, there appeared to be degradation in perceived vigilance from drivers after they sat in the industrial standard truck seat. However, the WBV magnitudes from this seat were below the ISO action limit. Therefore, discovering the minimum WBV level that the truck driver can be exposed to without a significant vigilance impairment could be of benefit.

Using experimental approach, this dissertation provided data and insights about the association between WBV and truck driver vigilance, which is an important step in discovering the cognitive effects of WBV on driver performance and vehicle operation. There are still many questions that need to be answered by the future research. What's the minimum WBV can induce truck driver drowsiness? Is there a long-term, cumulative effect of WBV on truck drivers' cognition? Further cost benefit analysis of applying vibration reduction truck seats is also necessary for stakeholders to apply these seating technologies in trucking industry.

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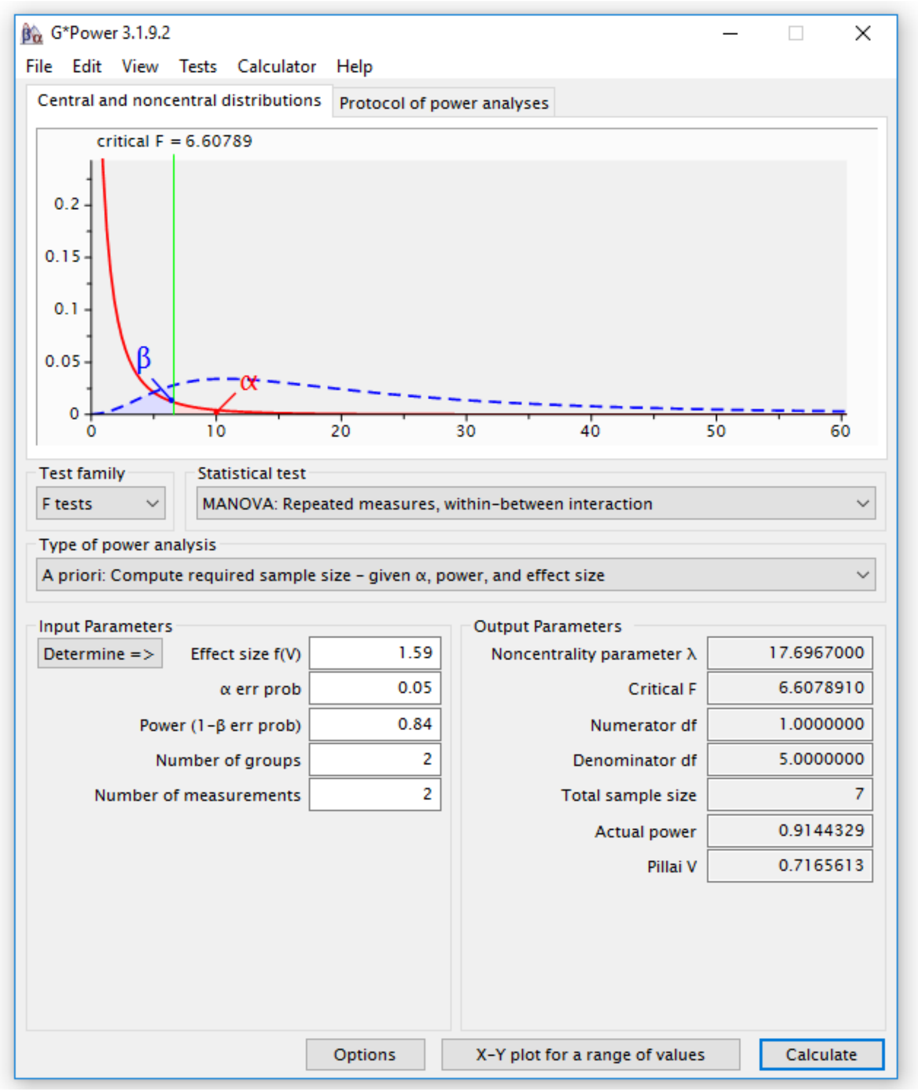
Appendix A Statistical Power

Sample Size for the Lab-Based Study

GPower software input, number of measurements and number of groups were based on the condition of two vibration levels, and test times (before and after). Effect size 1.59 was based on the study of Basner and Dinges (2011).



Test family: F tests

Statistical test: MANOVA: Repeated measures, within-between interaction

Type of power analysis: A priori: Compute required sample size – given α, power, and effect size

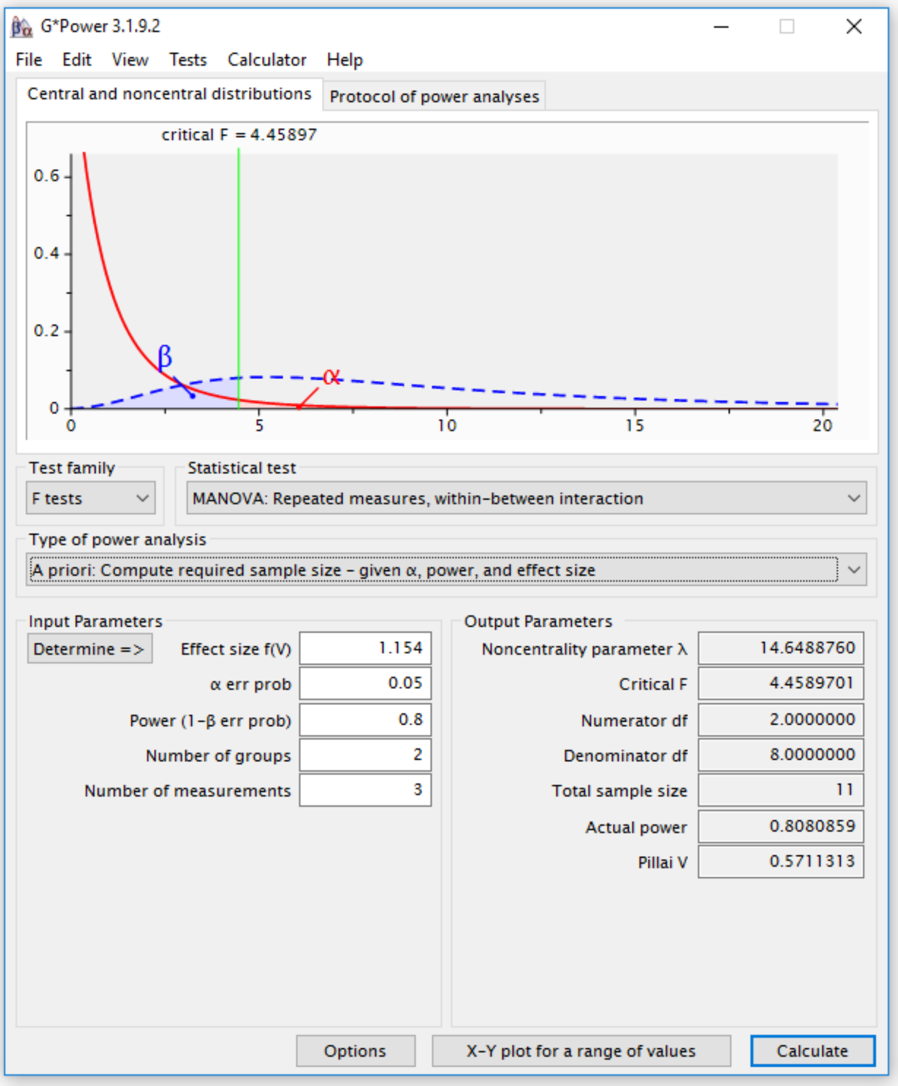
Input Parameters	
Effect size f(V)	1.59
α err prob	0.05
Power (1–β err prob)	0.84
Number of groups	2
Number of measurements	2

Output Parameters	
Noncentrality parameter λ	17.6967000
Critical F	6.6078910
Numerator df	1.0000000
Denominator df	5.0000000
Total sample size	7
Actual power	0.9144329
Pillai V	0.7165613

Figure 17 Sample size calculation for the lab study

Sample Size for the Field Study

GPower software input, number of measurements and number of groups were based on the condition of three vibration levels, and test times (before and after). Effect size 1.154 was calculated by the difference between the mean (0.03) divided by standard deviation (0.026) from the laboratory-based study in Chapter 3.



Test family: F tests

Statistical test: MANOVA: Repeated measures, within-between interaction

Type of power analysis: A priori: Compute required sample size – given α, power, and effect size

Input Parameters

Effect size f(V): 1.154
α err prob: 0.05
Power (1-β err prob): 0.8
Number of groups: 2
Number of measurements: 3

Output Parameters

Noncentrality parameter λ: 14.6488760
Critical F: 4.4589701
Numerator df: 2.0000000
Denominator df: 8.0000000
Total sample size: 11
Actual power: 0.8080859
Pillai V: 0.5711313

Figure 18 Sample size calculation for the field study

Appendix B PVT Outcome Metrics vs. WBV Exposures

Linear regression models were used to examine the relationship between the changes in each PVT outcome metrics and the WBV exposures A(8) and VDV(8) respectively. All statistical analyses were performed with statistical software R (R Core Team, 2021). Although p -value indicates statistical significance, the R^2 are low.

Table 27 Linear Regression parameter estimation and p-value for the changes in PVT outcomes based on the z-axis seat-top A(8) WBV exposures. (n = 21)

Changes in PVT Outcomes ~A(8)	**Covariates**	**Estimate**	**Std Error**	**t Ratio**	**p-value**	**R^2**
Mean RT	(Intercept)	-49.32	18.41	-2.68	0.01**	0.22
	A(8)	106.11	38.96	2.72	0.01**	
Mean 1/RT	(Intercept)	0.52	0.18	2.88	0.01**	0.25
	A(8)	-1.15	0.38	-2.98	0.01**	
Fastest 10% RT	(Intercept)	-23.57	13.73	-1.72	0.10**	0.15
	A(8)	62.65	29.06	2.16	0.04**	
Lapse Probability	(Intercept)	0.01	0.01	0.93	0.36	0.02
	A(8)	-0.02	0.03	-0.69	0.50	

Table 28 Linear Regression parameter estimation and p-value for the changes in PVT outcomes based on the z-axis seat-top VDV(8) exposures. (n = 21)

Changes in PVT Outcomes ~A(8)	**Covariates**	**Estimate**	**Std Error**	**t Ratio**	**p-value**	**R^2**
Mean RT	(Intercept)	-55.12	21.31	-2.59	0.02**	0.20
	VDV(8)	5.65	2.17	2.61	0.01**	
Mean 1/RT	(Intercept)	0.59	0.21	2.82	0.01**	0.24
	VDV(8)	-0.06	0.02	-2.90	0.01**	
Fastest 10% RT	(Intercept)	-30.31	15.56	-1.95	0.06	0.17
	VDV(8)	3.68	1.58	2.33	0.03**	
Lapse Probability	(Intercept)	0.01	0.02	0.50	0.62	0.00
	VDV(8)	0.00	0.00	-0.29	0.78	

Appendix C Potential Confounders

According to Section 5.3.1, although no notable difference was found for most of the demographic and shift- related variables across the four seats, it's still necessary to explore if these variables are potentially confounding effects that could contribute to the variation of the PVT outcome metrics besides seats and test time.

The pre-shift, baseline, the post-shift, and the changes in the outcome metrics were analyzed as separate scenarios. The correlations between the numerical variables, including both integer and continuous variables, were obtained at first. With each PVT outcome metric as the dependent variable, multiple one-way ANOVAs were performed for each demographic and shift related variable as its independent variable, and only the variables with statistical significance from the ANOVAs were treated as the potential confounding effects, which would be considered in the subsequent analysis.

Variables Affecting the Pre-Shift Baseline PVT Outcome Metrics

First, as shown in Figure 19, Pearson correlations of the pre-shift PVT outcome metrics and all the numerical independent variables were calculated. Correlation above 0.7 was interpreted as high correlation, between 0.5 and 0.7 as moderate correlation, and below 0.5 as low correlation (Mukaka, 2012). Among the pre-shift PVT outcome metrics, a very high negative correlation -0.99 was found between mean RT and mean 1/RT, since mean 1/RT was taken the mean of the reciprocal of RT from each PVT. Mean RT and mean 1/RT were found to have moderate correlation with mean fastest 10% RT. Weight was found to have moderate correlation with height. BMI was highly correlated with weight. Also, age was highly correlated with the years as truck driver.

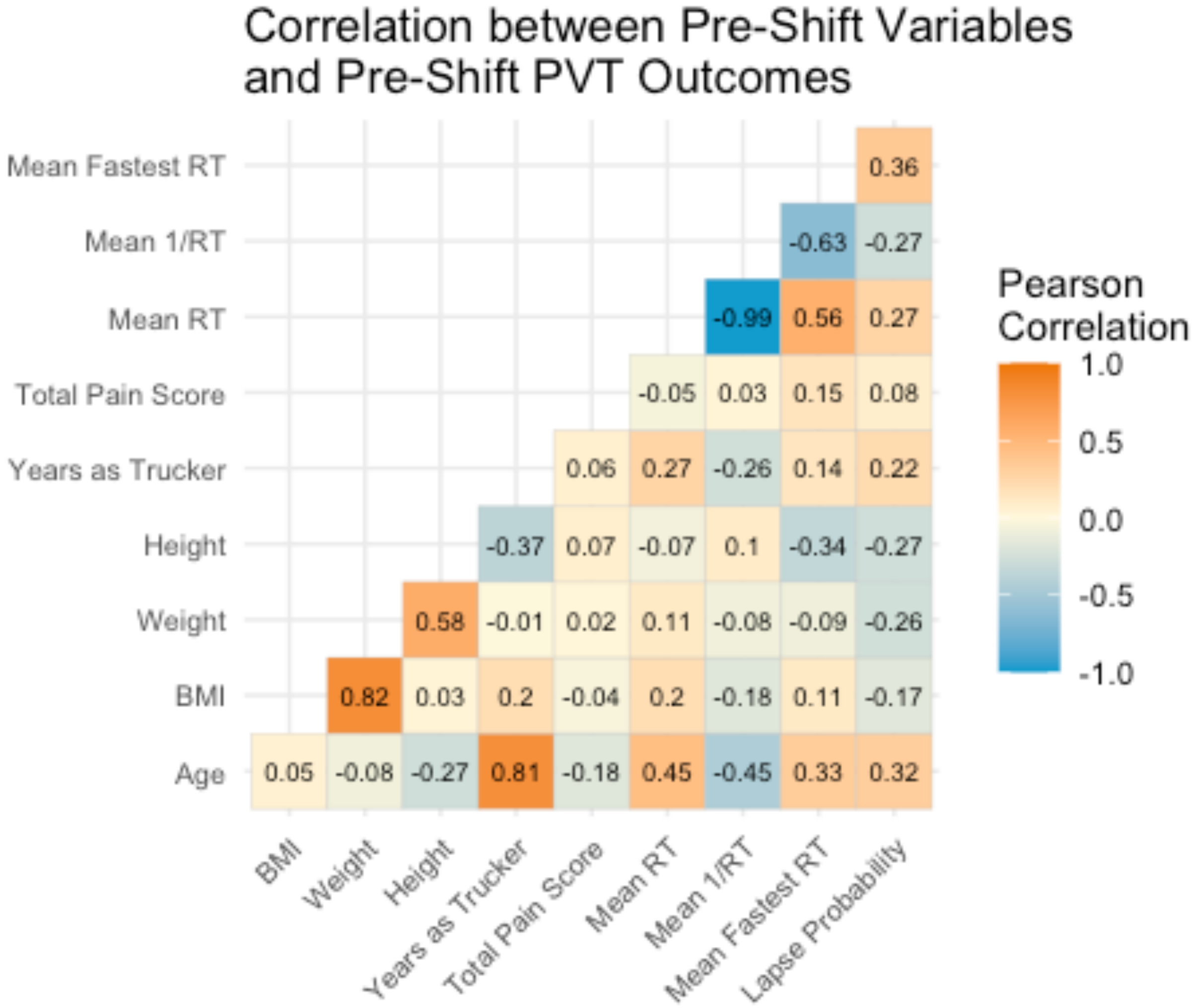


Figure 19 Pearson correlations of the pre-shift PVT outcome metrics and the demographic variables

As shown in Table 24, the baseline, pre-shift PVT measures were shown to have a trend of variation across the four seats in mean 1/RT. Besides the type of seats, there were other coexisting factors that could influence the PVT performance. In terms of the PVT baseline performance before the shift started, these factors were age, BMI, time of day when the shift started, sleep quality, and the pain score from the Standardized Nordic questionnaires.

Numerous studies have been done to explore the effects of age, BMI, and time of day on sustained attention (Kirton & Dostson,2015). Besides the reported pre-shift sleep quality, the time of day also partially determined the PVT performance because of circadian rhythms on human sustained attention.

Table 29 shows the variables that may contribute to the variation of the pre-shift PVT outcome metrics. Age demonstrated statistically significance towards all the four pre-shift PVT performance outcome as indicated by the p-values from the one-way ANOVAs. The correlation in Figure 19 also demonstrated that age was associated with degradation of all the PVT metrics. In addition, shift starting time, which was 15 minutes after the pre-shift PVT task was significant for the lapse probability metrics, and the lapse probability increased as the time of day got late.

Table 29 P-values and F-values from ANOVAs with pre-shift PVT outcome metrics as response variables and each demographic variable as independent variable. (n = 41)

Variables	ANOVA p and F-values	Mean RT	Mean 1/RT	Fastest 10% RT	Lapse Probability
Age	p	**0.003****	**0.003****	**0.03****	**0.04****
	F (1,39)	10.0	10.2	4.8	4.5
BMI	p	0.2	0.3	0.5	0.3
	F (1,39)	1.6	1.3	0.5	1.1
Weight	p	0.48	0.62	0.56	0.10
	F (1,39)	0.50	0.25	0.34	2.91
Years as Trucker	p	0.09	0.10	0.38	0.16
	F (1,39)	3.08	2.82	0.80	2.04
Time When Shift Started	p	0.5	0.5	0.3	**0.01****
	F (1,39)	0.5	0.6	1.1	6.9
Sleep Quality	p	0.1	0.2	0.5	0.5
	F (2,38)	2.2	1.5	0.8	0.8
Pain Score	p	0.7	0.9	0.3	0.6
	F (1,39)	0.1	0.03	0.9	0.3

Variables Affecting the Post-Shift PVT Outcome Metrics

As presented by Table 23, there were no significant differences in the PVT outcomes between pre-and post-shift, but near significant poorer vigilance was found with mean fastest 10% RT and lapse probability after the shift. Because age and years as truck driver, weight and BMI were highly correlated (>0.8) from Figure 19, only age and weight were included in the subsequent analysis. Besides age and weight, the correlations between the shift-related variables and the post-shift PVT outcome metrics were also calculated as shown in Figure 20. These shift-related variables included duration of the shift, caffeine intake, ratings of seat comfort levels, as well as the post-shift total pain scores.

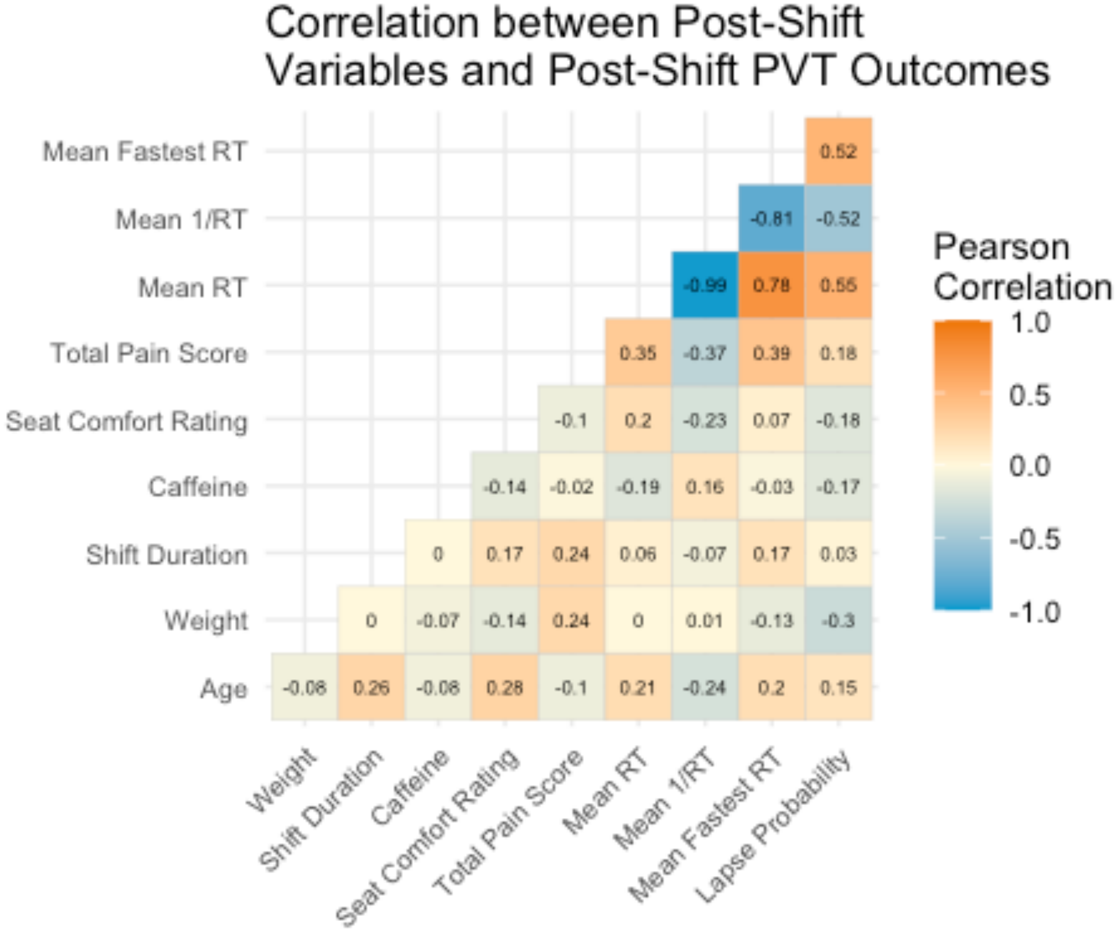


Figure 20 Pearson correlations of the post-shift PVT outcome metrics and the demographic variables and the shift-related variables

Higher correlations in the post-shift PVT metrics were observed compared with the pre-shift metrics in Figure 19, Similar to the correlations between the pre-shift PVT outcome metrics, a high negative correlation -0.99 was found between the post-shift, mean RT, and mean 1/RT. High and moderate correlations were found among the four PVT metrics. Correlations less than

0.5 were found between all the shift-related variables and the PVT outcome metrics. Like Figure 19, older age was associated with degraded PVT outcome metrics. Unlike the correlations for the baseline, pre-shift PVT outcome metrics, higher weight were weakly correlated with better PVT performance. Besides, the amount of caffeine intake was correlated with less degradation of the PVT performance.

Table 30 shows the demographic and shift-related variables that could potentially affect the post-shift PVT performance. Each variable was used as an independent variable of ANOVAs against the PVT metrics. Only the post-shift total pain score appeared to be significant toward the post-shift mean RT, mean 1/RT and fastest 10% RT. According to the correlation in Figure 20, increased total pain rating was correlated with degraded PVT performance.

Table 30 P-values and F-values from ANOVAs with post-shift PVT outcome metrics as response variables and each demographic /shift-related variable as independent variable. (n = 41)

Variables	ANOVA p and F-values	Mean RT	Mean 1/RT	Fastest 10% RT	Lapse Probability
Age	p	0.19	0.13	0.22	0.36
	F (1,39)	1.8	2.37	1.57	0.85
Weight	p	0.99	0.95	0.42	0.06
	F (1,39)	0	0	0.67	3.89
Shift Duration	p	0.73	0.67	0.28	0.84
	F (1,39)	0.12	0.19	1.2	0.04
Total Rest Duration	p	0.84	0.74	0.2	0.26
	F (1,39)	0.29	0.43	1.64	1.41
Caffeine Intake (cups)	p	0.24	0.32	0.87	0.29
	F (1,39)	1.42	1.03	0.03	1.16
Seat Comfort Rating	p	0.22	0.15	0.64	0.25
	F (1,39)	1.54	2.11	0.22	1.35
Post-Shift Pain Score	p	**0.02****	**0.02****	**0.01****	0.25
	F (1,39)	5.54	6.1	6.98	1.35

Variables Affecting the Change of PVT Outcome Metrics

The changes of PVT outcome metrics over the entire shift were initially studied in Section 5.3.3, and larger vigilance degradation was found with Seat 1 compared with the other three seats. There were still other variables that could contribute to the variation of the changes of PVT performance other than seat type. Firstly, the correlations between these variables were calculated. Like the post -shift PVT performance analysis, variables characterizing the drivers' behavior during the shift were also studied in the one-way ANOVAs. These shift-related variables included duration of the shift, caffeine intake, ratings of seat comfort levels, as well as the changes in the ratings of total pain scores.

Pearson correlations of the changes in PVT outcome metrics and the shift-related variables were obtained as Figure 21. Higher correlations in the changes of the PVT metrics were observed compared with the pre-shift metrics in Figure 19. Similar to the correlations between the pre-shift PVT outcome metrics, a high negative correlation -0.98 was found between the change of mean RT and mean 1/RT. The changes in mean RT and mean 1/RT were also found to have strong correlation with mean fastest 10% RT. No moderate to strong association was found between the other variables.

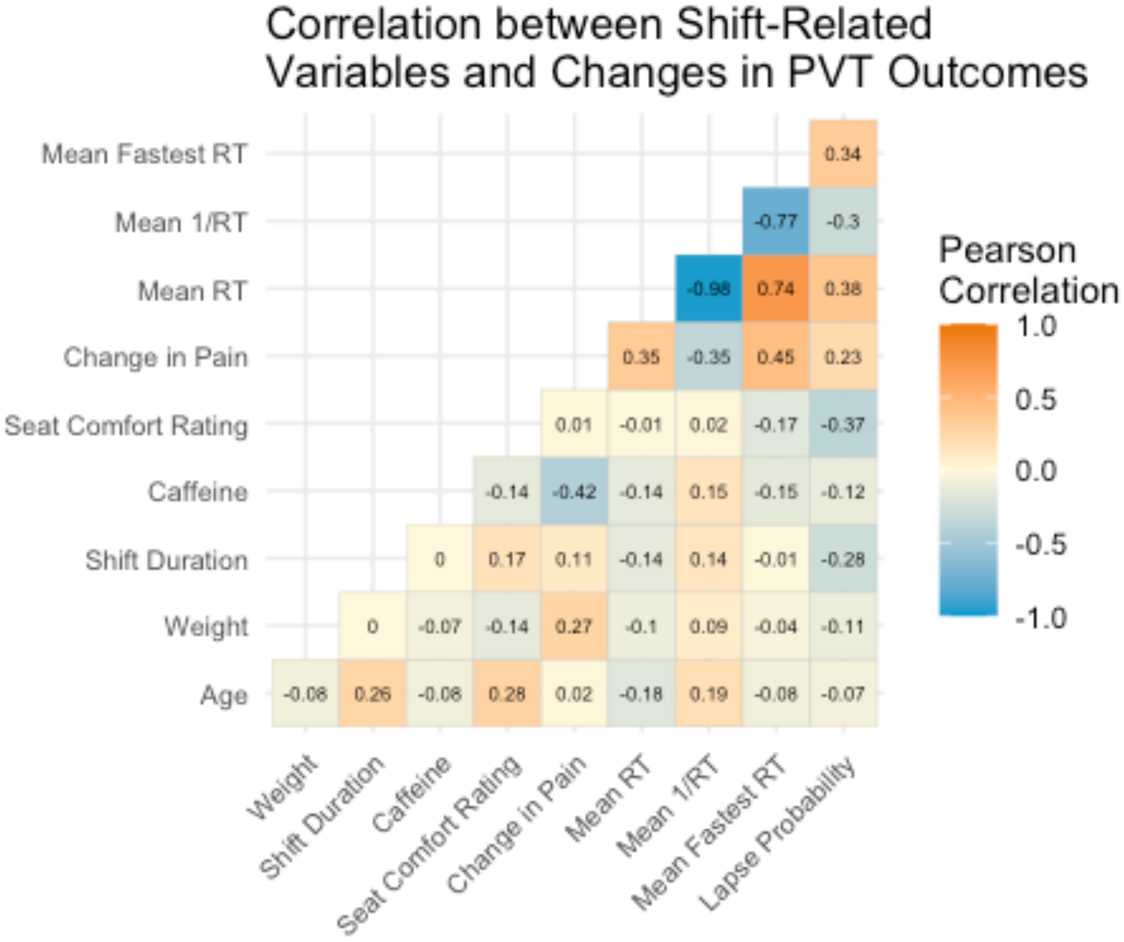


Figure 21 Pearson correlations of the changes in PVT outcome metrics and the demographic variables and the shift-related variables

Table 31 shows the demographic and shift-related variables that could potentially affect the changes of PVT performance over a shift. Each variable was used as an independent variable of ANOVAs against the PVT outcome metrics. Among these factors, seat comfort ratings were shown to be associated with lapse probability, and the changes in total pain score appeared to be significant toward the changes in mean RT, mean 1/RT and fastest 10% RT.

Despite that age was a significant contributor to the variation of the baseline, pre-shift PVT metrics, it wasn't significant towards the changes in the PVT metrics. Also, the pre-shift measured total pain score wasn't significant for the pre-shift measures. But the change in total pain score was significant to the changes in PVT metrics, and appeared to relate with the of PVT performance as shown in Figure 21. These findings indicated that taking the changes of the PVT metrics could eliminate part of the effects due to different baseline in the pre-shift measurements, which could further aid to the understanding of the variations resulting from the shift fulfillment.

Table 31 P-values and F-values from ANOVAs with the changes in PVT outcome metrics as response variables and each demographic variable as independent variable. (n = 41)

Variables	ANOVA p and F-values	Mean RT	Mean 1/RT	Fastest 10% RT	Lapse Probability
Age	p	0.25	0.24	0.60	0.66
	F (1,39)	1.37	1.45	0.28	0.20
Weight		0.53	0.58	0.78	0.48
	F (1,39)	0.40	0.32	0.08	0.51
Total Rest Duration	p	0.59	0.49	0.22	0.37
	F (3,37)	0.65	0.81	1.56	0.43
Caffeine Intake (cups)	p	0.39	0.36	0.36	0.47
	F (1,39)	0.75	0.85	0.85	0.52
Seat Comfort Rating	p	0.94	0.92	0.28	0.02**
	F (1,39)	0.01	0.01	1.18	6.28
Changes in Pain Score	p	0.02**	0.02**	0.003**	0.15
	F (1,39)	5.53	5.57	10.03	2.13

According to the results in Table 26, the changes in the four PVT outcome metrics for Seat 1 were significantly or nearly significantly different from the other three seats. In contrast, no significant differences in the four metrics were found between Seat 2, Seat 3, and Seat 4 except for the difference in the lapse probability between Seat 2 and Seat 3. Given the enhanced vibration attenuation performance of Seats 2, 3 and 4, and the similarity in PVT metrics across the three seats, final exploration was made for comparing the PVT performance between the original seat, to the three seats with the enhanced vibration attenuation performance.

Appendix D Comparison of the Confounders between Two Seat Groups

After dividing the four seats into the original seat group (Seat 1) and the enhanced seat group (Seats 2, 3 and 4), there were 19 pre- and post-shift PVT measurements from the original seat group and 22 measurements from the enhanced seat group. The changes in the four PVT outcome metrics between the two groups were compared.

Demographic and Shift-Related Variables by the Original Seat and the Enhanced Seat

Comparisons of the demographic and pre-shift sleep quality between the two seat groups is shown in Table 32 and 33, No significant differences were found in the demographic information and the shift-related variables including shift-starting time, driving hours, and the amount of caffeine intake between the two seat groups, which should lower the potential for confounding factors with respect to PVT performance. No significant difference in self-rated seat comfort levels was found between the two groups either.

Table 32 Mean (standard error) demographics and shift-related information of study participants by the two seat groups

Variables	Original Seat (n=19)	Enhanced Seats (n=22)	p-value
Age	50.5 (8.4)	51.8 (7.3)	0.59
BMI	29.9 (3.5)	30.4 (4.5)	0.91
Weight (kg)	94.4 (11.7)	94.9 (19.2)	0.91
Height (cm)	177.8 (7.4)	176.3 (8.6)	0.58
Shift Starting Time (hour)	15.5 (2.0)	15.7 (2.1)	0.70
Shift Duration	10.5 (0.7)	10.8 (0.8)	0.26
Cups of Caffeine	3.00 (4.7)	3.1 (2.8)	0.91
Seat Comfortable	4.0 (1.8)	4.4 (1.9)	0.48

According to Table 33, similar distribution of self-reported sleep quality ratings was found between the two groups.

Table 33 Distribution of participants' sleep quality of the two seat groups

Sleep Quality	Original Seat (n = 19)	Enhanced Seats (n = 22)
FAIRLY BAD	0	1
FAIRLY GOOD	10	13
VERY GOOD	9	8

From Table 34, the distribution of total rest duration was roughly balanced between the two seat types, which improved the imbalance in the total rest duration for the four seat types as shown in Table 22.

Table 34 Distribution of participants' total rest duration during a shift by four seats

Total Rest Duration	Original Seat (n = 19)	Enhanced Seats (n = 22)
0-10 min	11	12
10-20 min	6	6
20-30 min	1	3
30-40 min	1	1
>40 min	0	0

The Change of PVT Outcome Metrics by the Original Seat and the Enhanced Seat

To examine if the changes in the PVT metrics were normally distributed, Shapiro-Wilk tests were conducted among the changes of the PVT metrics, and the tests' p-values were presented in Table 35. Like the results in table 22, except for the lapse probability, the other three metrics were all normally distributed.

Table 35 P-values from Shapiro-Wilk normality tests for the four PVT metrics. P>0.05 indicates normality of the data tested (n=41)

Changes in PVT Outcome Metrics	Original Seat (n = 19)	Enhanced Seats (n = 22)
Mean RT (ms)	0.29	0.08
Mean 1/RT	0.84	0.05
Fastest 10% RT (ms)	0.66	0.86
Lapse Probability (%)	0.05**	0.00**

ANOVAs were conducted to examine the effects of two seat groups on PVT outcome metrics. As shown in Table 36, significantly longer mean RT, shorter mean 1/RT, and longer mean fastest 10% RT were found with the original seat after the shift. The lapse percentage was not significantly different between the two groups. The results were consistent with the non-parametric Kruskal Wallis tests in Table 26.

Table 36 Mean (SE) values for the change of the four PVT outcome metrics of the two seat groups with p-values from ANOVAs

Changes in PVT Outcome Metrics	Original Seat (n = 19)	Enhanced Seats (n = 22)	P-value
Mean RT (ms)	23.3 (6.7)	-6.2 (6.8)	0.0008**
Mean 1/RT (S^{-1})	-0.2 (0.06)	0.1 (0.06)	0.0007**
Fastest 10% RT (ms)	19.0 (4.8)	-4.0 (3.8)	<0.0001**
Lapse Probability (%)	1.1% (0.6%)	0.1% (0.4%)	0.11

To further explore if there were other variables besides seat type that contributed to the difference in the changes of PVT outcome metrics in each seat group, one-way ANOVAs were conducted to explore the potential confounding effects in each seat group as shown in Table 37, and Table 38. For the original seat, seat comfort ratings were shown to be associated with lapse probability, and the changes in total pain score appeared to be significant toward the changes in all the PVT metrics. Conversely, none of these variables appeared significant towards the changes of PVT metrics in the enhanced seat group.

Table 37 P-values and F-values from ANOVAs with changes in PVT outcome metrics for the original seat as response variables and each demographic variable as independent variable; **=p<0.05. (n = 19)

Variables	**ANOVA p and F-values**	**Mean RT**	**Mean 1/RT**	**Fastest 10% RT**	**Lapse Probability**
Age	p	0.63	0.60	0.90	0.70
	F (1,20)	0.24	0.28	0.02	0.15
Weight	p	0.64	0.72	0.82	0.59
	F (1,20)	0.23	0.13	0.05	0.31
Total Rest Duration	p	0.34	0.35	0.20	0.90
	F (3,37)	1.21	1.19	1.75	0.19
Caffeine Intake (cups)	p	0.73	0.68	0.53	0.31
	F (1,20)	0.12	0.18	0.41	1.12
Seat Comfort Rating	p	0.40	0.41	0.06	**0.04****
	F (1,20)	0.74	0.72	3.99	5.10
Changes in Pain Score	p	**0.03****	**0.03****	**0.00****	**0.03****
	F (1,20)	5.46	5.56	15.28	5.79

Table 38 P-values and F-values from ANOVAs with changes in PVT outcome metrics for the enhanced seats as response variables and each demographic variable as independent variable; **=p<0.05. (n = 22)

Variables	ANOVA p and F-values	Mean RT	Mean 1/RT	Fastest 10% RT	Lapse Probability
Age	p	0.36	0.35	0.78	0.97
	F (1,20)	0.88	0.90	0.08	0.00
Weight	p	0.66	0.67	0.65	0.13
	F (1,20)	0.20	0.19	0.21	2.52
Total Rest Duration	p	0.89	0.80	0.30	0.41
	F (3,37)	0.21	0.34	1.33	1.00
Caffeine Intake (cups)	p	0.29	0.28	0.43	0.40
	F (1,20)	1.20	1.23	0.65	0.73
Seat Comfort Rating	p	0.33	0.36	0.51	0.30
	F (1,20)	1.01	0.89	0.44	1.15
Changes in Pain Score	p	0.28	0.24	0.31	0.18
	F (1,20)	1.23	1.46	1.10	1.97

Subsequent analysis was conducted to further explore how seat comfort ratings and the changes in total pain score affected the changes in the PVT outcome metrics for the original seat. As shown in Figure 21, higher seat comfort rating was found to be associated with lower lapse probability, and higher changes in the total pain score appeared to be related to larger degradation in the four PVT outcome metrics.

Comprehensive Models with the Confounders

Furthermore, models with the two-seat groups, and the potential confounders were included in linear mixed effects models. The R statistical package nlme (Pinheiro, Bates, DebRoy, &Sarkar, 2021) was used to perform the linear mixed effects analysis. The two seat groups, the seat comfort ratings, and the changes in total pain score were entered as fixed effects while Subject ID entered as random effect as demonstrated in Equation 6

$$y = \beta_0 + \beta_1(Seat\ Group) + \beta_2(Seat\ Comfort\ Rating) + \beta_3(Changes\ in\ Pain\ Score) + \gamma_0 + \gamma_1(Subject\ ID) + \varepsilon \quad (6)$$

y: Response Variable, changes in PVT outcome metrics

β : Fixed effects

γ: Random effects

ε: Residual error

From the results in Table 39 to Table 42, higher degradation in the PVT performance was found in the original seat compared with the enhanced seats. The seat group was still a significant factor that contribute to the changes in the PVT outcomes even after adding the potential confounders except for the lapse probability. Besides the variable seat group, the changes in total pain score were significant or near significant to the increase of the changes in Mean RT, mean 1/RT, and fastest 10% RT. While for the lapse probability, higher comfort rating indicated lower changes in lapse probability. AIC_0 and $LogLikelihood_0$ were from the Null model only with an intercept.

Table 39 Linear Mixed Effects Model for the Changes in Mean RT and Potential Confounders

Changes in Mean RT	**Estimate**	**Std Error**	**Df**	**t-value**	**p-value**
(Intercept)	-14.35	12.11	20	-1.18	0.25
Seat Group: Original Seat	27.67	7.19	17	3.85	0.001**
Seat Comfort Rating	1.19	2.27	17	0.52	0.61
Changes in Pain Score	1.38	0.66	17	2.11	0.05
AIC	381.19	LogLikelihood	-184.59		
AIC_0	402.60	$LogLikelihood_0$	-198.30		

Table 40 Linear Mixed Effects Model for the Changes in Mean 1/RT and Potential Confounders

Changes in Mean 1/RT	**Estimate**	**Std Error**	**Df**	**t-value**	**p-value**
(Intercept)	0.15	0.11	20	1.31	0.21
Seat Group: Original Seat	-0.28	0.07	17	-3.91	0.001**
Seat Comfort Rating	-0.01	0.02	17	-0.50	0.62
Changes in Pain Score	-0.01	0.01	17	-2.18	0.04**
AIC	35.62	LogLikelihood	-11.81		
AIC$_0$	29.61	LogLikelihood$_0$	-11.80		

Table 41 Linear Mixed Effects Model for the Changes in Fastest 10% RT and Potential Confounders

Changes in Fastest 10% RT	**Estimate**	**Std Error**	**Df**	**t-value**	**p-value**
(Intercept)	-0.15	6.90	20	-0.02	0.98
Seat Group: Original Seat	19.92	4.01	17	4.96	0.0001**
Seat Comfort Rating	-1.37	1.29	17	-1.06	0.30
Changes in Pain Score	1.00	0.38	17	2.64	0.02**
AIC	339.73	LogLikelihood	339.73		
AIC$_0$	368.10	LogLikelihood$_0$	-181.05		

Table 42 Linear Mixed Effects Model for the Changes in Lapse Probability and Potential Confounders

Changes in Lapse Probability	**Estimate**	**Std Error**	**Df**	**t-value**	**p-value**
(Intercept)	0.02	0.01	20	2.44	0.02
Seat Group: Original Seat	0.01	0.00	17	1.29	0.21
Seat Comfort Rating	-0.0004	0.00	17	-2.89	0.01**
Changes in Pain Score	0.001	0.00	17	1.53	0.14
AIC	-156.24	LogLikelihood	84.12		
AIC$_0$	-183.05	LogLikelihood$_0$	94.53		

Appendix E Comparison of Sleep Duration and Exposure to WBV

Previous studies also showed that there was a near exponential relationship between the cumulative sleep loss and degradation in PVT performance (Banks & Dinges, 2007). In a study exploring the association between PVT performance and hours of recovery sleep, an asymptotic exponential dose-response relationship between the sleep duration of prior night and PVT performance was established by Equation 7, where A=190.92, C=23.74, and T=2.14 for the mean fastest 10% RT (Jewett et al., 1999).

$$Mean\ Fastest\ 10\%\ RT = A + Ce^{\left[\frac{-Hours\ of\ Sleep}{T}\right]} \tag{7}$$

From the values of pre- and post-shift median mean fastest 10% RTs from Table 23 and Table 24, the corresponding sleep durations were calculated, and the changes in the sleep duration over the entire shift were obtained. As shown in Table 43, the changes in the calculated sleep duration with Seat 1, the original-fitted seat, was -42.92 minutes, indicating around 42 minutes less sleep after driving in Seat 1 over the entire shift. Driving in Seat 2, 3, and 4 over the entire shift could be approximated as 23.15 minutes, 1.22 minutes, and 24.53 minutes more sleep. Since the mean fastest 10% RT of Seat 1 was significantly higher than the other three seats, driving in the three enhanced seats all demonstrated to have more calculated sleep compared with Seat 1 from around 44 minutes up to 67 minutes. Similarly, driving in the enhanced seats were on average equivalent to 63.22 minute more sleep compared with driving in the original seat over the entire shift as shown in Table 44. Though the form of the equivalence has its limitation, it still revealed that the excessive WBV exposures was similar to sleep loss and appeared to be associated with degraded vigilance performance over the shift.

Table 43 Post-Shift – Pre-Shift prior night sleep duration equivalence by seat types, and the difference with Seat 1

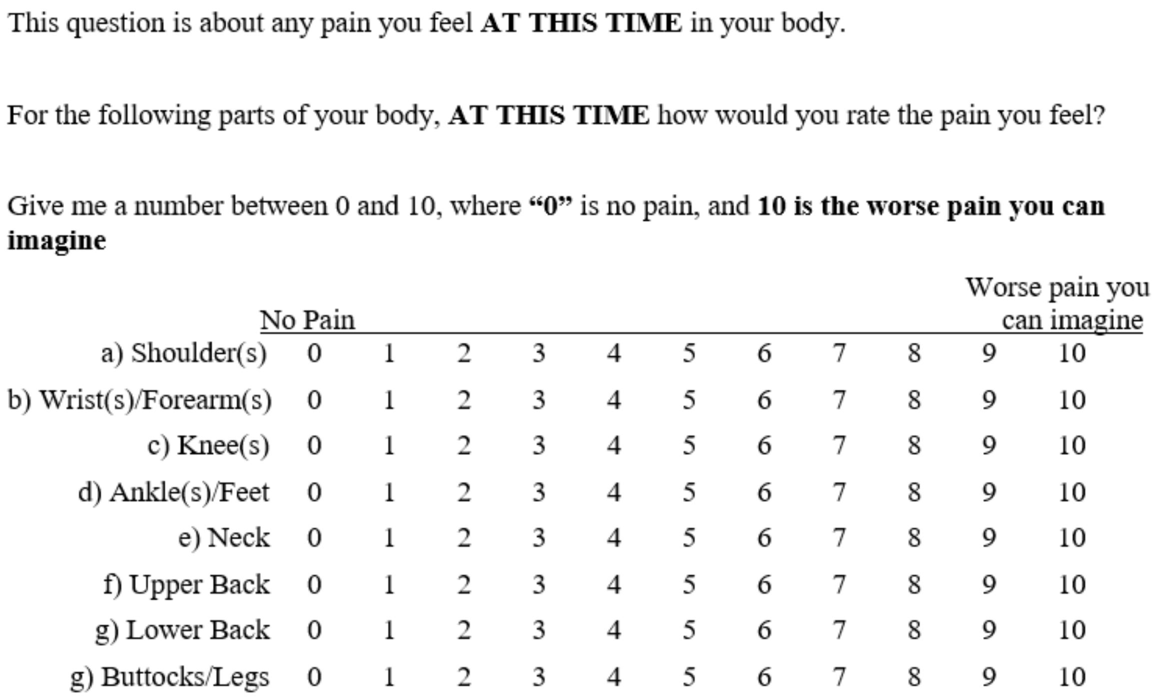
Seat Type	Changes in Sleep Duration over the Shift (min)	Difference from Seat 1
Seat 1	-42.92	
Seat 2	23.15	66.08
Seat 3	1.22	44.15
Seat 4	24.53	67.45

Table 44 Post-Shift – Pre-Shift prior night sleep duration equivalence by the original seat and the enhanced seat, and the difference with the original seat, Seat 1

Seat Type	Changes in Sleep Duration over the Shift (min)	Difference from the original seat
Original Seat	-42.92	
Enhanced Seat	20.3	63.22

Appendix F Health Questionnaire and Seat Satisfaction Questionnaire

Survey for Discomfort/Pain Scale



This question is about any pain you feel **AT THIS TIME** in your body.

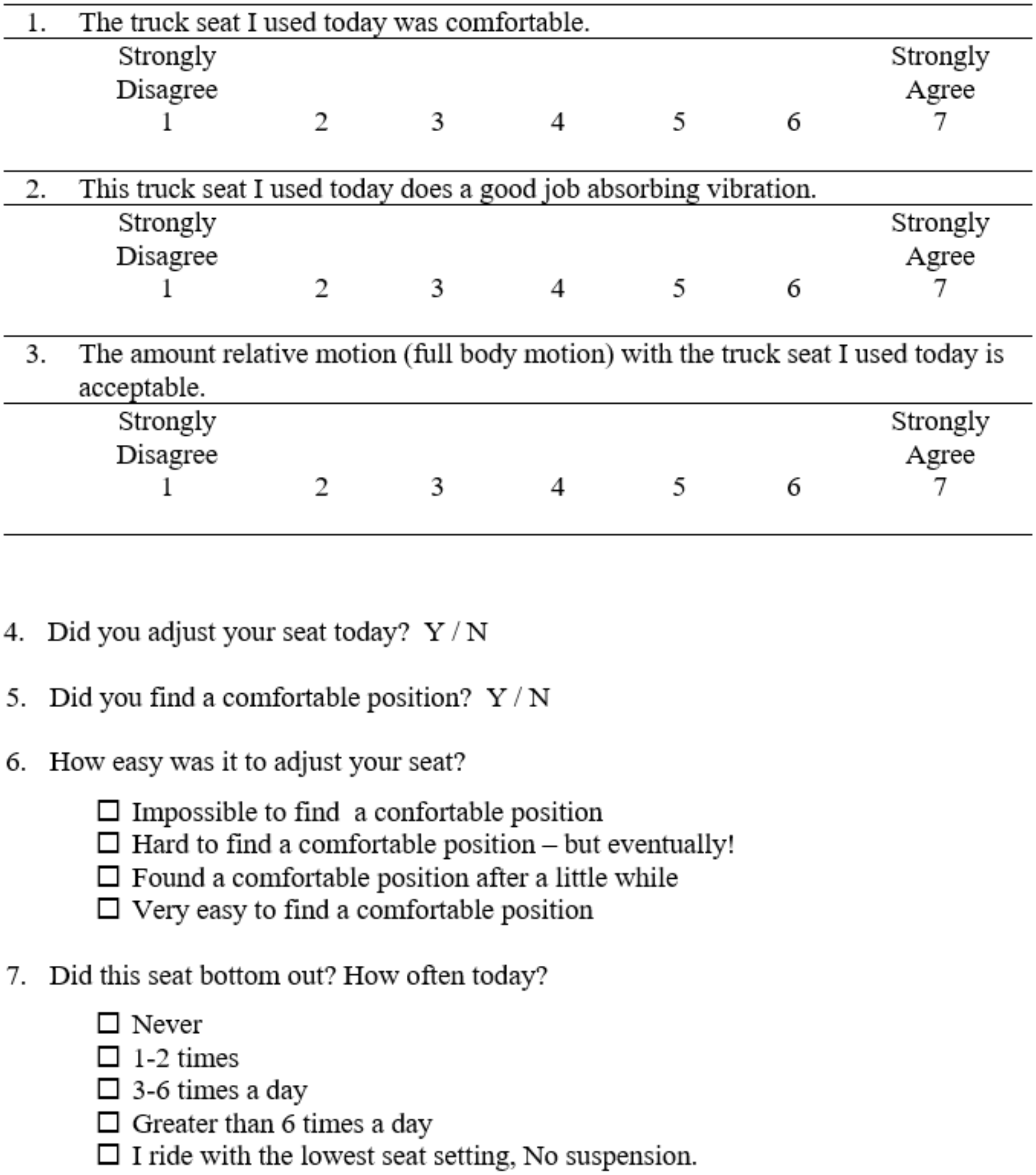
For the following parts of your body, **AT THIS TIME** how would you rate the pain you feel?

Give me a number between 0 and 10, where **"0"** is no pain, and **10 is the worse pain you can imagine**

	No Pain										Worse pain you can imagine
a) Shoulder(s)	0	1	2	3	4	5	6	7	8	9	10
b) Wrist(s)/Forearm(s)	0	1	2	3	4	5	6	7	8	9	10
c) Knee(s)	0	1	2	3	4	5	6	7	8	9	10
d) Ankle(s)/Feet	0	1	2	3	4	5	6	7	8	9	10
e) Neck	0	1	2	3	4	5	6	7	8	9	10
f) Upper Back	0	1	2	3	4	5	6	7	8	9	10
g) Lower Back	0	1	2	3	4	5	6	7	8	9	10
g) Buttocks/Legs	0	1	2	3	4	5	6	7	8	9	10

Figure 22 Survey about self-rated discomfort scales

Survey for Seat Satisfaction



1. The truck seat I used today was comfortable.

Strongly Disagree						Strongly Agree
1	2	3	4	5	6	7

2. This truck seat I used today does a good job absorbing vibration.

Strongly Disagree						Strongly Agree
1	2	3	4	5	6	7

3. The amount relative motion (full body motion) with the truck seat I used today is acceptable.

Strongly Disagree						Strongly Agree
1	2	3	4	5	6	7

4. Did you adjust your seat today? Y / N

5. Did you find a comfortable position? Y / N

6. How easy was it to adjust your seat?

   ☐ Impossible to find a confortable position
   ☐ Hard to find a comfortable position – but eventually!
   ☐ Found a comfortable position after a little while
   ☐ Very easy to find a comfortable position

7. Did this seat bottom out? How often today?

   ☐ Never
   ☐ 1-2 times
   ☐ 3-6 times a day
   ☐ Greater than 6 times a day
   ☐ I ride with the lowest seat setting, No suspension.

Figure 23 Seat satisfactory survey

Table 45 demonstrates the results of Question 1 to 3 of the seat satisfaction survey. The drivers reported that Seat 4 absorbed more vibration compared with the other three seats. There were trends showing that subjects were potentially least satisfied with Seat 1 and most satisfied with Seat 4. Moderate to high correlations were found between these three measures. The correlation between seat comfort level and seat absorbing vibration ratings was 0.63; the correlation between seat comfort level and relative motion acceptance was 0.58; and the correlation between absorbing vibration ratings and relative motion acceptance was 0.79.

Table 45 Mean values and standard errors of Question 1 to 3: seat comfort level ratings, absorbing vibration ratings, and relative motion acceptance ratings. (n=60)

Seat Satisfaction Questions	Seat 1 (n=24)	Seat 2 (n=13)	Seat 3 (n=12)	Seat 4 (n=11)	p-value
Seat Comfort Level	3.76 0.36	3.85 0.48	4.67 0.51	4.91 0.61	0.23
Seat Absorbing Vibration	3.96^a 0.36	4.85^a 0.36	4.46^a 0.53	5.91^b 0.46	**0.016****
Relative Motion Acceptance	3.80 0.36	5.00 0.36	4.54 0.45	5.23 0.59	0.07

Table 46 to 49 demonstrated the distribution of the answers to question 4 to 7 regarding seat adjustment. A chi-square test of goodness-of-fit was performed for each table to determine whether the four seats were equally performed in these questions. The p-values were all above 0.05, which indicated that the answers to the questions were similarly distributed across the four seats.

Table 46 Question 4: if the subjects adjusted the seat. $X^2(3, N=60)=0.015, p=0.99$

Adjust Seat	Seat 1	Seat 2	Seat 3	Seat 4
NO	2	1	1	1
YES	22	12	11	10

Table 47 Question 5: if the subjects found a comfortable position. $X^2(3, N= 60) =1.95, p=0.58$

Find Comfortable Position	Seat 1	Seat 2	Seat 3	Seat 4
NO	1	1	1	2
YES	23	12	11	9

Table 48 Question 6: how easy to adjust the seat. $X^2(9, N= 60) =5.28, p=0.81$

Easy to Adjust	Seat 1	Seat 2	Seat 3	Seat 4
After a Little While	2	2	4	2
Easy	18	9	7	8
Hard	2	1	0	1
Impossible	2	1	1	0

Bottom out means the driver sat in the seat without the function of suspension. Lowest seating indicates the driver adjust the seat to the lowest level without using the suspension system.

Table 49 Question 7: how often did the seat bottom out. $X^2(12, N= 60) =11.84, p=0.46$

Bottom Out	Seat 1	Seat 2	Seat 3	Seat 4
>6 Times	0	1	0	0
3-6 Times	2	0	0	1
1-2 Times	2	0	0	0
Never	14	7	8	9
Lowest Seating	6	5	4	1