Effects of Seat Suspension Types on Truck Drivers' Vigilance

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

BACKGROUND

Due to long work hours and irregular work schedules, truck drivers can become fatigued, which can increase the risk of traffic collisions. Further, professional truck drivers are at an increased risk for musculoskeletal problems such as low back pain due to prolonged sitting, poor posture and whole-body vibration (WBV). In particular, WBV has been shown to be correlated with many adverse health effects including headaches, sleeping problems and low back pain which may effect the drivers' ability to remain vigilant on the driving task. The purpose of this study was to determine whether prolonged driving and different levels of WBV exposures affected truck drivers' response times over a workday and workweek. The results of this study may be important in understanding how prolonged driving and WBV may affect driver performance in real life settings.

METHODS

This study used a repeated measures crossover design with 5 line-haul truck drivers (ages 43-64) who had a regular route typically lasting 10 hours a day. The first week (5 days) drivers operated their truck with their existing, air-suspension truck seat; then an electromagnetically active vibration-cancelling (EAVC) seat was installed, and the drivers operated their truck with the EAVC seat in the second week. Previous studies have shown the EAVC seats can reduce WBV exposure by 50% on average. For five days each week, each participant completed a questionnaire about their sleep, caffeine consumption, and discomfort and a 10-minute sustained reaction time task called the Psychomotor Vigilance Task (PVT) was performed immediately before and after their shift. The PVT characterized response times (RT) by the mean RT, inverse mean RT, 10% fastest and 10% slowest RT, variability of the RT and lapses, which are the number of responses greater than 500 ms. WBV exposures were also collected from the drivers' seat using a tri-axial accelerometer.

The average changes in PVT response times pre- and post-shift were calculated and compared using mixed model methods to determine whether response times increased over the workday as workweek, as well as whether there were differences between the two seating

conditions. In addition, z-axis daily time weighted average A(8) WBV exposures were also calculated to verify that the WBV exposures were different between the two seats.

RESULTS

Four and five WBV measurements were completed on the existing and EAVC seats, respectively. There was a significant difference ($p < 0.001$) in A(8) WBV exposures between the existing and the EAVC seats with mean (standard error) z-axis exposures of 0.49 m/s^2 (±0.03) and 0.22 m/s^2 (±0.01). With respect to driver vigilance, out of 25 possible measurements, 20 pre-shift and 20 post-shift PVT were collected in the existing air suspension seating condition and 22 pre-shift and 22 post-shift PVT were collected in the EAVC seating condition. Regardless of the seat being used, degradation in PVT performance after the work shift was found in mean 1/RT and variability of RT. Further, there were significant degradations in PVT performance (increases in mean RT and fastest 10% RT) over the course of the workday with the existing seats but not the EAVC seats ($p=0.47$ and $p=0.020$, respectively).

DISCUSSION

The purpose of this study was to determine whether truck driving had any effect on RT and whether the RT may be influenced by reducing drivers' exposure to WBV. The study results indicated increased RT after a full day of driving and that reducing drivers' exposure to WBV may have a positive effect on RT, which may translate to lower risks of truck collisions. Five truck drivers represent a relatively small sample; so repeating this study on a larger scale is merited.

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Many thanks to Dr. Bigelow for opening so many doors for me and providing me with opportunities. To Dr. Wells, for teaching me that no idea, no matter how crazy it may seem, is out of reach. To Dr. Johnson, for sharing with your passion and drive in research with me, it is infectious.

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Dedication

For Grandpa.

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List of Abbreviations

BMI: Body Mass Index
EAVC: electromagnetically active vibration-cancelling
EEG: electroencephalography
EOG: electrooculography
ISO: International Organization for Standardization
LBP: low back pain
PVT: Psychomotor Vigilance Task
SD: standard deviation
SE: Standard error
LSM: Least squared means
WBV: Whole-body vibration

1.0 Introduction and Overview

Of the annual average of 50 372 heavy vehicle collisions in Canada, driver fatigue accounts for 1.5% of it, according to police reports from the *National Collision Database* (Thiffault, 2011). This value differs in different countries and ranges from 2% in Norway (Phillips & Sagberg, 2013) to 25% in Australia (Naughton & Pierce, 1991). 47.1% of truck drivers have fallen asleep behind the wheel at some point in their career, and 25.4% have done so in the previous year (MaCartt *et al*., 2000). Though it is clear drowsiness has major impacts on driving performance, it is difficult to attribute drowsiness as the cause of a collision unless the driver has fallen asleep behind the wheel (Thiffault & Bergeron, 2003). Therefore, the true extent of fatigue-related collisions is underestimated (Dinges, 1995). For example, 70% of vehicle accidents are due to a driver's *improper lookout* or *inattention*, both of which are indicators of fatigue (Thiffault & Bergeron, 2003). The cause of driver drowsiness is multifactorial, and many studies have correlated health and wellness, work hours, and sleep deprivation to a truck driver's potential to fall asleep behind the wheel. Assessing the parameters that cause driver drowsiness are essential in its mitigation and consequently the reduction of vehicle collisions and road-related injuries.

The inherent nature of truck driving itself is fatiguing[1]. Truck drivers often drive up to 13 hours a day, and they must be vigilant throughout the shift. However, a cross-sectional survey conducted in Peru found that 55% of professional drivers had less than six hours of sleep per day, 31% had fewer than six hours of sleep within the past 24 hours, 56% had been tired

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[1] For this report, driver fatigue and driver drowsiness are used synonymously; which is defined as the process of when the driver's state of wakefulness moves towards the sleep end of the sleep-wake continuum, or the inclination (increase in sleep drive) to fall asleep, which decreases the alertness of the driver (Thiffault, 2011).

while driving, and an astonishing 32% had drove with their eyes fallen shut (Castro, Gallo, & Loureiro, 2004). Sleep deprivation has negative impacts on vigilance, which may negatively impact driving performance. Further, driving trucks are more demanding than driving passenger vehicles and a commercial driver's license is required to operate a commercial motor vehicle, an eighty-ton-eighteen-wheeler when fully loaded. For example, trucks have a unique braking system: there is a one-second brake lag and the stopping distance is approximately 50% greater than passenger vehicles (Ministry of Transportation, 2013). Rounding and turning corners also require a greater turning radius. Trucks also have up to eighteen gears in comparison to the six of passenger vehicles, thus more time is necessary for trucks to accelerate (manually or automatically). Moreover, unlike cars, trucks cannot easily maneuver lane changes due to visibility and the vehicles' mass. Drivers must also operate their trucks through various terrains as well as varying weather and traffic conditions (e.g. mountains, plains, rain, snow, winds, heavy traffic, narrow lanes, construction, *etc.*). Such conditions must be considered when planning the trip for on-time deliveries (van der Beek, 2012). Therefore, driving trucks require drivers to plan their actions earlier in advance and be more vigilant of their driving conditions than driving passenger vehicles.

Drowsiness is impacted by health status (Taylor & Dorn, 2006); unfortunately, truck drivers face a disproportionately high risk for serious health disorders. For example, truck drivers have a life expectancy of 12-20 years shorter than the average general population (Saltzman & Belzer, 2007), along with an increased prevalence of cardiovascular disease, obesity, cancer (lung, bladder, and gastrointestinal tract), chronic stress, fatigue, and musculoskeletal disorders (Apostolopoulos, Sönmez, & Shattell, 2010). The poor health status may be associated with poor diet, a sedentary lifestyle, smoking, and/or alcohol consumption

(Apostolopoulos, Sönmez, & Shattell, 2010). While workplace health promotion programs exist with some trucking companies, there has been limited evidence of its efficacy (Lemke & Apostolopoulos, 2015).

As an administrative control to mitigate driver fatigue, federal governments began regulating the hours of service for professional drivers. In Canada, drivers are allowed a maximum on-duty time of 14 hours and a daily driving time of 13 hours per 24-hour period. They may drive up to 70 hours per 7 days, and then must take 36 hours off afterwards (Government of Canada, 2009; Jensen & Dahl, 2009). In the USA, drivers are also allowed 14 hours of on-duty time and 11 hours of driving time. They may drive up to 60/70 hours over 7/8 consecutive days, and must take 34 hours off afterwards (Federal Motor Carrier Safety Administration, 2014). However, it is difficult to monitor adherence to the new regulations, and some evidence suggests that drivers are actually driving more after the regulations were implemented (McCartt, Helligna, & Solomon, 2008).

In the hierarchy of controls for prevention approaches, engineering controls are ranked higher as these controls are built into the work environment and require little behavior change or regulation. One new promising engineering control are seat suspensions using electromagnetically active vibration-cancelling (EAVC) technology. These seats significantly reduce the levels of whole-body vibration (WBV) exposed to drivers (Blood *et al.* 2011). Prolonged exposure to WBV may adversely affect many systems of the body, including the musculoskeletal, cardiovascular, cardiopulmonary, metabolic, endocrinologic, nervous and gastrointestinal systems (Griffin, 1990; Thalheimer, 1996). A vast literature has emphasized low back pain as the prime consequence of prolonged exposures to WBV (Bovenzi & Hulshof, 1999; Lings & Leboeuf-Yde, 2000; Burström, Nilsson, & Wahlström, 2015). In turn, low back pain can have negative impacts on sleep quality and duration which influences alertness during the day (See **Fig. 1**) (Alsaadi *et al*. 2011; Artner *et al*., 2013; Kelly *et al*., 2011; Moldofsky, 2001; Lautenbacher, Kundermann, & Krieg, 2006). WBV could also have a direct impact on driver fatigue by increasing physical stress on the driver, leading to both cognitive and physical exertion, which could impair performance (Conway, Szalma, & Hancock, 2007). Ultimately, WBV may be an underlying cause for driver drowsiness. Therefore, a reduction in WBV exposure has potential to increase driver vigilance by reducing discomfort while driving (see **Fig.1**).

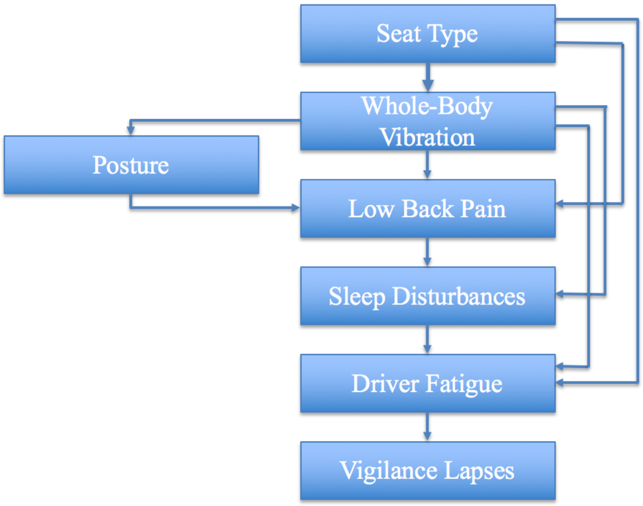

Figure 1. Causal diagram indicating the ways in which whole-body vibration from truck seats can affect vigilance.

The following sections summarize the scientific literature pertaining to driver vigilance and whole-body vibration followed by the methodology of the study to evaluate the effectiveness of the EAVC seats on vigilance. Finally, the results, the interpretation of the data and recommendations for future studies will be discussed.

2.0 Literature Review

2.1 Vigilance

Vigilance is defined as the ability to sustain attention on a particular task over a period of time, such as driving (Warm, Parasuraman & Matthews, 2008). The concept of vigilance is defined within the sleep-wake axis, where the ability to be vigilant is associated with being fully awake and cognitively functioning (Warm, Parasuraman & Matthews, 2008). In contrast, hypovigilance indicates the first sign of sleepiness where there are decrements, and increased variability in performance; however, the individual may not be aware of it (**Fig. 2**) (Thiffault, 2011). Important to note is that hypovigilance is not a result of inattention from distractions or dual tasking such as using a cellular phone while driving. In other words, hypovilgilance is sleep or monotony-related inattention, whereas divided attention is distraction-based. The most prominent effect of driver drowsiness is hypovigilance.

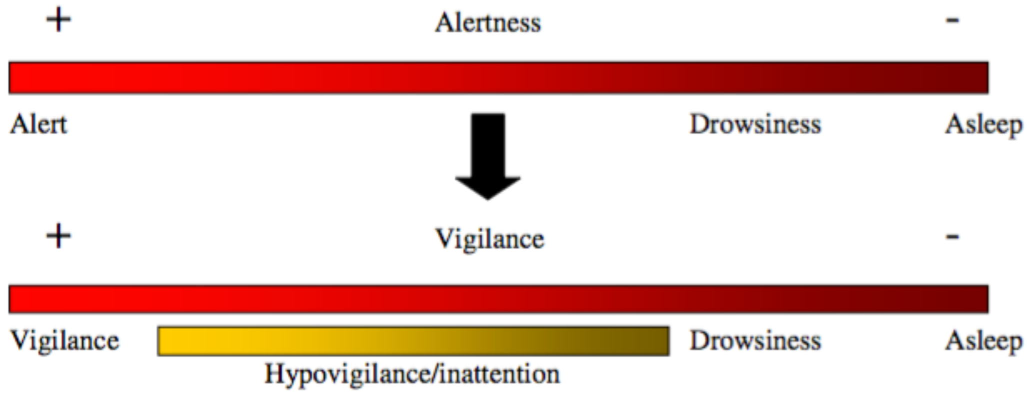

Figure 2. "Importance of hypovigilance as an early manifestation of fatigue" (taken from Thiffault, 2011)

2.1.1 Measuring Vigilance

Since drowsiness is a common problem in trucking, many driver drowsiness detection technologies have been developed to alarm drivers before they fall asleep or when their performance deteriorates. Such technologies consider variables including performance (e.g. standard deviation of lane position), behaviour (e.g. eyelid movements), and physiology (e.g. heart rate variability). Generally, these technologies have been developed for commercial use as a safety mechanism to alarm drivers or their dispatchers about their state of alertness while driving, and recommend when rest breaks should be taken. Although these devices are able to detect the drivers' drowsiness state in real time, they are costly and use different patented algorithms that are not disclosed to researchers. Consequently, little about exactly what these technologies measure and how drowsiness is assessed are known to researchers. To validate these technologies, the devices are tested against gold standard measures of alertness, which include standard deviation of lane position, electrooculography (EOG), electroencephalography (EEG), the Karolinska Sleepiness Scale (KSS) and the Psychomotor Vigilance Task (PVT) (Golz *et al.,* 2010). For research purposes, it is best to be able to use gold standard measures. Although applying physiological measures such as the EOG and EEG may not be feasible in the field setting, the PVT is an appropriate test that can be used to study driver drowsiness interventions. In fact, a recent review recommended that all fatigue monitoring devices should be validated against the PVT since it is the gold standard in measuring the vigilance of drivers (Dawson, Searle, & Paterson, 2014).

2.1.2 The Psychomotor Vigilance Task (PVT)

The PVT is a sustained reaction time task that uses the subject's response times (RT) to visual stimuli as a measure of their vigilance state and cognitive function. Subjects are instructed to press a button as soon as they see numbers or a dot appear on a screen. The stimulus appears randomly every two to ten seconds for five or ten minutes for a total of 40-80 trials. However, the test can last up to twenty minutes to increase sensitivity.

2.1.2.1 History

Since 1985, when the PVT was first introduced, hundreds of peer reviewed articles used this test to evaluate the effects of sleep deprivation, circadian rhythm, time-on-task, and sleep interventions on wakefulness and performance (Dinges & Powell, 1985; Atzram *et al.,* 2001; Graw *et al.,* 2004; Dinges *et al.,* 1987; Wright *et al.,* 1997; Dinges *et al.,* 2000; Van Dongen *et al.,* 2003; Wyatt *et al.,* 2004). The PVT has also been used in the field for astronauts, airplane pilots and truck drivers (Dijk *et al.,* 2001; Neri *et al.,* 2002; Russo *et al.,* 2004). In fact, the PVT is a common measure used to validate driver drowsiness detection devices (Dinges *et al.,* 1998; Forsman *et al.,* 2013; Golz *et al.,* 2010). The PVT is advantageous because it is non-intrusive, highly reliable and valid. It is also easy to learn and score as it uses simple metrics.

2.1.2.2 Reliability

In psychometrics, reliability is defined as the consistency of a measurement, meaning that it produces similar results under consistent conditions (Carlson *et al.,* 2009). The PVT has high test-retest reliability, as demonstrated in two studies. First, in a large chronic partial sleep deprivation protocol, the control group (n=9) had the opportunity to sleep for eight hours per night and performed the PVT at 09:30, 11:25, 13:20, and 15:15 for one baseline day and five consecutive experimental days. The interclass correlation coefficient (ICC) was high for both the PVT lapses (ICC=0.888, p<0.001) and median RT (0.826, p<0.001) meaning that most (>80%) of the variance in the PVT scores was explained by between-subject differences rather than within-subject error (Van Dongen *et al*., 2003). Similar results were found in another study where participants underwent 36 hours of sleep deprivation on two separate occasions; the differences between subjects explained 78.9% of the variance in PVT lapses (Van Dongen, Rogers, & Dinges, 2003). These high ICC's are considered to be "substantial" to "almost perfect" on the standardized range for agreement measures for categorical data (Landis & Koch, 1977).

2.1.2.3 Validity

Validity refers to how well an assessment tool measures what it claims to measure. In terms of the PVT, it was originally designed to assess the changes of states of vigilance throughout the day. Specifically, the PVT is a "neurocognitive test to track the temporally dynamic changes induced by interactions of the homeostatic drive for sleep and endogenous circadian pacemaker by measuring an individual's ability to sustain attention and respond to salient signals in a timely manner" (Dinges & Powell, 1985). The PVT has demonstrated its sensitivity in measuring theorized functions of sleep, different variables that affect wakefulness, and performance in everyday functioning (Dorrian, Rogers, & Dinges, 2005).

2.1.3.3.1 Theoretical Validity

There is an abundance of evidence supporting theories of sleep loss affecting cognitive functions using the PVT as a measure. A dominant hypothesis proposed by Bills in the 1930's was that people deprived of sleep were still able to maintain baseline measures for functional performance; however, they had pauses that were twice as long as their average RT, and there was more variability in their performance (Bills, 1931; Bills, 1937). These pauses, now known as lapses, are defined as a RT greater than 500 ms, and Doran, Van Dongen, and Dinges (2001) showed a positive relationship between number of lapses and sleep deprivation. Lapses occur in parallel with changes in brain activity (measured by electroencephalography) and eye movements (measured by electrooculography) (Bjerner & Frey, 1949). The PVT defines a lapse as a RT that is greater than 500 ms and it has been able to show an increasing number of lapses in individuals at increasing times of sleep deprivation of 12, 36, 60, and 84 hours (Doran, 2001).

Vigilance lapses are only one of the hypotheses of performance decrements from sleep loss; other changes in performance can also be detected using the PVT such as response slowing. Increases in RT of the PVT have also been associated with sleep loss (Lisper & Kjellberg, 1972; Van Dongen, Rogers & Dinges, 2003). For example, the 25% fastest RT on the PVT were slower when participants were sleep deprived compared to their baseline scores (Van Dongen, Rogers, Dinges, 2003)

2.1.3.3.2 Convergent Validity

Convergent validity is defined as the sensitivity of an assessment to detect the various forms of whatever it is trying to detect (Dorrian, Rogers & Dinges, 2005). The PVT has been shown to be sensitive in detecting changes of alertness and cognitive function from a variety of factors including circadian rhythms (Graw *et al*., 2004), chronic or partial sleep deprivation (Doran *et al*., 2001), interventions to reduce sleepiness (naps and caffeine) (Ramakrishnan *et al*., 2014), and obstructive sleep apnea (Batool-Anwar *et al*., 2014). Although much of the research using the PVT has been conducted on sleep deprivation, it is also sensitive in non-sleep deprived conditions, such as truck driving (Smiley *et al*., 2009).

2.1.3.3.3 Ecological Validity

The PVT has high ecological validity as it is sensitive in detecting performance changes in daily activities. Assessments of tasks that require high attention and quick responses such as operating any transportation vehicle, monitoring radar, x-ray, and surveillance equipment may prefer using the PVT because it tests the ability of the operator to sustain attention and respond quickly to a stimulus (Dorrian, Rogers, & Dinges, 2005). In trucking, the PVT is strongly correlated with the percentage of slow eyelid closures (PerClos): in a 42-hour sleep deprivation test, participants performed a 20-minute PVT every two hours, while being recorded for slow eyelid closures. Frequency and duration of PVT lapses were significantly associated (mean $r = 0.875$, $p<0.001$ for lapse frequency; mean $r = 0.919$, $p<0.001$ for lapse duration). These results have strong implications for driving, since driving inattentively with nearly-closed eyes is a high risk for accidents (Dinges *et al*., 1998). PerClos is now a common variable used in many driver drowsiness detection devices (Golz *et al*., 2010). Also, performance measures for the driver, including standard deviations of lane position and steering variability, are correlated with vigilance lapses of the PVT (Forsman *et al*., 2013). Therefore, the PVT is an appropriate assessment tool to track changes in the vigilance state of truck drivers in the field.

2.1.3 Factors Affecting Vigilance in Drivers

There are two main types of factors that alter the wakefulness of the drivers: endogenous and exogenous. Endogenous factors are the individual's baseline state of alertness, whereas exogenous factors are task- or environmentally-induced alertness (see **Fig. 3**).

2.1.3.1 Endogenous Factors

Quality and duration of sleep, circadian rhythm, drugs, medication, health, personality, and age are some key endogenous factors that affect the baseline alertness status of drivers (May & Baldwin, 2009). For example, both acute (short-term) and chronic (long-term) sleep deprivation, defined as having less than six hours of sleep, result in performance decrements on the PVT. Common health issues of truck drivers (such as low back pain or obstructive sleep apnea) are associated with higher levels of fatigue in drivers (Weigand *et al*., 2009; Christensen, Petersen & Spencer-Hwang, 2013). People with extraversion and sensation-seeking personalities are also at a higher risk to fatigue from boredom because they generally invest less effort when driving through monotonous roads (Thiffault & Bergeron, 2003). Younger drivers have been shown to have higher sensation-seeking personalities compared to middle aged drivers, and tend to feel less alert in monotonous conditions with less traffic (Otmani, Rogé, & Muzet, 2005). Circadian rhythm plays a dominant role in the alertness of the driver: during low hours (between 2 am to 6 am and 2 pm to 4 pm), biological mechanisms attempt to induce sleep, which decreases alertness levels (Thiffault, 2011).

2.1.3.2 Exogenous Factors

Exogenous factors are external factors relating to the task or the environment that affect driver vigilance. In conditions of task under-stimulation, a driver may feel bored, and passive task-related fatigue may occur. For example, a monotonous task such as driving in an isolated area with little turns, cars, scenery or other stimulus may decrease alertness. Similarly, under conditions of task overload in which a driver has an increased workload, active task-related fatigue may occur. For example, multi-tasking while driving, such as texting on the phone or looking for directions require elevated mental capacity. Multi-tasking may not induce fatigue or decrease alertness immediately, but may do so after a period of time. Task complexity such as driving in urban areas, braking, accelerating, reading signs, or changing lanes is more demanding than driving in low traffic under monotonous conditions. There are also negative impacts on alertness with increasing time-on-task. Prolonged driving impairs concentration and alertness, which causes delayed reaction times and feelings of drowsiness (McDonald, 1984).

A significant environmental factor to which drivers are constantly exposed to is WBV. WBV is the oscillation of the human body that is caused by the vibration of the truck engine and the road. One study using EEG as a measure of wakefulness showed decreases in wakefulness after a 20-minute exposure to WBV (Satou, 2007). Other studies using self-reports of alertness found similar results after acute exposures of WBV (Ljungberg, 2007).

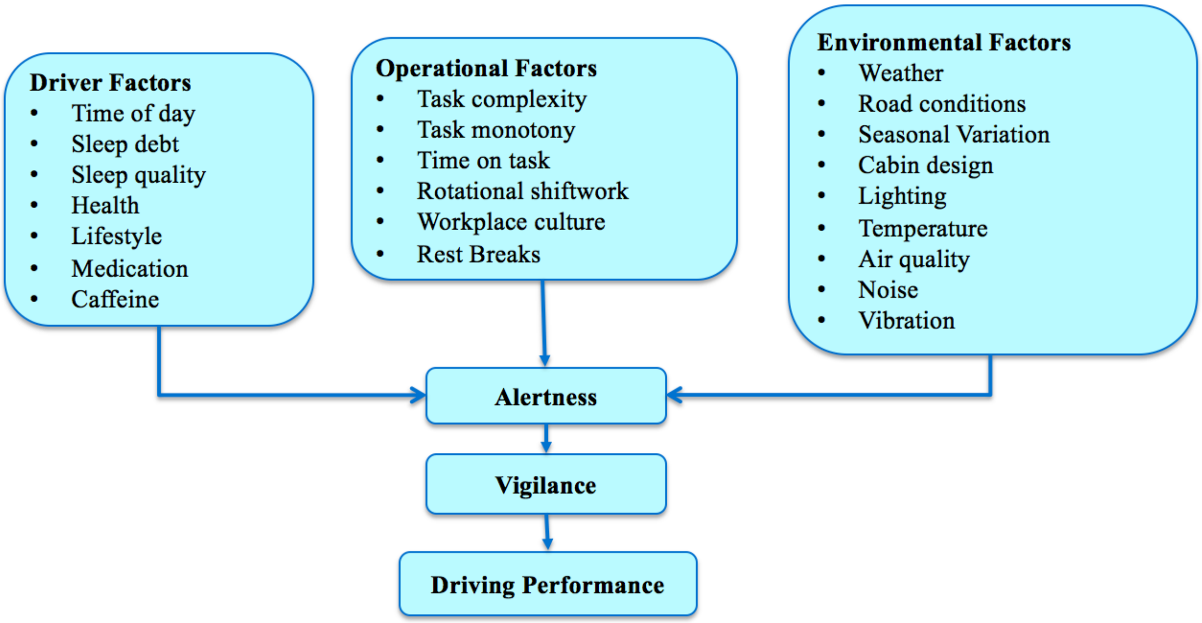

Figure 3. Factors influencing driver alertness – and ultimately driving performance – are endogenous such as the driver him/herself, or exogenous such as operational and environmental factors. (modified from May & Baldwin, 2009; Moscovitch *et al*. 2006)

2.1.4 Managing Driver Drowsiness

Each factor that affects sleepiness requires a unique coping method. For example, if a driver is fatigued due to sleep deprivation, then consuming caffeinated beverages or taking a nap can help increase alertness. In contrast, if a driver is experiencing passive task-related fatigue, engaging in stimulating activities such as drinking beverages, listening to the radio, talking to a passenger or stretching/shifting in their seat can help alleviate sleepiness (Barr *et al*., 2005). For active task-related fatigue, advanced technologies such as having automated transmissions, anti-lock braking systems, cruise control, lane tracking and warning systems can help decrease the driver's workload and allow them to allocate their attentional resources elsewhere.

Regarding environmental factors, WBV-related fatigue would require a reduction in WBV exposure. Numerous intervention strategies have been proposed to reduce WBV exposures in heavy machine operators since it is associated with many adverse health effects. WBV is especially hazardous to truck drivers because of the chronic exposures to the resonating frequencies of the body and lifting after prolonged exposures to seated WBV. Interestingly, exposure to WBV has also been evaluated as a treatment modality for spinal cord patients, osteoporotic patients, and astronauts to prevent muscular dystrophy and bone loss. However, these bouts of WBV are acute exposures (approximately 20 minutes compared to 8 hour daily exposures) in a standing or lying position (Cardinale & Pope, 2003). Since WBV can be generated and controlled in many ways, the following section will go more depth to describe what is WBV and how it can be controlled.

2.2 Whole-body Vibration

WBV is the oscillation of a mass about a fixed point and often occurs in large vehicles such as tractors, trucks, earth-moving machineries, mine and quarry equipment, and helicopters. WBV causes the body to accelerate in a motion, which is hazardous with long-term exposures (Benstowe, 2008). WBV is categorized into 4 types of vibration: 1) sinusoidal vibrations are oscillations that repeat over time at a constant frequency and amplitude (e.g. an out-of-balance car tire); 2) periodic vibrations are the combination of two or more sinusoidal vibrations; 3) random vibrations occur when the oscillations do not repeat themselves (e.g. driving on a bumpy road); and 4) transient vibrations occur for a short time (e.g. driving over a pot-hole). Generally, truck drivers – both long or short haul – experience a combination of periodic, random and transient vibrations.

2.2.1 Measurements and Assessments of Whole-Body Vibration

When measuring WBV, four domains should be taken into account: direction, intensity, frequency, and duration. Direction is measured in three dimensions using the x (fore-aft), y (side to side) and z (up and down) axes. Intensity is measured as acceleration using units of m/s^2. Frequency is the rate of the oscillations measured as the amount of complete oscillation per second using units of Hertz (Hz). Finally, duration of exposures can be measured in seconds, minutes, hours, or years.

The levels of WBV exposure and its characteristics can be described by three common measures: 1) the frequency-weighted root mean square (RMS) acceleration (A_w); 2) the eight-hour equivalent frequency-weighted RMS acceleration (A(8)); and 3) the vibration dose value (VDV). The A_w describes the average intensity of the vibration over the collection period; however, it is not time-normalized and thus not the favourable metric to compared WBV exposures of different durations. The A(8) is normalized to eight hours of WBV exposure (*regular* work shift) but will underestimate WBV exposure if there are high peaks and jarring. The VDV, however, is more sensitive to high peaks and jarring and it accounts for the cumulative WBV exposure transmitted to the body for the day. The predominant axis is often used to calculate the three aforementioned measures.

The A(8) or VDV(8) can be used to assess the risk of adverse health effects due to WBV. The European Directive has set eight-hour action and exposure limit values (0.5 and $1.15 m/s^2$, respectively) for WBV exposures, requiring employers to reduce the exposure intensity and/or duration. Currently, there are no regulations for WBV exposure in many Canadian jurisdictions. The Canadian Centre for Occupational Health and Safety (CCOHS) states that “it is prudent to reduce the level of exposure as much as practical since vibration causes ill health effects”

(CCOHS, 2008). Although there are no formal regulations, Canadians agencies usually follow the limit values recommended by the International Organization for Standardization 2631-1 (ISO 2631-1) (see **Table 1**).

Table 1. International Organization for Standardization (ISO) 2631-1 Health guidance caution zones for whole-body vibration exposure.

	ISO 2631-1	
	A(8) (m/s^2)	VDV(8) ($m/s^{1.75}$)
Action Limit	0.5	9.1
Exposure Limit	0.8	14.8

2.2.2 Factors Influencing Drivers' Whole-Body Vibration Exposures

Numerous factors influence exposure to WBV, including road conditions, vehicle type and characteristics, vehicle speed, driving characteristics, and seat types (Village *et al.,* 2012; Tiemessen, Hulshof, & Frings-Dresen, 2007; Blood *et al*., 2011). By altering or improving a factor, exposure to WBV can be reduced. A systematic review of the strategies to reduce WBV exposure in drivers found that alteration of the following factors was effective in reducing the magnitude of WBV: seat type (with/without backrest), seat and cabin suspension, as well as the weight and posture of the driver (Tiemessen Hulshof, & Frings-Dresen, 2007). Of particular interest is a new seat suspension that uses EAVC technology to reduce vibration. When compared against the conventional passive air suspension seats, the EAVC seats reduced WBV exposure in the z-axis by up to 55% while the passive air suspension seats attenuated only 5% of the WBV (Blood *et al*., 2012). In addition, 75% of truck drivers that used the EAVC seats reported reductions in fatigue, soreness, and stiffness (Parison, 2010). EAVC seats have been shown to improve recovery time and reduce low back pain (Parison, 2010), but relatively little is known on the impacts of a reduction in WBV exposure on the alertness of truck drivers.

2.3 WBV and Vigilance

The relationship between WBV and wakefulness was first examined in 1985 in a lab setting using electroencephalography (EEG) and a vibrating platform. Participants were exposed to two different types of vibration – sinusoidal (3 Hz) and random between (2-20 Hz) – with an average intensity of 0.3 m/s^2. Wakefulness was measured as the ratio of alpha to theta activity; a decrease in wakefulness was indicated by a combined increase in theta and decrease in alpha activity. A significant decrease in wakefulness was observed in both vibration conditions compared with the static resting period (both $p<0.01$) (Landström & Lundström, 1985). In a similar experiment, Satou *et al*. (2007) measured the alpha attenuation coefficients (AAC) of EEG signals before, during and after vibration exposure at 10 Hz (z-axis) with an intensity of 0.6 m/sec^2 for 12 min. Results from this study showed that there were decreases in AAC in the WBV group compared to the control group ($p<0.01$). In 2009, Satou *et al.* followed-up with another study attempting to differentiate wakefulness responses between different vibration frequencies of 10 Hz and 20 Hz. Once again, results showed that the measures of wakefulness based on the AAC were significantly lower in the group exposed to vibration but there were no differences between the two frequency groups. In a recent study, Wang and Johnson (2014) compared PVT performance of eight truck drivers sitting on an EAVC seat that was either turned on or off on a vibration simulation platform. PVT performance was better (mean RT, variability of RT, and number of lapses) when the EAVC suspension was turned on, suggesting that a reduction in WBV exposure improves vigilance.

The effects of WBV on alertness have also previously been evaluated using self-reports (Borg CR 10 scale) (Ljungberg & Neely, 2007). In one of the studies, participants performed cognitive tasks while exposed to 44 minutes of WBV (Ljungberg & Neely, 2007); in another study, participants passively watched a film of a driver's view from the cabin of a lorry while exposed to 15 minutes of WBV (Ljungberg, 2007). However, results were conflicting as the former study showed an increase in reported alertness with WBV exposure, while the latter showed a decrease. Since decrements in vigilance occur in earlier stages of the sleep-wake axis, a subject may not be able to accurately and reliably detect the change. Also, performance of a cognitive task requires more attention than passively watching a film, which may also explain the contrasting results (Ljungberg & Neely, 2007).

To date, most laboratory studies have evaluated the relationship between acute exposures to WBV (less than one hour) and vigilance, using both objective and subjective measures. Generally, results show that vibration has a negative impact on vigilance in a controlled setting. However, lab settings are not fully realistic of environmental conditions and what a truck driver experiences on duty. Thus, it is critical to assess the impacts of reducing WBV exposure on vigilance in the field to provide contextual relevance. There are currently no field studies that explore this relationship; rather, much of the research has focused on the relationship between WBV and low back pain (Burström, Nilsson, & Wahlström, 2015; Tiemessen, 2007). The data that does exist on driver drowsiness are mainly self–reports or accident reports from analyses of collisions, and many of these studies focus on extreme cases of sleepiness, such as drivers with chronic fatigue or obstructive sleep apnea. Studying these populations vulnerable to falling asleep while driving is important in determining fitness for duty, but there is also a need to investigate the earlier decrements of wakefulness in healthy drivers, before they start to feel drowsy.

As EAVC seats are now commercially available, there has been heavy interest from drivers, employers, and the manufacturers to assess the health and safety effects of reducing

WBV. Drivers want to maximize the comfort of their working environment. Employers want to know the cost to benefits to investing in the premium seats. Manufacturers want sales, and improving public road safety via reducing driver fatigue is a strong selling point. Therefore, the primary objective of this study is to

1) Determine if a EAVC seat intervention affects discomfort.
2) Determine if a EAVC seat intervention affects PVT performance over the course of a workday.
3) Determine if EAVC seat intervention affects PVT performance over the course of a workweek.

A secondary aim is to…

4) Explore the relationship between the five-minute and ten-minute PVT to determine if a shorter PVT can be used in future studies.

2.4 Research Questions

1) Do the EAVC seats reduce the increments of pain and discomfort (in 8 body areas) over the course of the workday and workweek compared to the conventional passive air suspension seat?
2) Do the EAVC seats reduce the decrements of PVT performance (6 PVT outcome metrics) over the course of the workday and workweek compared to the conventional passive air suspension seat?
3) Can the five-minute PVT be used in the future instead of the longer ten-min PVT?

2.5 Hypotheses

1) Driving in the EAVC seats would result in less increments of pain and discomfort over the course of a work shift and workweek than driving in the conventional passive air suspension seat.
2) There would be less decrements in PVT performance over the course of a work shift and workweek when driving in the EAVC seats compared to driving in the conventional passive air suspension seat.
3) The five-minute PVT is less sensitive then the ten-minute PVT in detecting significance.

3.0 Methods and Materials

This section describes the study setting, study population, and study design, followed by a description of the independent and dependent variables and their associated measurement tools.

3.1 Study Setting

The study was conducted during Winter (February 2015) on the premises of a delivery terminal hub (Wellington, CT, USA), where delivery runs are contracted to companies who hire their own drivers and have their own trucks. The study sample was taken from one contractor with a fleet of 15 tractors and holds day contracts where the drivers depart and return to the same terminal each day. There are packagers that load the trailers at the terminal, so when the driver arrives, they are only required to hook-up their trailers and conduct their pre-trip check before leaving en route.

3.1.1 Job description

Drivers arrive to the terminal at their scheduled time and meet in the dispatch office to determine the trailers they are taking for the day. Drivers then proceed to drive around the parking lot in their trucks in search for a dolly and their trailers for the day. Note that during winter, it was difficult find a working dolly that was not buried in the snow (**Fig. 4**). Next, drivers look for their designated loads in a parking lot full of trailers (**Fig. 6**). Sometimes, it would take up to one hour to complete hooking up the tractor-trailer (**Fig. 4** and **5**). Afterwards, drivers perform a safety check to ensure the air lines, break lights, and break chains are working. Some paperwork is completed, and drivers are then ready to leave for delivery. Once the drivers arrive to their destination (approximately a four and a half hour drive), they switch trailers, and drive back to the terminal. However, many times their incoming load would be late and the drivers could wait up to two hours. Upon returning to the terminal, there is a security check, before the trailers are refueled and parked.

Figure 4. A) Dollies are buried in the snow during the winter season, making it a challenge for drivers to pull out of the snow; B) The driver has to lift, pull and push the dolly to hook up the trailers; C) The driver also has to lift, pull, and push a lever to release the landing gear of the trailers.


[redacted]
[redacted]

Figure 5. A fully hooked-up double tractor-trailer ready to leave the terminal.

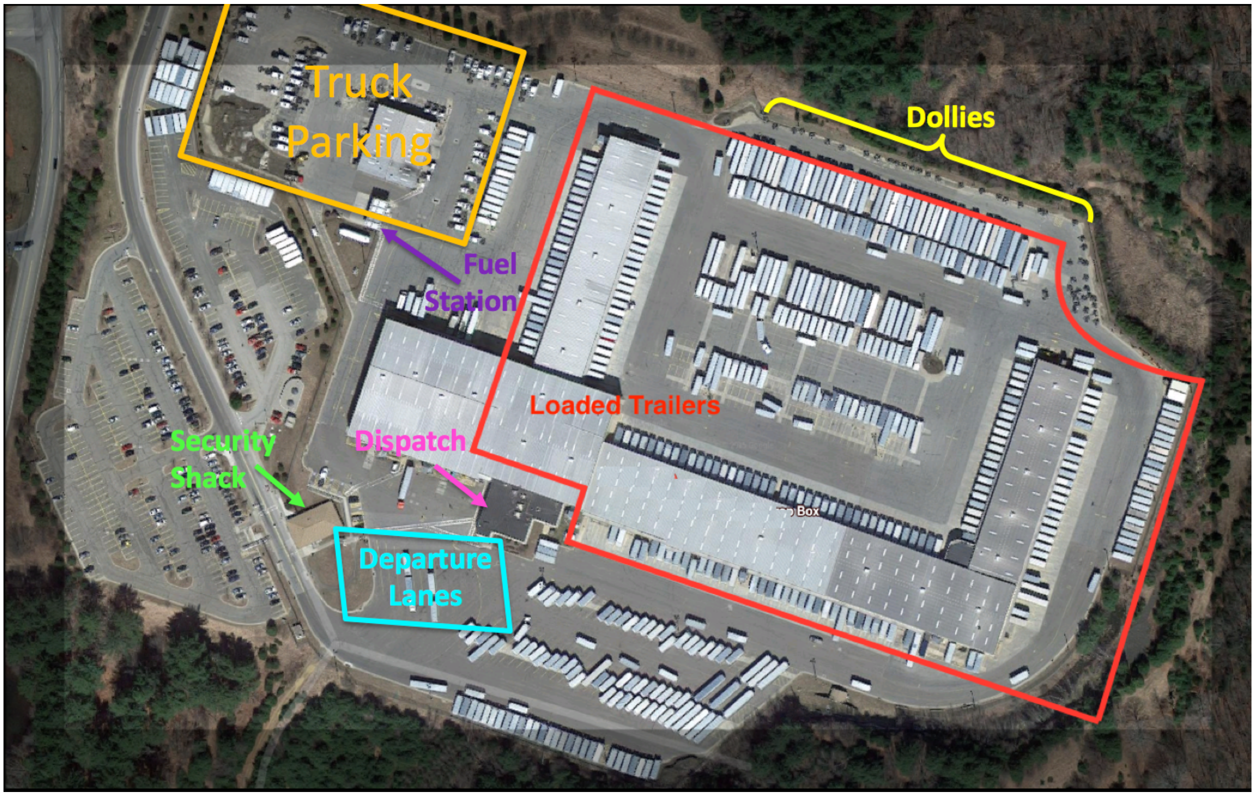

Figure 6. An aerial view of the packaging and delivery center (Wellington, CT). The drivers have to look through many trailers to find their designated load. Space is limited to hook up double trailers, especially during a snowy winter.

3.2 Study Population

Potential participants of a small trucking fleet who had never experienced using an EAVC truck seat were invited to attend a breakfast recruitment presentation. During the presentation, attendees were provided with a description of the purpose, methods, and implications of the study, as well as the remuneration for their participation (paid time and a tablet). All eligible participants signed the consent form and completed a demographics survey immediately after.

To be eligible for the study, the driver must have a regular route and schedule, and operate the same tractor on a regular basis. These inclusion criteria were selected to help control for road conditions, scenery, circadian rhythm, time-on-task, and truck type. Also, to be eligible, participants must be short-haul drivers who start and end their shifts at the fleet terminal, since the researcher must be able to administer the assessment at both the beginning and end of their shifts.

3.2.1 Power Calculation

From a previous lab study, the expected mean difference for the five-minute PVT was approximately 20 ms with a standard deviation (SD) of 10 ms after two hours of exposure on a simulated WBV platform while seated on the EAVC seat either turned on or off (Wang & Johnson, 2014). Similar data was used for the sample size calculation, however the SD of the PVT was increased to 25 ms because a ten-minute PVT is expected to have more variability than the five-minute PVT. To achieve a power of 0.8 with the alpha of 0.05 for a two-sided test, a minimum of four truck drivers were needed to participate in the study (see **Appendix A-1** for power calculation).

3.3 Study Design and Protocol

The study used a repeated measures crossover design (**Table 2)**. Thus participants were exposed to both seating conditions for five days each and the PVT was repeated throughout both conditions, once immediately before the driving shift and once more immediately after. There was a washout period of two days after the first seating condition and before the second seat intervention to avoid potential carry over effects and to allow time for the installing of the EAVC seats. Due to logistical restrictions, the order of seating conditions was not randomized. However, the order of the seating conditions reflected reality, where the EAVC seats are upgraded to replace the older conventional one. Each participant had one full day of WBV measurement during their shift for each seat type. Information about the time and amount of caffeine consumption, duration of sleep, time on task, and discomfort was collected using a questionnaire along with the PVT. The study has been approved by the Office of Research Ethics at the University of Waterloo.

Table 2: Example of Study Protocol

	Conventional Seat							EAVC Seat				
Day	1	2	3	4	5	6	7	8	9	10	11	12
Pre-Shift	Questionnaire PVT					Seat Installation		Questionnaire PVT				
Work Shift	WBV measurement							WBV measurement				
Post Shift	PVT Questionnaire							PVT Questionnaire				

3.4 Independent Variables

3.4.1. Baseline - Existing Seat

As a baseline for comparison, the drivers were driving in their current trucks which all have passive air suspension seats. This type of seat suspension has been shown to attenuate up to 7% of vibration from the truck floor (Blood *et al.*, 2011).

3.4.2. Intervention – Electromagnetically Active Vibration Cancelling Seat

The EAVC seats were installed for the second week of data collection. This seat reduced WBV exposure by up to 55% from the truck floor, a significantly greater reduction than in the passive air suspension seats (Blood *et al.*, 2011). This seat uses an accelerometer to measure vibration at the truck floor and those signals are used to generate seat movement that attenuates the vibration in real time. The active vibration-cancelling feature can be activated simply by turning a switch on; when this feature is off, the seat functions similar to a passive air suspension seat. The drivers were told to drive with the active suspension on.

3.5. Dependent variables and Assessment Tools

Three main outcome measures were collected: vigilance, discomfort and WBV. Additional information on potential factors that could affect vigilance were also collected. Vigilance scores were collected using the ten-minute PVT. WBV characteristics were measured for an entire work shift using two tri-axial accelerometers (floor and seat) according to ISO 2631-1. Discomfort was collected on a ten-point discomfort Likert scale, and covariates were collected with a questionnaire pre and post workday.

3.5.1 Vigilance

Six variables were used from the ten-minute PVT:

1) Number of vigilance lapses
2) Fastest 10% RT
3) Slowest 10% RT
4) Mean RT
5) Variability of RT
6) Mean 1/RT

3.5.1.1 PVT Assessment Tool

The ten-minute PVT was performed using a custom LABVIEW *PVT Program* on an 8” Windows tablet (ASUS Vivotab Note, Beitou District, Taipei, Taiwan) connected with a micro USB keyboard case (Kamor 8” PU Leather Stand Case). The PVT was administered by the researcher, for more information on the protocol, see **Appendix C-1**.

Figure 7. Driver performing the tablet-based PVT inside the truck using a steering wheel desk

3.5.2 Whole-Body Vibration

Three different WBV measures were used to describe the levels of WBV of seat and floor:

1) A(8)
2) VDV(8)
3) Vector sum of the A(8) and VDV(8)

3.5.2.1 Whole-Body Vibration Assessment Tools

An eight-channel data logger (model DA-40; Rion Co., LTD.; Japan) was used to collect raw, unweighted tri-axial WBV at 1280 Hz. Seat vibrations were collected with a tri-axial accelerometer (model 356B40; PCB Piezotronics, Depew, NY, USA) mounted in a rubber seat pad placed on the truck seat as per ISO 2631-1 (see **Fig. 8**). Floor vibrations were collected using an identical magnet mounted accelerometer secured on the floor of the drivers' truck seat. The data logger started collecting once the equipment was set up on the truck.

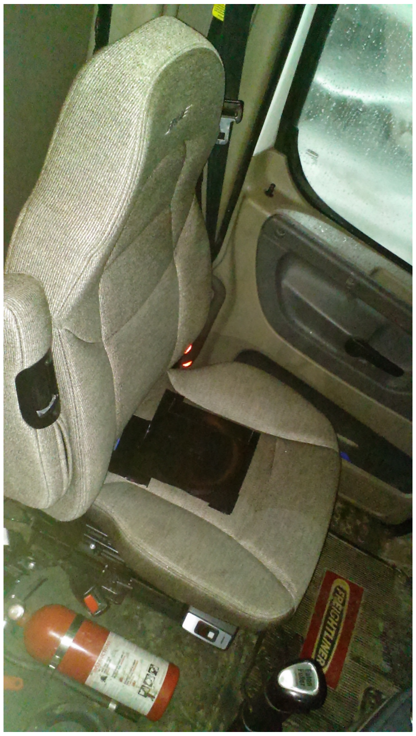

Figure 8. Set-up of the accelerometer and seat pan secured onto the truck seat.

3.5.3 Discomfort

Self reported discomfort was obtained using a ten point Likert scale where zero is no pain at all and ten is the worse pain that the participant could imagine at the current moment (pre/post-shift) for eight body parts:

1) Shoulder(s)
2) Wrist(s)/Forearm(s)
3) Knee(s)
4) Ankle(s)/Feet
5) Neck
6) Upper Back
7) Lower Back
8) Buttocks/Legs

3.5.4 Other Covariates

When studying a specific exposure-response, it is important to consider additional external factors that are variables that are not the exposure of interest but may negatively or positively affect the outcome. Thus a study that has not accounted for effect modifiers may have increased variability in the results, and may not detect significant differences even if one truly exists. Since the PVT is sensitive to many different factors, it is to important look at other covariates of the PVT measures. Aforementioned in Section 2.1.3.3.2, ‘Convergent Validity’, the PVT is sensitive in detecting changes in sleep deprivation, time of day, time-on-task, caffeine, naps. In a laboratory setting, it is possible to request that participants not drink coffee, not exercise and get adequate rest prior to the attending the study. In addition, the researchers can control for the timing of the experiments. In field studies however, it is more difficult to control for these variables. It would be unethical to request truck drivers to do anything that might affect their ability to perform on the job, such as limiting their coffee intake to help them stay awake, or setting a scheduled time to perform the PVT. Therefore, it is imperative to take into consideration of these factors (the amount coffee consumption, duration of sleep and time spent driving and the time of performing the PVT task).

3.5.4.1 Questionnaire for Discomfort and Covariates

Information on the covariates and discomfort were collected using a paper based questionnaire performed before the PVT. See **Appendix B-4 and B-5** for pre and post-shift questionnaire.

3. 6 Data Processing

3.6.1 Whole Body Vibration Exposure

WBV data were processed using custom interactive LABVIEW programs at Ergolab in the University of Washington (Dr. Peter W. Johnson). The beginning and end of each data file were removed to reflect the start and finish of each drivers' actual route because the logger was recording prior to the start of the drivers' shift and stopped after the end of the drivers' shift. Therefore, any data collection before the driver leaves and returns to the terminal was removed from the analysis. A second LABVIEW program created one second files. Then the data was filtered through an error checking programs to identify and remove false peaks, abnormal drift and variability in the data (the threshold points were set as 29.4 m/s^2, 1 m/s^2, and 6 m/s^2, respectively). Finally, various WBV parameters were calculated and normalized to eight hours to allow for comparisons between seats and between past and future studies. The specific formulas used to calculate each whole-body vibration parameter is described in the following sections.

Eight-hour equivalent Frequency-Weighted RMS Acceleration (A(8))

The A(8) can be calculated for each of the axis and compared across seating conditions, however the axis with the highest A(8) value is compared with the health guidelines.

$$A(8) = \left[\frac{8hr}{MT}\right]^{\frac{1}{2}} \times \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{\frac{1}{2}} \qquad \text{units is is m/s}^2$$

Where

$a_w(t)$ = instantaneous frequency-weighted acceleration (m/s^2)
T = Duration of WBV measurement in one vehicle condition (s)
MT = Duration of measurement time (hr)

Daily eight-hour Vibration Dose Value (VDV(8))

Since the A(8) may underestimate the exposure levels when the crest factor is greater than nine, the VDV is calculated because it takes the root mean quad (RMQ) of the accelerations which is more sensitive to transient shocks. Similar to the A(8) in that the highest value of the three axis is compared with the health guideline, and the other axis is compared across seats.

$$VDV(8) = \left[\frac{8hr}{MT}\right]^{\frac{1}{4}} \times \left[\int_0^T a_w^4(t)dt\right]^{\frac{1}{4}} \quad \text{units is is m/s}^{1.75}$$

Where

a_w = frequency-weighted acceleration in metres per second squared (m/s^2)
T = Total duration of WBV measurement, in seconds (s)
MT = Duration of measurement time (hr)

Vector Sum

The vector sum of the A(8) is the sum of the RMS of all three A(8) axis.

$$A_{VSUM} = \sqrt[2]{a_x^2 + a_y^2 + a_z^2}$$

The vector sum of the VDV(8) is the sum of the root mean quad of all three VDV(8) axis.

$$VDV_{VSUM} = \sqrt[4]{vdv_x^4 + vdv_y^4 + vdv_z^4}$$

3.6.2 Psychomotor Vigilance Task (PVT)

From the ten-minute PVT, six different outcome metrics were calculated and used in subsequent data analyses. First, the first two responses of the PVT were excluded because the participants needed time to get into the groove of the task. To prevent vigilance lapses from skewing the mean RT and variability of RT, lapses were substituted with the mean RT within the range of 100-500 ms for that given trial plus three SD (Wang & Johnson, 2014). For calculating the mean 1/RT, each RT (ms) was divided by 1,000, reciprocally transformed, then calculating the mean of the reciprocally transformed values (Basner & Dinges, 2011). The number of lapses (RT>500 ms) for each PVT were summed. The fastest and slowest 10% RT for the the given trial were averaged. The same data processes were repeated for the first and last half of the trials.

3.7 Statistical Analysis

Separate statistical analyses were performed to answer each of the research questions. All analyses were perform using JMP®, Version 12 (SAS Institute Inc., Cary, NC, 1989-2015) with the alpha level set to 5%. The following section describes the specific statistical test used for each aspect of the study.

Whole-Body Vibration

Since different seats were measured in the same trucks across participants, matched pairs T-tests were performed on the WBV exposures of the two different seats. In addition, the WBV exposures of each seat were compared to the action and threshold limits of the health guidance zones in the ISO 2631-1.

Psychomotor Vigilance Task and Discomfort

To determine significant factors that may have had an effect on PVT performance and discomfort, each PVT and discomfort parameter was analyzed using mixed model repeated measures with time of day (two-levels), seat type (two levels) and day of workweek (five levels) as within-subject factors. The analysis was repeated using outcomes from the first half of the 10-minute PVT to account for the whether the sensitive of the five-minute PVT is adequate. Additional post hoc analysis (student t-tests) was performed when an overall effect was found. All data are presented as least squared mean±standard error, unless otherwise stated.

Five-minute vs. Ten-minute PVT Durations

Matched pairs T-test were used to determine if there were differences between PVT outcome metrics for the 5 and 10 minute durations. An additional matched pairs T-test was performed to determine whether the first and last half of the PVT is different from each other.

4.0 Results

Five drivers participated in the study and a total of 84 assessments were completed – 40 in the first week with the trucks' existing conventional passive air suspension seats (20 pre-shift, 20 post-shift), and 44 in the second week with the EAVC seats (22 pre-shift, 22 post-shift) (see **Table 3**). During the first week, one study truck was disabled, and a truck without a passive air suspension seat had to be used for three days. Also, two drivers' shifts were cancelled on the fifth day of their first workweek. During the EAVC seating condition (second week), one driver missed three days of work due to illness. One WBV measurement for the passive air suspension seat was not performed because the scheduled run was cancelled, and one floor WBV measurement was missing due to technical issues in the first week.

Table 3. Completed and missing data: the green boxes indicate that data were collected during the assessment time, while red boxes indicate that data for those time points are not available.

Subject	Time	Day of Week									
		Existing					EAVC				
		1	2	3	4	5	1	2	3	4	5
1	Pre-Shift	✔	✔	✔	✔	✖	✔	✔	✖	✖	✖
	Post -Shift	✔	✔	✔	✔	✖	✔	✔	✖	✖	✖
2	Pre-Shift	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
	Post -Shift	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
3	Pre-Shift	✔	✔	✔	✔	✖	✔	✔	✔	✔	✔
	Post -Shift	✔	✔	✔	✔	✖	✔	✔	✔	✔	✔
4	Pre-Shift	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
	Post -Shift	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
5	Pre-Shift	✖	✖	✖	✔	✔	✔	✔	✔	✔	✔
	Post -Shift	✖	✖	✖	✔	✔	✔	✔	✔	✔	✔

4.1 Demographics of Study Participants

The mean±SD age and BMI of the participants were 54.4+8.35 years and 35.8±7.76, respectively. All participants were experienced drivers having worked at least 16 years in the trucking industry, with 4.2±4.87 years of tenure with the company. Participants reported working between 45 to 65 hours per week, with 40 to 60 hours spent driving. Refer to **Table 4** for more details on the demographics and characteristics of the study population.

Table 4: Description of study participants, N=5, SD=standard deviation

Characteristic	Mean	SD	Range
Age (yrs.)	54.4	8.35	(43 - 64)
Height (m)	1.73	0.10	(1.57 - 1.83)
Weight (kg)	108	27.01	(79-140)
Body mass index	35.8	7.67	(27.3 - 44.6)
Time in trucking industry (yrs.)	23.9	13.74	(16 - 44)
Time with company (yrs.)	4.2	4.87	(1.33 - 12.83)
Hours of work per week	57	7.58	(45 - 65)
Hours of driving per week	46.5	7.83	(40 - 60)

4.2 Characteristics of Work Shift

Participants maintained similar routes, driving distance, time on task, hours of sleep, and caffeine consumption between the two seating conditions. There was insufficient variability within each participant to necessitate stratification or inclusion of covariates in further analyses. Four participants were line-haul drivers who delivered double trailers to another terminal, waited for their ‘bump,’ and returned back to the base terminal. One short-haul driver had three or four trips to a closer destination, so this driver had more frequent stops to hook-up and unhook the trailer, and consequently left the truck and walked around more often than the other subjects. The line-haul drivers spent most of their time driving on the freeway whereas the short-haul driver spent more time on city routes. Overall, there were no differences between the work characteristics between the two weeks (**Appendix A-2**). Therefore, the data obtained from the questionnaire are displayed descriptively to provide a better understanding of the study population (**Table 5**). One participant had less than six hours of sleep for two nights, once during the existing seat condition and once during the EAVC condition.

Table 5. Description of sleep duration, time on task, distance driven and caffeine consumption for each seating condition. There were no significant differences between the two seating conditions. SD=standard deviation; h=hours; m=minutes

Work Characteristic	Seat Type	Mean	SD	Range
Sleep Duration	**Existing**	**7h 16m**	**43m**	**6h 26m - 8h 09m**
	EAVC	**7h 15m**	**49m**	**6h 30m - 8h 16m**
Time on Task	**Existing**	**9h 44m**	**1h 08m**	**8h 29m – 11h 16m**
	EAVC	**10h 11m**	**1h 12m**	**9h 05m - 12h 10m**
Distance (km)	**Existing**	**669**	**188**	**341 - 822**
	EAVC	**662**	**136**	**431 - 766**
# of Caffeinated Beverages/shift	**Existing**	**1**	**2**	**0 - 4**
	EAVC	**1**	**2**	**0 - 4**
# of Coffee/shift	**Existing**	**1**	**2**	**0 - 4**
	EAVC	**1**	**2**	**0 - 4**
# of Energy Drinks/shift	**Existing**	**0**	**0**	**0 - 1**
	EAVC	**0**	**0**	**0 - 0**
# of Soda/shift	**Existing**	**0**	**0**	**0 - 1**
	EAVC	**0**	**0**	**0 - 1**
# of Tea/shift	**Existing**	**0**	**0**	**0 - 1**
	EAVC	**0**	**0**	**0 - 1**

4.3 Whole-Body Vibration Exposure

All WBV measurements have been standardized to the A(8) and VDV(8) to allow for comparison between seat types, and $A(8)_{vsum}$ and $VDV(8)_{vsum}$ were calculated and compared with the ISO 2631-1 Health Guidance Zones (**Table 1**). Normally, the dominant axis is compared with the action limits and threshold limit values; however, when all three axes have similar levels of vibration, it is not clear as to which axis should be used. Thus the vector sum is a more conservative measure that accounts for exposure from all directions and is relevant when all three axes are very similar (Jonsson *et al.,* 2014). The ISO 2631-1 scaling factors for health analysis has applied to each of the axis (x-axis = 1.4; y-axis = 1.4; z-axis = 1).

4.3.1 Eight-hour equivalent frequency-weighted RMS acceleration (A(8))

Drivers were exposed to lower levels of WBV in the EAVC seats than in the existing seats. The existing seats put the driver at moderate health risks, whereas the EAVC seats put the drivers at low health risks (**Table 6**). Existing seats had an $A(8)_{vsum}$ of 0.64±0.02 m/s^2, which is above the ISO Health Guidance Zone action limit of 0.5 m/s^2 (ISO 2631-1, 1997). Similarly, the A(8) of the dominant axis in two of the four trucks were above the action limit. In contrast, the average A(8) of the dominant axis (0.28 m/s^2 ± 0.01) and $A(8)_{vsum}$ (0.44 m/s^2 ± 0.02) of the EAVC seat were both in the low health risk zone. The vector sum in one out of five trucks equipped with EAVC seats were above the action limit, while the A(8) of the dominant axis were all well below the action limit (**Table 6**). The existing seat and EAVC seats reduced floor vibrations by 7.5% and 55% respectively.

Table 6. A(8) whole-body vibration exposure of the floor and seat of the existing conventional air suspension seats and the electromagnetically active vibration-cancelling (EAVC) seats. X=fore-aft; Y=lateral direction; Z=vertical; V_{sum}=Vector Sum; SE=standard error; **=p<0.05

Parameter (axis)	EXISTING (m/s^2) (n=4 for seat; n=3 for floor)	EAVC (m/s^2) (n=4)	SE (m/s^2)	p > |t|
Floor (Z)	0.53	0.49	0.03	0.017**
Seat (X)	0.31	0.28	0.01	0.031**
Seat (Y)	0.27	0.25	0.02	0.286
Seat (Z)	0.49	0.22	0.03	0.002**
Seat V_{sum}	0.64	0.44	0.02	0.003**

4.3.2 Eight-hour Normalized Vibration Dose Values (VDV(8))

EAVC seats exposed drivers to lower levels of WBV that are below the action limit compared to the existing conventional passive air suspension seats (**Table 7**). The average VDV(8) of the dominate axis and $VDV(8)_{vsum}$ (7.02±1.11 $m/s^{1.75}$ and 8.82±0.69 $m/s^{1.75}$, respectively) of the EAVC seat were both below the action limit, and only one of the drivers had $VDV(8)_{vsum}$ exposures above the action limit. In contrast, the average VDV(8) of the dominant axis and VDV(8)$_{vsum}$ (11.37±1.11 m/s$^{1.75}$ and 12.38±0.69 m/s$^{1.75}$, respectively) of the existing seats were both above the action limit. In fact, the VDV(8)$_{vsum}$ of one of the existing seats was above the threshold limit. The existing seat amplified the floor VDV by 5%, whereas the EAVC reduced vibration by 40%.

Table 7. VDV(8) whole-body vibration exposure of the floor and seat with the conventional passive air suspension seats and the electromagnetically active vibration-cancelling (EAVC) seats. X=fore-aft; Y=lateral direction; Z=vertical; Vsum=Vector Sum; SE=standard error.

Parameter (axis)	EXISTING (m/s$^{1.75}$) (n=4 for seat; n=3 for floor)	EAVC (m/s$^{1.75}$) (n=4)	SE	p > |t|
Floor (Z)	10.82	11.63	0.21	0.060
Seat (X)	8.21	6.88	0.11	0.001
Seat (Y)	6.33	5.56	0.54	0.247
Seat (Z)	11.37	7.02	1.11	0.030
Seat V$_{sum}$	12.38	8.82	0.69	0.014

4.4 Psychomotor Vigilance Task (PVT)

The effects of seat type (existing or EAVC), time of day (pre- or post-shift), and day of workweek (1, 2, 3, 4, or 5) on PVT performance from the mixed model analysis are presented. Since there was not a significant three-way interaction (refer to **Appendix A-3** three-way interaction results), only the main effects and the two-way interactions of each PVT outcome metrics from the ten-minute PVT are presented (refer to **Appendix A-4** for results from the five-minute PVT). Further, the similarities and differences from the results of the five and ten-minute test durations are presented.

4.4.1. Main Effects

4.4.1.1 Existing Seat vs. EAVC Seat

Table 8 shows the effect of seat type on PVT performance while holding the day of workweek and the time of day constant. PVT performance was significantly better in the EAVC seat than in the existing seat base on the the mean RT (324±10 vs. 310±10 ms), mean 1/RT

(3.15±0.09 vs. 3.26±0.09), variability of RT (47±4 vs. 37±4 ms), and slowest 10% RT (487±33 vs. 425±33 ms). Although the fastest 10% RT and the number of lapses are not significantly different between the two seating conditions, the trend continues to show that performance is better with the EAVC seat.

Table 8. Least square mean values and standard errors of the six PVT outcome metrics presented by seat type. SE=standard error; **=p<0.05

PVT Outcome Metric	Existing	SE	EAVC	SE	p-value
Mean RT (ms)	324.70	10.07	310.70	10.06	0.0326**
Mean 1/RT	3.15	0.09	3.26	0.09	0.0151**
Variability (ms)	46.83	3.97	37.82	3.96	0.0019**
Fastest 10% RT (ms)	266.02	5.28	262.89	5.26	0.1303
Slowest 10% RT (ms)	486.70	32.90	425.39	32.72	0.0575**
# of Lapses	1.82	0.52	1.04	0.52	0.1749

4.4.1.2 Pre vs. Post-shift

The effects of the time of day on PVT performance while holding the day of workweek and seat type constant is shown in **Table 9**. Performance significantly decreased over the workday for the mean 1/RT (3.28±0.09 vs. 3.13±0.09 ms) and variability of RT (40±4 vs. 45±4 ms) and almost reached significance (p< 0.1) for three outcome metrics (mean RT, fastest 10% RT and slowest 10% RT). Although not significant, there were more lapses at the end of the shift than at the start of the shift.

Table 9. Least square mean values and standard errors (SE) of the six PVT outcome metrics presented by the time of the workday. SE=standard error; *=p<0.1; **=p<0.05

PVT Outcome Metric	Pre-Shift	SE	Post-Shift	SE	p-value
Mean RT (ms)	310.37	10.28	325.03	10.28	0.0615*
Mean 1/RT	3.28	0.09	3.13	0.09	0.0400**
Variability (ms)	39.69	3.96	44.95	3.96	0.0232**
Fastest 10% RT (ms)	260.66	5.38	268.25	5.38	0.0644*
Slowest 10% RT (ms)	433.27	32.29	478.81	32.29	0.0928*
# of Lapses	1.17	0.50	1.69	0.50	0.2597

4.4.1.3 Day of Workweek (between day effects)

The day of workweek variable shows if there are any differences in PVT performance over the course of the week, while holding the time of day and the seating condition constant. There were no differences detected by the statistical analysis for both PVT test durations over the course of the workweek (see **Table 10**)

Table 10. Least square mean values and standard errors (SE) of the six PVT outcome metrics presented by the day of workweek.

PVT	Day of Workweek										
Outcome Metric	1	SE	2	SE	3	SE	4	SE	5	SE	p-value
Mean RT (ms)	308.9	10.47	320.15	10.47	319.41	10.52	318.35	10.47	321.69	10.72	0.2164
Mean 1/RT	3.3	0.1	3.16	0.1	3.19	0.1	3.19	0.1	3.19	0.1	0.2062
Variability (ms)	42.16	4.09	44.03	4.09	42.1	4.12	39.26	4.09	44.06	4.18	0.1328
Fastest 10% RT (ms)	258.39	5.77	265.44	5.77	266.49	5.8	267.67	5.77	264.27	6.01	0.2144
Slowest 10% RT (ms)	473.59	33.94	494.11	33.94	436.63	34.76	434.28	33.92	441.6	35.57	0.117
# of Lapses	1.49	0.55	2.04	0.55	1.18	0.57	1.25	0.55	1.2	0.59	0.4289

4.4.2 Two-Way Interactions

4.4.2.1 Seat Type by Time of Day

The seat type by time of day interaction tests if there is a change in PVT performance over the shift between the two seating conditions (see **Table 11**). Over the workday, fewer significant decrements in PVT performance were found in the EAVC seat than in the existing seat based on the mean RT (10.3 vs. 19.0 ms slower) and the fastest 10% RT (4.0 vs. 11.2 ms slower). The other PVT outcome metrics were not significant but followed the same trend. The post-hoc Student's T-test indicated that the post-shift PVT performance of the mean RT and the fastest 10% RT of the existing seat was significantly slower than the other conditions (see **Table 12**).

Table 11. Least square mean values and standard errors (SE) of the six PVT outcome metrics presented by the seat type and time of day. **=p<0.05

PVT Outcome Metric	Seat Type	Time of Day Pre-Shift	SE	Post-Shift	SE	p-value
Mean RT (ms)	Existing	315.21	10.51	334.2	10.51	0.047**
	EAVC	305.53	10.49	315.87	10.49	
Mean 1/RT	Existing	3.24	0.1	3.05	0.1	0.163
	EAVC	3.33	0.1	3.2	0.1	
Variability of RT (ms)	Existing	43.47	4.07	50.19	4.07	0.268
	EAVC	35.92	4.05	39.72	4.05	
Fastest 10% RT (ms)	Existing	260.41	5.51	271.63	5.51	0.020**
	EAVC	260.91	5.49	264.86	5.49	
Slowest 10% RT (ms)	Existing	460.11	36.02	513.28	36.02	0.697
	EAVC	406.43	35.58	444.34	35.58	
Number of Lapses	Existing	1.41	0.6	2.24	0.6	0.46
	EAVC	0.94	0.59	1.15	0.59	

Table 12. Student's T-test to determine the differences in the mix model. Notice that pre-shift PVT performance for the mean RT and fastest 10% RT are the same. In the post-shift, however, driver's PVT performance declined in the existing seat and remain the same in the EAVC seat. LSM=least square means

Level	Mean RT Letter		LSM	Fastest 10% RT Letter		LSM
Existing, Post	A		334.20	A		271.63
EAVC, Post		B	315.87		B	264.86
Existing, Pre		B	315.21		B	260.41
EAVC, Pre		B	305.53		B	260.91

4.4.2.2 Seat Type by Day of Workweek

Table 14 shows the seat type by day of workweek interaction which describes whether PVT performance differs over the course of a five-day workweek between the two seating conditions. There were no significant differences in the interaction between day of workweek and seating condition; however, significance was almost reached for the mean RT and the mean 1/RT. The other parameters (fastest 10% RT, slowest 10% RT, variability, number of lapses) remained the same.

4.4.2.3 Day of Workweek by Time of Day

The day of workweek and time of day interaction shows whether PVT performance differed over a shift between days (**Table 15**). There was a significant interaction between the time of day and day of workweek in the fastest 10% RT parameter and was almost significant in the variability of RT. However, all of the other parameters remained null. The Student's T-Test shows that the best PVT performance of the fastest 10% RT taken on the pre-shift of the first day in the workweek (see **Table 13**).

Table 13. Student's T-test to determine the differences in the mix model. Notice that pre-shift PVT performance for 10% RT is fastest at the beginning of their shift on day one of the work week. LSM=least square means

	Fastest 10% RT		
Level	**Letter**		**LSM**
Day 4,Post	A		271.18
Day 3,Post	A		269.28
Day 2,Post	A		268.54
Day 1,Post	A		266.76
Day 5,Post	A		265.47
Day 4,Pre	A		264.16
Day 3,Pre	A		263.70
Day 5,Pre	A		263.08
Day 2,Pre	A		262.34
Day 1,Pre		B	250.03

Table 14. Least square mean values and standard errors (SE) of the six PVT outcome metrics presented by the seat type and day of workweek. *=p<0.1

PVT Outcome Metric	Seat Type	Day of Workweek										
		1	SE	2	SE	3	SE	4	SE	5	SE	p-value
Mean RT (ms)	Existing	311.03	10.96	327.38	10.96	325.27	10.96	331.06	10.71	328.77	11.34	0.052*
	EAVC	306.77	10.71	312.91	10.71	313.55	10.95	305.64	10.95	314.61	11.01	
Mean 1/RT	Existing	3.29	0.1	3.09	0.1	3.13	0.1	3.08	0.1	3.14	0.11	0.074*
	EAVC	3.3	0.1	3.24	0.1	3.24	0.1	3.3	0.1	3.23	0.1	
Variability of RT (ms)	Existing	46.01	4.38	46.7	4.38	44.95	4.38	44.98	4.25	51.5	4.57	0.152
	EAVC	38.31	4.25	41.36	4.25	39.25	4.38	33.54	4.38	36.63	4.37	
Fastest 10% RT (ms)	Existing	257.63	6.1	268.68	6.1	268.97	6.1	271.78	5.92	263.05	6.46	0.118
	EAVC	259.16	5.92	262.2	5.92	264.02	6.1	263.57	6.1	265.49	6.18	
Slowest 10% RT (ms)	Existing	505.64	41.74	536.13	41.74	453.58	41.72	464.6	38.96	473.52	45.28	0.948
	EAVC	441.53	38.96	452.09	38.96	419.68	41.67	403.96	41.68	409.68	41.56	
# of Lapses	Existing	1.69	0.75	2.78	0.75	1.49	0.75	1.4	0.68	1.75	0.83	0.868
	EAVC	1.3	0.68	1.3	0.68	0.86	0.75	1.09	0.75	0.65	0.75	

Table 15. Least square mean values and standard errors (SE) of the six PVT outcome metrics presented by the time of day and day of workweek. *=p<0.1; **=p<0.05

PVT Outcome Metric	Time of Day	Day of Workweek										
		1	SE	2	SE	3	SE	4	SE	5	SE	p-value
Mean RT (ms)	Pre-Shift	299.88	11.02	311.26	11.02	315.54	11.09	313.66	11.02	311.49	11.34	0.22
	Post-Shift	317.93	11.02	329.03	11.02	323.28	11.09	323.04	11.02	331.89	11.34	
Mean 1/RT	Pre-Shift	3.41	0.1	3.24	0.1	3.24	0.1	3.25	0.1	3.29	0.11	0.388
	Post-Shift	3.19	0.1	3.09	0.1	3.14	0.1	3.14	0.1	3.09	0.11	
Variability of RT (ms)	Pre-Shift	40.3	4.31	39	4.31	40.97	4.36	38.97	4.31	39.22	4.47	0.076*
	Post-Shift	44.03	4.31	49.06	4.31	43.24	4.36	39.54	4.31	48.9	4.47	
Fastest 10% RT (ms)	Pre-Shift	250.03	6.09	262.34	6.09	263.7	6.15	264.16	6.09	263.08	6.4	0.046**
	Post-Shift	266.76	6.09	268.54	6.09	269.28	6.15	271.18	6.09	265.46	6.4	
Slowest 10% RT (ms)	Pre-Shift	464.76	39.96	468.3	39.96	406.64	41.27	414.16	39.94	412.49	43.12	0.954
	Post-Shift	482.42	39.96	519.91	39.96	466.62	41.27	454.41	39.94	470.71	43.12	
# of Lapses	Pre-Shift	1.69	0.7	2.07	0.7	0.49	0.74	0.91	0.7	0.71	0.78	0.636
	Post-Shift	1.3	0.7	2.01	0.7	1.87	0.74	1.58	0.7	1.7	0.78	

4.4.3 Five vs. Ten-minute Psychomotor Vigilance Task

Between the five and ten-minute PVT, four out of six PVT outcome metrics (mean RT, mean 1/RT, fastest 10% RT, number of lapses) were significantly different (see **Table 16**). Number of lapses were included in this analysis, however it is important to note that this parameter is a cumulative count, thus more lapses will occur in the longer PVT. Although, these four parameters are significantly different, the mean differences are very small (greatest mean difference was 3.5 ms) and the results between the two test durations are highly correlated (R> 0.9).

Table 16. Comparison of the 5 and 10-minute PVT. SE=standard error; **=p<0.05

PVT Outcome Metric	5-min PVT	10-min PVT	Mean Difference	SE	Correlation	P> |t|
Mean RT (ms)	314.79	318.12	-3.34	0.63	0.98	<0.001**
Mean 1/RT	3.24	3.21	0.03	0.01	0.97	<0.001**
Variability (ms)	42.88	42.82	0.05	0.49	0.94	0.917
Fastest 10% RT (ms)	262.28	263.80	-1.52	0.60	0.93	0.013**
Slowest 10% RT (ms)	461.68	460.97	0.71	7.83	0.86	0.928
Number of Lapses	0.80	1.51	-0.71	0.14	0.75	<0.001**

The performance between the first and last half of the PVT was also compared (see **Table 17**). There were no differences in the variability of RT, slowest 10% RT and the number of lapses between the first and last half of the PVT. However, the differences occurred in the mean RT, mean 1/RT, and the fastest 10% RT where performance was superior in the first half.

Table 17. Comparison of the first and last half of the PVT. SE=standard error; **=p<0.05

PVT Outcome Metric	First Half	Last Half	Mean Difference	SE	Correlation	P>|t|
Mean RT (ms)	320.59	325.93	5.34	2.12	0.82	0.014**
Mean 1/RT	3.24	3.18	-0.06	0.01	0.89	<0.001**
Variability (ms)	42.88	41.76	-1.12	0.96	0.75	0.250
Fastest 10% RT (ms)	262.28	268.53	6.25	1.32	0.73	<0.001**
Slowest 10% RT (ms)	461.68	455.02	-6.66	15.85	0.39	0.421
Number of Lapses	0.80	0.71	-0.08	0.13	0.47	0.524

4.4.4 Important PVT outcome metrics to note

The sensitivity of each PVT outcome metrics in this population of truck drivers (including results from both the 5 and 10-minute PVT) for detecting changes is ranked in the table below from the most sensitive to the least sensitive (**Table 18**). It appears that the mean RT is the most sensitive parameter and the least sensitive is the number of lapses occurred.

Table 18. 5 and 10 minute PVT outcome metrics ranked based on its ability to detect differences in PVT performance in truck driving population. Sig.=significant

	5-minute PVT		10-minute PVT			
PVT outcome metrics	**Sig.**	**Almost**	**Sig.**	**Almost**	**Significant Findings Only**	**Total (Sig. + Almost)**
Mean RT	3	1	2	2	5	8
Mean 1/RT	1	3	2	1	3	7
Variability	2	1	2	1	4	6
Fastest 10% RT	2	0	2	1	4	5
Slowest 10% RT	0	1	1	1	1	3
# of Lapses	0	1	0	0	0	1
Total	8	7	9	6	-	-

4.4.5 PVT Results Summary

In summary, the five-minute PVT detected eight significant differences and seven almost significant differences ($p < 0.10$), whereas the ten-minute PVT detected nine and six, respectively (**Table 19**). When the results of the ten-minute PVT reached significance, five out of the nine times, the results of the five-minute PVT agreed with the findings; and in three out of nine times, significance was almost reached. Similarly, when the five-minute PVT reached significance, the significance level of the ten-minute PVT either matched it or was almost significant. There was only one instance (fastest 10% RT in the time of day and day of workweek interaction) where the results of the 10-minute PVT were significant while the results of the five-minutes PVT were not in-line with that result.

Table 19. 5 and 10-minute PVT summary results of p-values from full factorial mix model (excluding three-way interaction). *p<0.1; **p<0.05

PVT outcome metrics	PVT Duration	Condition	Day of Workweek	Time	Condition by Time	Condition by Day of Workweek	Time by Day of Workweek
Mean RT	5-minutes	0.062*	0.369	0.021**	0.029**	0.025**	0.334
	10-minutes	0.033**	0.216	0.062*	0.047**	0.052*	0.220
Mean 1/RT	5-minutes	0.051*	0.428	0.027**	0.073*	0.064*	0.609
	10-minutes	0.015**	0.206	0.040**	0.163	0.073*	0.388
Variability	5-minutes	0.005**	0.157	0.006**	0.579	0.835	0.078*
	10-minutes	0.002**	0.133	0.023**	0.268	0.152	0.076*
Fastest 10% RT	5-minutes	0.166	0.217	0.013**	0.002**	0.141	0.281
	10-minutes	0.130	0.214	0.064*	0.020**	0.118	0.046**
Slowest 10% RT	5-minutes	0.096*	0.299	0.318	0.590	0.390	0.537
	10-minutes	0.058**	0.117	0.093*	0.697	0.948	0.954
# of Lapses	5-minutes	0.309	0.658	0.259	0.090*	0.224	0.569
	10-minutes	0.175	0.429	0.260	0.460	0.868	0.636

4.5 Discomfort

There were not many significant differences and/or changes found in the self-reported discomfort questionnaires except for two body areas: the lower back and the wrist(s)/forearm(s) (see **Table 20**). The lower back was affected by both the seating condition and the time of day, both as a main effect, as well as an interaction between the two. In other words, the drivers felt more low back discomfort at the end of a shift with the existing seats than the EAVC, increases of 2.5 vs. 0.2 on the 10-point discomfort scale, respectively (**Figure 9)**. Further, there were greater increases in low back discomfort over the course of the work-shift when driving with the existing seat compared to the EAVC seat. Similarly, there were greater increases in wrist(s)/forearm(s) discomfort over the course of the shift when driving in the existing seat compared to the EAVC seat, with increases of 1.0 vs 0.1 on the discomfort scale (**Figure 10**).

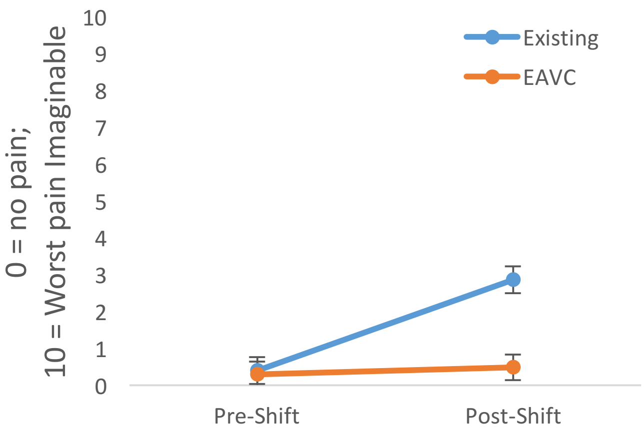

Figure 9. Changes in lower back discomfort over a shift between seat types

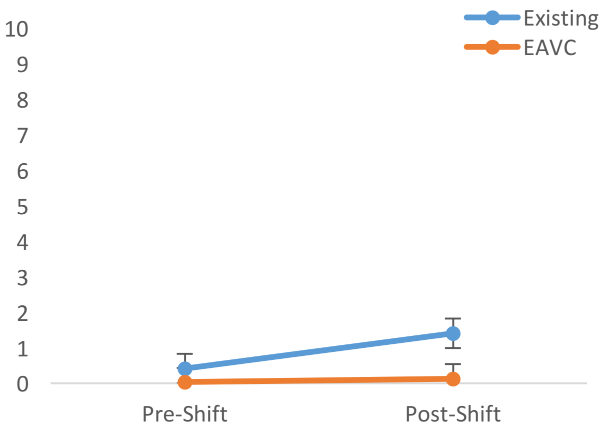

Figure 10. Changes in wrist(s)/forearms(s) discomfort over a shift between seat types

Table 20. Self-reported discomfort summary results of p-values from full factorial mix model (excluding three-way interaction); *p<0.1; **p<0.05

Body Part	Condition	Time	Day of Workweek	Condition by Day of Workweek	Condition by Time	Time by Day of Workweek
Shoulder(s)	0.298	0.220	0.790	0.072	0.633	0.550
Wrist(s)/Forearm(s)	0.133	0.229	0.562	0.268	0.012**	0.930
Knee(s)	0.332	0.248	0.094*	0.401	0.377	0.388
Ankle(s)/Feet	0.298	0.220	0.790	0.072	0.633	0.550
Neck	0.844	0.197	0.775	0.353	0.794	0.650
Upper Back	0.131	0.155	0.685	0.617	0.143	0.469
Lower Back	0.044**	0.040**	0.780	0.608	<0.001**	0.913
Buttocks/Legs	0.747	0.168	0.764	0.203	0.590	0.811

5.0 Discussion

Our study supports that a reduction in WBV exposure is associated with improved alertness and low back comfort. Compared to the conventional passive air suspension seats, truck drivers using the EAVC seats were able to maintain vigilance to a higher degree over the workday. Further vigilance is affected by the course of the workday (i.e. driving for a day is fatiguing). In this study methodology, we were able to detect changes in vigilance using the PVT and the most sensitive outcome metrics were mean RT, mean 1/RT, variability of RT, and fastest 10% RT. In contrast, slowest 10% RT and number of lapses were less sensitive. Further, the four sensitive PVT outcome metrics were highly correlated between the five- and ten-minute PVT, which resulted in similar findings between the two test durations. The following discussion will be based on the results of the ten-minute PVT as the primary measure.

The study participants' BMI (mean±SD) was 35.8±7.67, which was higher than expected, with four out of five drivers having a BMI of 30 or greater (obese status). However, studies indicate that truck drivers have a high prevalence of obesity, up to 69% in a recent US study (Sieber *et al.,* 2014). Thus our study sample is representative of the truck driver population. Further, our study also consisted of one female driver out of the five participants which over-represents the female driver populations of six to ten percent (Renner, 1998). However, there is no reason to believe there are sex differences in responses to WBV exposure (Seidel, 2005).

The EAVC seats were effective in reducing driver exposure to WBV. We found that EAVC seats reduced the A (8) z-axis of floor by 55%, compared to a 7.5% reduction by the existing conventional passive air suspension seats, similar to previously reported values (Blood *et al.*, 2011). However, Blood *et al.* (2011) reported relatively lower WBV exposure values than what our study found (A(8) of seat Z-axis was approximately 0.18 m/s^2 with the EAVC seat, and 0.39 m/s^2 in the conventional seat). The differences in results may be due to their reduced driving speed of 34 km/h (Chen *et al*. 2003; Malchaire *et al*. 1996). Relative to other heavy machinery, the WBV exposure of trucks (floor z-axis) is on the lower end (**Fig. 11).** However, note that the A(8) calculated in our study includes a time domain, whereas **Figure 11** only shows the magnitude of the WBV and does not account for rest periods.

Inline with our study, other studies have also found vigilance to worsen over a workday. In a study using the ten-minute PVT to determine the effectiveness of a driver fatigue management intervention, baseline pre- and post-shift performance (mean RT, mean 1/RT, number of lapses) were measured for 40 drivers who were at low risk for falling asleep during the day (score on Epworth Sleepiness Scale: 0 – 10), and they found similar results (Smiley, 2009). From the main effect of time of day (includes all other ESS scores, n=51), Smiley (2009) found a significant increase in mean RT (mean±SD) from 291±61 to 294±61 ms over a workday; our study found a significant increase from 317±29 to 337±28 ms. For the mean 1/RT, Smiley found a significant decrease from 3.59±0.56 to 3.55±0.54 over the workday; and our study also found a significant decrease from 3.23±0.28 to 3.05±0.23. Further, both Smiley's and our study did not find a difference in the number of lapses outcome metric. Similarly, a study of crane operators found significant declines in visual motor RT (from 290±80 to 310±90 ms) and increases in error rate (from 2.67±3.29 to 4.23±4.37%) over a workday (Tian *et al*., 1996).

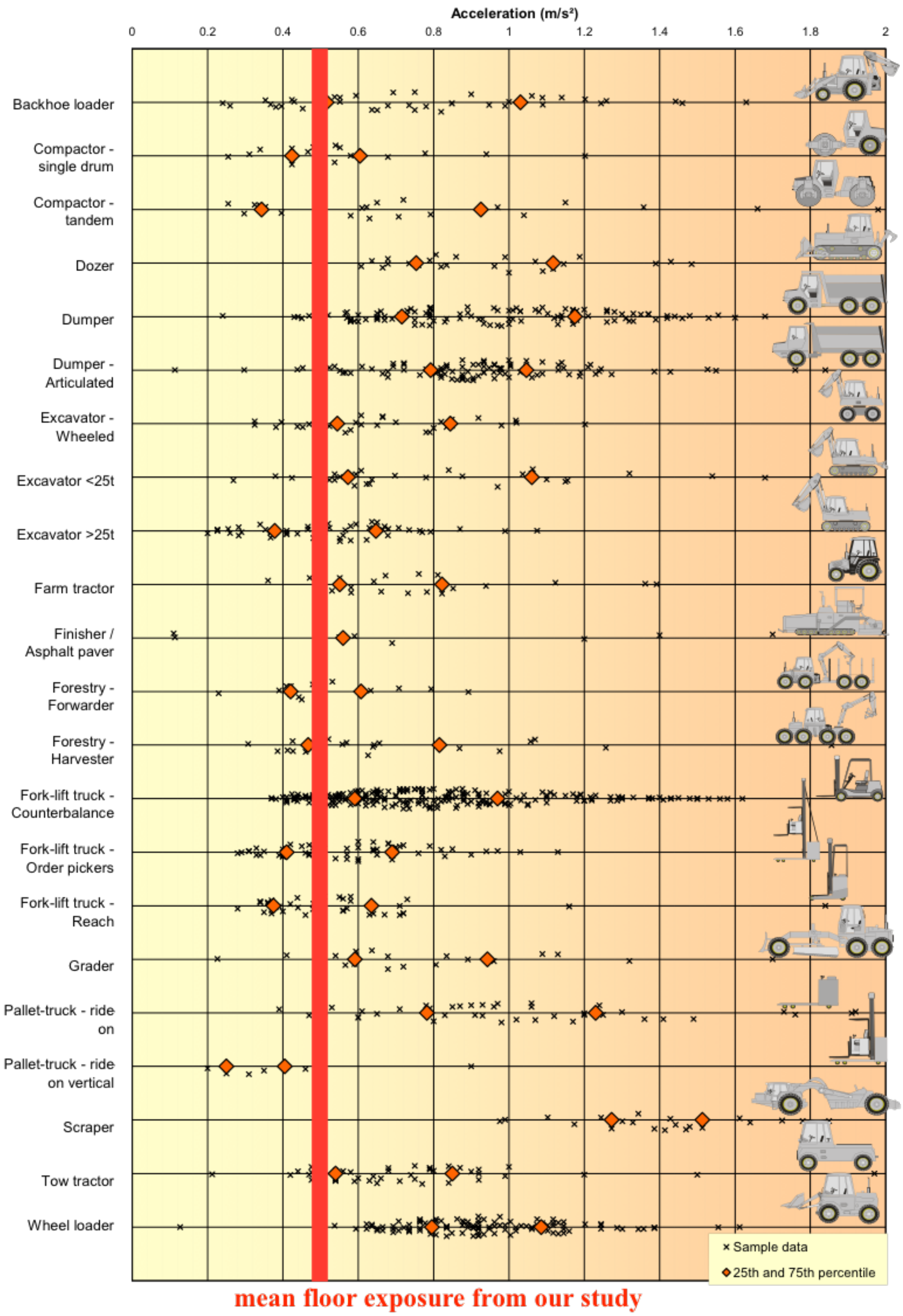

Figure 11. "Examples of vibration magnitudes for common machines. Sample data based on workplace vibration measurements of highest axis vibration values by INRS (with the assistance of CRAM and Prevencem), HSL and RMS Vibration Test laboratory between 1997 and 2005. These data are for illustration only and may not be representative of machine use in all circumstances. The 25th and 75th percentile points show the vibration magnitude that 25% or 75% of samples are equal to or below." (Image taken from EU good practice Guide WBV, 2008)

Though PVT performance decreased over a workday, we found that EAVC seats helped with maintaining (PVT) performance. Wang and Johnson[2] (2014) also found similar results using the five-minute PVT. In a crossover design, they had eight drivers perform a simulated driving task for two hours while sitting on an EAVC seat (either turned ON or OFF) installed on a vibration simulating platform. They found an increase of 5 ms with the EAVC seat turned ON and 15 ms with it turned OFF. Our study found an increase of 10 ms in the EAVC seat and 19 ms in the existing seat over a workday. Since the same seat was used in both conditions in Wang's study, it was possible to control for the ergonomics of the seats such as the form, material and adjustments of the seat. In addition, a lab study by Newell and Mansfield[2] (2007) found a significant increase of approximately 50 ms in visual motor choice reaction times while exposed to WBV. Our study adds evidence to support the literature that reducing WBV exposure can improve performance.

5.1 Interaction of Seat Type and Day of the Workweek

EAVC seats appeared to help with the maintenance of vigilance over the course of the workweek, whereas conventional passive air suspension seats did not. This interaction of seat type and day of workweek were marginally significant for the mean RT and the mean 1/RT (p=0.052 and 0.074, respectively). Given the small sample size of the study, some further discussion is worthwhile. On the first day of the workweek during the pre-shift, the mean RT were the same between the two seats. However, as the week progressed, the drivers' pre-shift mean RT increased in their existing seats whereas it remained constant in the EAVC seat (refer to **Appendix A-5**). Thus, there was a trend

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[2] Values taken from these studies were presented in a graph without exact values. The author estimated the values based on his best judgment.

showing that vigilance decreased over the workweek while vigilance was maintained with the EAVC seat. Other studies found a similar trend in the physical domain. For example, maximal grip strength decreased over the workweek in plumbers (Yung *et al.*, 2014). A possible explanation is that one night's rest is inadequate for drivers to recover from WBV exposures; and perhaps reducing WBV exposures by use of an EAVC seat or reducing driving time, would decrease recovery time. The WBV exposure of the EAVC seat is below the action limit and thus, less time (one night) may be required to recover from the fatigue accumulated over a shift. Yet, after a weekend (three nights of rest), it appears that the drivers are well rested and can start the week with a strong baseline again. This trend, however, may not apply to those working with alternating shifts (e.g. 6 day shifts, 3 days off, 6 night shifts, 3 days off) as most of the time 'off' is spent adjusting to the new work schedule.

5.2 PVT Outcome Metrics

Not all PVT outcome metrics responded to the effects of workday, seat type, or day of workweek the same way. In general, the mean RT, mean 1/RT, variability of RT, and fastest 10% RT were more sensitive in detecting significant differences compared to the slowest 10% RT and the number of lapses. One major difference between these two groups is that the less sensitive metrics included lapses (RT greater than 500 ms) whereas the others either processed all the lapses to be three standard deviations above the mean, weighted it less, or did not include it at all. The slowest 10% RT only had one significant finding and the number of lapses had none. It is interesting that lapses were not sensitive under these conditions given that lapses are used as a key metric to validate driver drowsiness devices, and are the most frequently used PVT outcome metric (Basner & Dinges, 2011). In fact, lapses are the main metric used in sleep deprivation research to assess the wakefulness of total or partially sleep deprived participants, and are, therefore, at a much higher risk of falling asleep. Since the drivers in this study did not undergo total or partial sleep deprivation during the study period (except for two instances), lapses may be less relevant for the purposes of our study. Nonetheless, it is worth noting that drivers in this study were generally not sleep deprived while operating their trucks and did were not so fatigued as to having frequent lapses.

The more sensitive PVT measures also detects different aspects of driver vigilance. For example, the mean RT accounts for all reaction times and represents overall performance, but it does not provide information on the performance's stability or consistency. Mean 1/RT is another 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. The fastest 10% RT is a unique parameter because it is limited by how fast an individual can physiologically respond. Other PVT metrics lack this type of limit and thereby allow for more variability in the data.

5.3 Discomfort

EAVC seats reduced low back discomfort in drivers after a work shift better than the conventional passive air suspension seat. Previous research has demonstrated a strong association between WBV and low back pain, and a recent meta-analysis showed that exposure to WBV increases risk of low back pain by 2.2-fold (Burström, Nilsson, & Wahlström, 2015). Parison (2010) found that 40% of drivers had low back discomfort that interfered with their jobs, but this was reduced to 1% after switching to EAVC seats. Though the study shows positive results, it also suffers from expectation effects due to lack of blinding and randomization.

It is interesting to find that drivers using EAVC seats had reduced levels of discomfort in their wrist(s) and/or forearm(s) over the workday. A possible explanation is that drivers are more stable in their seats, so they can grip the steering wheel with less force to keep themselves from bouncing in their seats.

5.4 Five vs. Ten-minute PVT

There were little differences in the results collected from the five and ten-minute PVT's, signifying similar sensitivities in measuring vigilance. The shorter test duration may be used in the field to quickly detect changes in driver vigilance in the future. In fact, the shorter PVT was more sensitive in detecting some conditions than the ten-minute PVT (i.e. time of day for mean RT and fastest 10% RT, seat type by day of workweek for mean RT). The more sensitive metrics (mean RT, mean 1/RT, variability of RT, and fastest 10% RT) were significantly different between the two test durations, but had strong correlations (R>0.9). Although the five and ten-minute PVT are both sensitive in detecting differences, the results are not identical. This can be explained by the differences found between the first and last half of the PVT. It is possible that if the length of the PVT increases, performance degrades due to boredom or loss of attention. Thus, performance during the last five minutes was worse than in the first five minutes.

5.5 Strengths

Within-subject crossover study designs are advantageous as measures are taken from the same individuals across different conditions. Therefore, individual differences such as gender, age, body mass index, general health and well-being, as well as lifestyle habits such as physical activity, sleeping patterns, medication, and caffeine consumption are similar, if not identical, between conditions. In addition, the drivers had regular routes and scheduled start times which help account for workload and diurnal effects. Hence, the differences detected in the changes in PVT performance are more likely due to the EAVC seat intervention rather than covariates. Likewise, the variability of WBV exposures for each seat is reduced because the same trucks (same level of care, maintenance, and mileage) were used under the same driving conditions (same driving style and road conditions). WBV exposures were also measured, and showed significant differences between the EAVC seats and the conventional passive air suspension seats already existing in the trucks. Therefore, we can better isolate the effects of WBV exposure on vigilance and performance while remaining in a field environment.

5.6 Limitations

Although our study had numerous strengths and accounted for many factors, it is not without limitations. Due to the nature of the fieldwork, it was not possible to control for time-on-task or environmental conditions such as traffic or weather. These covariates may blur the relationship between WBV exposure and vigilance in drivers. In addition, drivers were asked to perform the ten-minute PVT at the beginning and the end of each shift, which assesses the cumulative effects of the entire work shift, but does not provide real-time counts of vigilance lapses. Thus it is not possible to calculate the number of vigilance lapses throughout the entire shift, a more practical method in evaluating performance.

The small sample size of five participants is another limitation of the study for two reasons. Firstly, there may not be adequate power to detect significance as seen in six of PVT performance statistical analyses that almost reached significance ($p < 0.1$). Perhaps there would be stronger relationships had there been more participants to account for missing data. Ultimately, having a larger sample size would reduce the possibility of type 2 error. Secondly, we had missing data points from individuals, which may have large impacts especially when the sample size is small. For example, when looking at the interaction between seat type and day of workweek, there was one day (day 5 in the existing seat) where there was missing data for two participants; thus on that certain day, four out of ten data points were missing. In the two-way interaction between seat type and day of workweek, there was minimal power for each condition, and as a result, there was almost an interaction between the two variables. From the power calculation, a minimum of four participants were required. Therefore, there would only be adequate statistical power for the three-way interaction (seat type, time of day, and day of workweek) if all data was present. Though more participants were needed for the day of workweek interactions, there was adequate data points to analyze the relationship between the seat type and time of day.

One could argue that a learning effect was present because there was no randomization in the order of the baseline and intervention conditions. All the participants were assessed in their existing seat first, then in the EAVC seat. If there was indeed a learning effect, drivers would be expected to have better PVT performance with increasing number trials completed. If so, it would be reasonable to expect that participants performed better in the EAVC seat because they already had one week of PVT practice. However, the mean RT did not improve in the baseline measurements with use of the existing seats. In contrast, mean RT increased over the course of the workweek, indicating that the drivers were becoming increasingly fatigued. Since baseline PVT performance did not improve over the week, it reduces the possibility of a learning effect. Previous research has also shown a minimal learning curve for the PVT (Dorrian, 2005).

Another possible explanation for the superior PVT performance in drivers using the EAVC seat is the expectancy effect; where the drivers perform better when seated on the EAVC seat because they expect it would improve their reaction times and/or reduce fatigue. If the driver puts more effort into the PVT assessments during the EAVC intervention (or in contrast, less effort during their first week on the existing seats), then we would expect an improved fastest 10% RT in the EAVC or increased number of lapses in the existing seat. However, the number of lapses and the fastest 10% RT were not different between both seat types, providing evidence that participants were not intentionally biasing results. Regardless, though there is little evidence to show there was an expectancy effect, it cannot be ruled out.

A solution to the expectancy effect altogether would be to blind the drivers from knowing the seating condition. However, the experienced drivers in our study would immediately realize that their seats were changed. To reduce bias, we did not inform the drivers of the ability of the EAVC seats to attenuate WBV, nor the expected outcome. Participants were only told they may experience a different sensation with the EAVC seat. Using the EAVC seat and blinding participants knowing whether it is turned on or off in a between subjects design would be another solution, similar to Wang and Johnson's (2014) lab experiment.

Aforementioned, our study found an average increase in the mean RT of 10 ms in the EAVC seat and 19 ms in the existing seat over a workday, indicating that there was a 47% decrease in vigilance decrements throughout the day with the EAVC seat. The standardized mean difference effect size, Hedges g, was -0.31 in comparison to -0.38 found in the meta-analysis of WBV and RT tasks of five studies (Conway, Szalma, & Hancock, 2007), indicating that WBV has a moderate effect on reaction times.

Further, the mean difference in RT of the EAVC seat compared to the existing seat was 14 ms, which equates to an additional 38.8 cm of braking distance when travelling at a speed of 100 km/hr, potentially reducing the severity of crashes and the number of near misses on the road. In addition, and perhaps more importantly, increases in mean RT (~15 ms) on the PVT have been correlated with decreases in driving performance by almost doubling the amount of lane drift incidents during a non-sleep deprived state with eight to ten hours of wakefulness. Important to note is that the PVT is a sustained attention RT task where the participant is required to respond to one stimulus by pressing one button. However, RT significantly increases when there are multiple stimuli and response options (Hick, 1952). In real world settings, drivers must recognize and process information on traffic, road and weather conditions and respond appropriately through lane tracking, accelerating, and braking for a prolonged period of time. As a result, the 14 ms RT difference between the two seats has significant implications on driving performance and road safety.

We also provide evidence that truck seats – and ultimately WBV – influence driver fatigue and performance. This study shows that driver vigilance can be improved with ergonomic changes such as vibration-cancelling seats. Driver drowsiness is multifactorial and WBV is one factor that can help improve vigilance. Other parameters that we can also aim to improve are sleep schedules and work environments. In this study we show that reducing vibration decreases the rate of fatigue over the course of a workday.

6.0 Contributions

1) Truck seat suspension technologies can affect driver vigilance over the course of a workday.
2) The five-minute PVT has adequate sensitivity to detect changes in driver fatigue and can be used in future studies with similar conditions.

7.0 Study Findings

1. The EAVC seats exposed drivers to significantly less WBV than their existing seats.
2. There was a reduction in discomfort in the low back and wrist(s)/forearm(s) over a workday in the EAVC seat
3. When seated in the EAVC seats, drivers had fewer decrements in PVT performance over the course of a workday compared to seated in their existing passive suspension seats.
4. Pre-shift mean RT tended to become slower over the course of the workweek when drivers were seated in the existing seats, but remained constant in the EAVC seat.
5. The five-minute PVT can be used in the field rather than the ten-minute PVT as they are both highly correlated in all six parameters (R >0.75) and they provide similar results.

8.0 Future Directions

Our study was the first to evaluate the impacts of WBV exposure reduction on driver vigilance in the field using a truck seat intervention. We have provided evidence to support the relationship between seat type and three parameters: WBV, low back pain, and driver fatigue (**Fig. 13**). Future studies can explore relationships between other parameters associated with vigilance and fatigue.

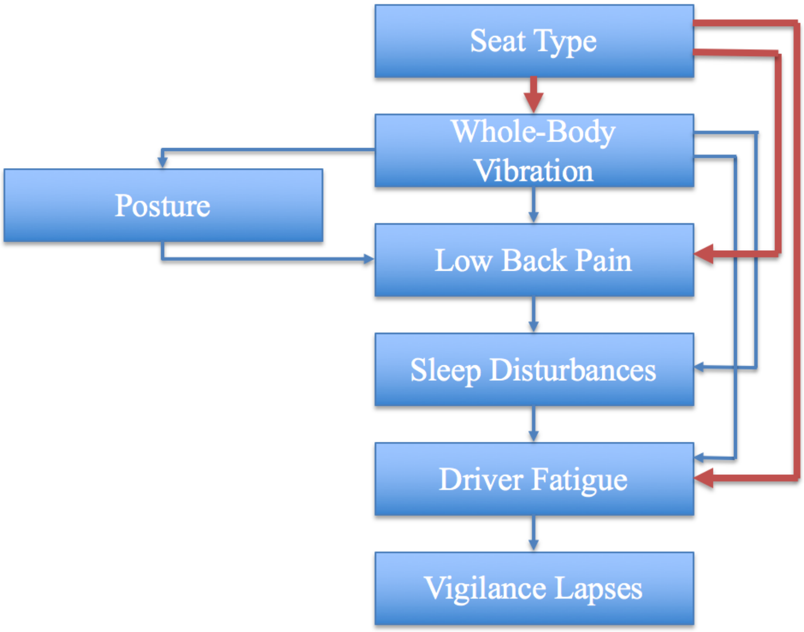

Figure 12. Causal diagram indicating the ways in which whole-body vibration created from truck seats can affect vigilance. Linkages supported by our study is highlighted in red.

A study with more participants and higher statistical power is warranted to further understand the long term effects of reduced WBV exposures on driver vigilance. Future studies can also use real-time detectors of driver drowsiness and performance to understand how vigilance may change during a work shift, as we may be missing unique patterns or fluctuations that occur during a workday when we only have pre- and post-shift measurements. Commercially, there are many products available that are used to alert drivers by measuring blink duration, blink frequency, facial droop, or head nodding. Driver performance measurements such as standard deviation of lane position can also be used and has been previously correlated with the PVT.

Future studies should also integrate objective measures with self-reports of fatigue, comfort and usability of EAVC seats in order to have a holistic approach on measuring cognitive fatigue, as measuring RT is only one aspect. Additional covariates that should also be acquired are sleep quality, number of cigarettes per day, and noise.

Although many lab studies have found changes in vigilance over a short periods of exposure time, EAVC seats will most benefit long-haul drivers as they spend more time driving, and less time (un)loading and (un)hooking trailers. Drivers who are able to leave the truck to perform these activities have the opportunity to stretch, walk around, and have a change of task. Future studies with the EAVC seat should more heavily focus on this population to potentially show a greater impact.

9.0 Conclusion

The adverse health effects of WBV have been studied since the 1980's, yet, until recently, there have been little advances to reduce exposures in the trucking industry. The new technology of the EAVC seats are able to reduce WBV exposures up to 55% from the floor vibrations, and consequently reduce the rate of driver fatigue over a day, and even perhaps over the course of a week.

This was the first field study to look at the effects of WBV on vigilance in truck drivers. These findings have important implications on the health and well-being of the drivers, as well as driving performance and public road safety.

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Appendices

A-1 Power Calculation

Sample size calculation based on 5 min PVT use in study by Wang (2014).

$$\boldsymbol{n = 2\left[\frac{\left(Z_{\frac{\alpha}{2}} - Z_{\beta}\right)^{2} \sigma^{2}}{d^{2}}\right]}$$

where:

$Z_{\beta} = 0.84$ - Value from the standard normal distribution that corresponds to the desired 80% power

$Z_{\alpha/2} = 1.96$ - Desired level of statistical significance; value of the standard normal distribution corresponding to 95% confidence

$\sigma^2 = 625$ – assuming SD is 25 ms (study by Fang Fang Wang, 2014 showed only showed S.D. of ~10ms in a controlled lab setting. Since there would be more variability expected in the field, I increased the S.D. by 2.5 folds.

d = 20 ms – the mean difference shown is Fang Fang Wang's study was 20 ms.

$$n = 2[\ \{(1.96-0.84)^2 \times 625\} / 400]$$
$$\mathbf{= 3.92 \rightarrow 4}$$

Therefore, a minimum sample size of 4 participants per study group is needed to reliably say that there is a difference in PVT scores between seats.

A-2 Results from matched pairs T-tests for work characteristics

Work Characteristic	Mean EAVC	Mean Existing	Mean Difference	Std Error	Correlation	Prob > |t|
Mileage (mi)	411.3	415.98	-4.68	20.6589	0.94569	0.8319
Time on Task (min)	611.2	584	27.2	26.2291	0.65367	0.3583
Sleep Duration (min)	434.6	436.35	-1.75	7.70876	0.94026	0.8315
Total # of Caffeinated Beverage	1.16	1.19	-0.03	0.04899	0.99944	0.5734

A-3 Three-way Interactions of seat type, time of day and day of workweek for each of the ten-minute PVT outcome metrics. There were no significance. LSM=least square mean; SE=standard error

			Fastest 10% RT		Slowest 10% RT		Mean RT		Variability of RT		Mean 1/RT		Number of Lapses	
Seat	Time of day	Day of Workweek	LSM	SE	LSM	SE	LSM	SE	LSM	SE	LSM	SE	LSM	SE
EAVC	Pre	1	253	6	417	48	299	11	36	5	3.39	0	1.2	0.9
EAVC	Pre	2	263	6	415	48	306	11	35	5	3.30	0	1.0	0.9
EAVC	Pre	3	264	7	405	52	311	12	40	5	3.28	0	0.6	1.0
EAVC	Pre	4	261	7	410	52	306	12	35	5	3.32	0	1.2	1.0
EAVC	Pre	5	263	7	386	52	305	12	33	5	3.34	0	0.7	1.0
EAVC	Post	1	265	6	466	48	314	11	40	5	3.22	0	1.4	0.9
EAVC	Post	2	262	6	490	48	319	11	48	5	3.18	0	1.6	0.9
EAVC	Post	3	264	7	434	52	316	12	38	5	3.20	0	1.1	1.0
EAVC	Post	4	266	7	398	52	306	12	32	5	3.29	0	1.0	1.0
EAVC	Post	5	268	7	434	52	324	12	40	5	3.12	0	0.7	1.0
Existing	Pre	1	247	7	513	52	301	12	44	5	3.42	0	2.2	1.0
Existing	Pre	2	262	7	522	52	316	12	43	5	3.18	0	3.1	1.0
Existing	Pre	3	263	7	408	52	320	12	42	5	3.20	0	0.4	1.0
Existing	Pre	4	267	6	418	48	322	11	43	5	3.18	0	0.6	0.9
Existing	Pre	5	263	7	439	58	318	12	45	5	3.23	0	0.8	1.1
Existing	Post	1	268	7	498	52	321	12	48	5	3.16	0	1.2	1.0
Existing	Post	2	275	7	550	52	339	12	50	5	3.00	0	2.4	1.0
Existing	Post	3	275	7	499	52	331	12	48	5	3.07	0	2.6	1.0
Existing	Post	4	276	6	511	48	340	11	47	5	2.99	0	2.2	0.9
Existing	Post	5	263	7	508	58	340	12	58	5	3.05	0	2.7	1.1
	p-value		0.3910		0.5767		0.7691		0.4259		0.7481		0.4823	

A-4: Result of the five-minute PVT: main effects and two-way interactions

A-4a: Time of day

	Time of Day				
PVT Parameter	**Pre-Shift**	**(SE)**	**Post-Shift**	**(SE)**	**p-value**
Mean RT (ms)	305.77	9.90	321.74	9.90	0.0212**
Mean 1/RT	3.32	0.09	3.16	0.09	0.0272**
Variability or RT (ms)	39.04	3.91	45.76	3.91	0.0062**
Fastest 10% RT (ms)	257.43	4.53	268.33	4.53	0.0129**
Slowest 10% RT (ms)	443.79	35.67	471.12	35.67	0.3179
# of Lapses	0.63	0.29	0.92	0.29	0.2589

A-4b: Day of Workweek

	Day of Work Week										
PVT Parameter	**1**	**(SE)**	**2**	**(SE)**	**3**	**(SE)**	**4**	**(SE)**	**5**	**(SE)**	**p-value**
Mean RT (ms)	305.56	10.42	315.91	10.42	314.72	10.50	314.50	10.42	318.07	10.74	0.3693
Mean 1/RT	3.32	0.10	3.21	0.10	3.24	0.10	3.23	0.10	3.21	0.10	0.4276
Variability of RT (ms)	45.05	4.37	44.75	4.37	43.64	4.40	37.84	4.37	40.74	4.49	0.1565
Fastest 10% RT (ms)	255.69	5.43	263.78	5.43	263.85	5.47	267.51	5.43	263.56	5.80	0.2167
Slowest 10% RT (ms)	506.45	40.95	471.51	40.95	446.19	42.39	425.14	40.92	437.99	44.21	0.2992
# of Lapses	0.63	0.36	0.97	0.36	0.89	0.37	0.47	0.36	0.93	0.39	0.6576

A-4c: Seat Type

	Seat Type				
PVT Parameter	**Existing**	**(SE)**	**EAVC**	**(SE)**	**p-value**
Mean RT (ms)	321.01	10.08	306.50	10.06	0.0618*
Mean 1/RT	3.18	0.09	3.31	0.09	0.0513*
Variability of RT (ms)	48.07	3.91	36.73	3.91	0.0054**
Fastest 10% RT (ms)	264.53	4.63	261.22	4.60	0.1655
Slowest 10% RT (ms)	496.75	38.51	418.16	38.18	0.0956*
# of Lapses	1.02	0.34	0.53	0.33	0.3089

A-4d: Seat Type by Time of Day

		Time of Day				
PVT Parameter	**Seat**	**Pre-Shift**	**(SE)**	**Post-Shift**	**(SE)**	**p-value**
Mean RT (ms)	Existing	309.99	10.37	332.03	10.37	0.029**
	EAVC	301.55	10.34	311.44	10.34	
Mean 1/RT	Existing	3.28	0.10	3.08	0.10	0.072*
	EAVC	3.36	0.10	3.25	0.10	
Variability of RT (ms)	Existing	44.29	3.98	51.86	3.98	0.579
	EAVC	33.80	3.98	39.66	3.98	
Fastest 10% RT (ms)	Existing	256.28	4.71	272.79	4.71	0.002**
	EAVC	258.58	4.68	263.86	4.68	
Slowest 10% RT (ms)	Existing	475.86	42.73	517.63	42.73	0.590
	EAVC	411.71	41.94	424.61	41.94	
# of Lapses	Existing	0.68	0.38	1.37	0.38	0.090*
	EAVC	0.59	0.37	0.48	0.37	

A-4e: Seat Type by Day of Workweek

PVT Parameter	Seat	Day of Workweek										p-value
		1	(SE)	2	(SE)	3	(SE)	4	(SE)	5	(SE)	
Mean RT (ms)	**Existing**	306.44	11.27	325.16	11.27	319.36	11.27	329.38	10.90	324.70	11.77	0.025**
	EAVC	304.68	10.90	306.67	10.90	310.08	11.26	299.61	11.26	311.44	11.30	
Mean 1/RT	**Existing**	3.31	0.11	3.11	0.11	3.20	0.11	3.11	0.10	3.17	0.11	0.064*
	EAVC	3.33	0.10	3.31	0.10	3.28	0.11	3.35	0.11	3.26	0.11	
Variability of RT (ms)	**Existing**	50.73	4.70	50.22	4.70	47.92	4.70	45.16	4.57	46.35	4.80	0.835
	EAVC	39.36	4.57	39.27	4.57	39.36	4.72	30.53	4.72	35.13	4.75	
Fastest 10% RT (ms)	**Existing**	253.64	5.90	266.69	5.90	267.11	5.91	271.96	5.64	263.27	6.45	0.141
	EAVC	257.74	5.64	260.86	5.64	260.60	5.91	263.06	5.90	263.85	6.02	
Slowest 10% RT (ms)	**Existing**	589.36	53.98	529.66	53.98	457.38	53.96	442.65	49.12	464.69	59.95	0.390
	EAVC	423.54	49.12	413.36	49.12	434.99	53.87	407.62	53.88	411.30	53.60	
# of lapses	**Existing**	1.17	0.50	1.53	0.50	0.77	0.50	0.80	0.45	0.84	0.55	0.224
	EAVC	0.10	0.45	0.40	0.45	1.01	0.49	0.14	0.49	1.02	0.49	

A-4f: Time of Day by Day of Workweek

PVT Parameter	Time	Day of Work Week										p-value
		1	(SE)	2	(SE)	3	(SE)	4	(SE)	5	(SE)	
Mean RT (ms)	**Pre-Shift**	297.03	10.91	305.74	10.91	311.36	11.02	308.30	10.90	306.42	11.34	0.334
	Post-Shift	314.10	10.91	326.08	10.91	318.09	11.02	320.69	10.90	329.71	11.34	
Mean 1/RT	**Pre-Shift**	3.41	0.10	3.30	0.10	3.28	0.10	3.29	0.10	3.32	0.11	0.609
	Post-Shift	3.23	0.10	3.13	0.10	3.20	0.10	3.17	0.10	3.10	0.11	
Variability of RT(ms)	**Pre-Shift**	43.59	4.63	39.94	4.63	40.76	4.69	37.32	4.64	33.60	4.76	0.078*
	Post-Shift	46.50	4.63	49.55	4.63	46.51	4.69	38.36	4.64	47.88	4.76	
Fastest 10% RT (ms)	**Pre-Shift**	246.97	5.68	257.88	5.68	259.94	5.75	261.91	5.68	260.44	6.08	0.281
	Post-Shift	264.41	5.68	269.67	5.68	267.76	5.75	273.11	5.68	266.68	6.08	
Slowest 10% RT (ms)	**Pre-Shift**	528.03	49.52	471.57	49.52	406.86	51.64	415.07	49.48	397.42	54.72	0.537
	Post-Shift	484.87	49.52	471.45	49.52	485.52	51.64	435.20	49.48	478.57	54.72	
# of Lapses	**Pre-Shift**	0.68	0.43	1.05	0.43	0.45	0.45	0.21	0.43	0.77	0.49	0.569
	Post-Shift	0.58	0.43	0.88	0.43	1.33	0.45	0.73	0.43	1.09	0.49	

A-5: Student T-test of Pre-shift between seat types over workweek

Level	Letter				Least Sq Mean
Existing, Day 4	A		C		321.67769
Existing, Day 3	A	B	C		320.41056
Existing, Day 2	A	B			319.19602
Existing, Day 5	A	B	C	D	316.30522
EAVC, Day3	A	B	C	D	315.48746
EAVC, Day 4		B		D	306.84700
EAVC, Day 5	A	B	C	D	306.54682
EAVC, Day 2			C	D	306.44899
Existing, Day 1				D	301.76793
EAVC, Day1				D	299.17646

B-1: Information Letter

February 2015

Title of project: The Effects of Reducing Whole-body Vibration Exposure on Truck Drivers' Vigilance: A Pilot Study

Dear potential participant:

This is an invitation letter to participate in a pilot study conducted by Bronson Du from the University of Waterloo. This pilot study is funded and sponsored by Bose Corporation and will be supervised by Dr. Philip Bigelow from the University of Waterloo. We would like to provide you with more information about this project and what your involvement would include if you decide to take part.

What is the purpose of this study?

The purpose of this pilot research is to get a sense of how vibration of the entire body affects alertness, which is particularly important in driving for long periods of time.

What will you be asked to do?

Participation in this study is voluntary. If you decide to volunteer, you will be asked to complete a 10-minute reaction time task on a tablet immediately before and after your work shift. This will take place over 10 days while using two different truck seats. In addition to the reaction time task, you will also be asked about your coffee consumption, rest breaks and hours of sleep at the end of each shift. For the first five days, you will be driving your truck with its current seat. Afterwards, a new seat will be installed into your truck and you will carry out your regular duties for the next five days with the new seat.

We would also like to measure the vibration of each truck seat. In order to measure vibration throughout the day, a thin rubber seat pad with a motion sensor will be secured onto your seat for an entire work shift. You will be asked you sit on the rubber seat pad for your entire shift. You and the researcher will arrange a date for the set up and take down the of the vibration measurement tools.

Figure 13: Here is a picture of the rubber seat pad that you will be sitting on. The rubber can bend and conform to your buttocks.

In total the study will take approximately 5 hours of your time outside of your regular work shift.

In summary you will be asked to:

1. Complete an initial questionnaire that asks for your age, weight, height and health as well as information about your job.
2. Meet with the researcher at the beginning and end of each day to complete…
    - a 10-minute reaction time task on a tablet immediately before and after each shift for 10 days
    - a 1-minute questionnaire that asks about your coffee intake, sleep, pain and breaks during the day for 10 days.
3. Have the vibration levels of your truck seat measured for 2 full work shifts, 1 measurement per seat.

Are there any risks in participating in the study?
There are no known or anticipated risks in participating in this study. You will be parked at the fleet terminal when you complete the reaction time task and the questionnaire. However, you will have to arrive and stay 15 minutes before and after your shift to perform the reaction time task on the tablet and the questionnaire. For the days that you have agreed to have the vibration levels of your truck seat measured, you will have to arrive 20 minutes prior to your shift.

Will I be remunerated for my time?
Yes, Herzig Hauling will reimburse you for up to 5 hours of your time. The remuneration will be added to your pay cheque. Furthermore, in appreciation of your participation in the pilot study, you will get to keep the tablet upon completion of the study. The amount received is taxable. It is your responsibility to report this amount for income tax purposes.

How does this research benefit society?
Driver alertness is vital in maintaining road safety. Keeping in mind that there are many factors that affect alertness, we hope to explore one potential factor. With this pilot study, we hope to learn more about how vibration of the body affects driver alertness. With this information, certain seats can be recommended to trucks that may help improve alertness.

Will the information I provide in the study be kept confidential?
Yes, all information you provide is considered to be completely confidential meaning that people outside of the research team will not be able to associate you with any of the results from the study or the questionnaires. All data will not contain personal identifiers; participants will only be identified with a numeric code. Also, in order to protect the confidentiality of your reaction times, only the averages of the participants will be reported. Your name will not appear in any report resulting from this study. However, due to the small amount of participants, there is a greater risk that fellow workers and managers will know that you are participating in the study.

Electronic data will be kept on the researcher's password-protected laptop. The electronic data will also be backed up onto a hard drive stored in a locked cabinet in BMH 2307 at the University of Waterloo along with the questionnaires for 1 year after the data analysis has been completed. After which, the data will be deleted and shredded.

What if I don't want to participate anymore?

You can decline to participate in any part of this study or withdraw from this study at any time without any negative consequences or loss of remuneration by simply telling the researcher "I would not like to participate in this study any longer." You may remove the vibration measurement pad at any time or not complete the reaction time task or survey at any time point. Withdrawal from the study will not impact your work or relationship with your employer.

Questions and Research Ethics Clearance

If after receiving this letter, you have any questions about this study, or would like additional information to assist you in reaching a decision about participation, please feel free to ask me, the student investigator at 917-222-8341 or b2du@uwaterloo.ca or the faculty supervisor, Dr. Philip Bigelow at 1-519-888-4567 Ext. 38491 or pbigelow@uwaterloo.ca.

I would like to assure you that this study has been reviewed and received ethics clearance through a University of Waterloo Research Ethics Committee. However, the final decision about participation is yours. If you have any comments or concerns resulting from your participation in this study, please contact Dr. Maureen Nummelin, the Director, Office of Research Ethics, at 1-519-888-4567, Ext. 36005 or maureen.nummelin@uwaterloo.ca.

I very much look forward to speaking with you and thank you in advance for your assistance in this project.

Sincerely,

Bronson Du

University of Waterloo
School of Public Health and Health Studies
b2du@uwaterloo.ca

B-2: Consent Form

By signing this consent form, you are not waiving your legal rights or releasing the investigator(s) or involved institution(s) from their legal and professional responsibilities.

I have read the information presented in the information letter about a study being conducted by Bronson Du under the supervision of Dr. Philip Bigelow of the Department of School of Public Health and Health Systems at the University of Waterloo. I have had the opportunity to ask any questions related to this study, to receive satisfactory answers to my questions, and any additional details I wanted. I am aware that I may withdraw from the study without any impact on my work or relationship with my employer at any time by advising the researchers of this decision.

I have made this decision based on the information I have read in the Information Letter. All the procedures, any risks and benefits have been explained to me. I have had the opportunity to ask any questions and to receive any additional details I wanted about the study. If I have questions later about the study, I can ask one of the researchers:

Bronson Du	Email: b2du@uwaterloo.ca
Dr. Philip Bigelow	Email: pbigelow@uwaterloo.ca

This project has been reviewed by, and received ethics clearance through a University of Waterloo Research Ethics Committee. I was informed that if I have any comments or concerns resulting from my participation in this study, I may contact the Director, Office of Research Ethics, at 1-519-888-4567, Ext. 36005 or at maureen.nummelin@uwaterloo.ca.

With full knowledge of all foregoing, I agree, of my own free will, to participate in this study.

Name of Participant ______________________________

Date ______________________________

Signature of Participant ______________________________

Signature of Witness ______________________________

B-3 Demographics Questionnaire

ID:_________

Age: __________ Height: _________ Weight: _____________

1. How long have you worked in the trucking industry? _____Years _____Months
2. How long have you worked at this company? _____Years _____Months
3. What is your normal work shift? (check then fill in normal shift start and end time)
   - ☐ Day shift (early morning to evening): __________________________
   - ☐ Swing shift (afternoon to late night): ___________________________
   - ☐ Night shift (late evening to early morning):______________________
   - ☐ Long haul: ____
   - ☐ Other: ____
4. On average, how many hours do you work in a normal week? _____ hours/week
5. How many hours are spent driving? _____ hours/week
6. On average, for work, how many miles would you estimate you drive your truck in a typical year? ________________ miles/year
7. On average, how many miles would you estimate you drive outside of work in a typical year (commuting to work, vacations, other driving, etc)?

   ________________ miles/year

8. Has you doctor ever told you that you have any of the following?

	Yes	No	Don't Know
High Blood Pressure			
Heart Attack			
Low Back Disease or Spine Problem			
Elevated Cholesterol Level			
Arthritis			
Asthma			
Diabetes / Sugar in Urine			
Sciatica			
Lumbago			
Spinal Fracture			
Back Sprain or Strain			
Hernia			
Digestive Disorder			
Circulatory Problems			
Reynaud's Syndrome			
Urinary Disorder			
Vestibular Disturbances			

Thank You!

Date: ________________

B-4: Pre-Shift Questionnaire

Time: ________________

ID#:____

1. At what time did you sleep last night? _____:_____ am / pm
2. At what time did you wake up? _____:_____ am / pm
3. 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

Mileage: ________________

Destination: ______________

Estimated return time: ______________

Date: ________________

B-5: Post-Shift Questionnaire

Time: ________________

ID#: ____

Caffeine Intake

1. Did you drink consume any caffeinated beverages today? Y / N

2. If yes, what did you drink (coffee, tea, energy drink, soda) and what time did you drink it?

1st Drink: __________________ _____:_____ am / pm

2nd Drink: __________________ _____:_____ am / pm

3rd Drink: __________________ _____:_____ am / pm

4th Drink: __________________ _____:_____ am / pm

5th Drink: __________________ _____:_____ am / pm

Work Shift

3. Did you take any naps today? Yes / No

4. If yes, at what time? _____:_____ am / pm

5. What time did you take your **MEAL** breaks today?

_____:_____ am / pm **to** _____:_____ am / pm

_____:_____ am / pm **to** _____:_____ am / pm

6. What time did you take your **REST** breaks today?

_____:_____ am / pm **to** _____:_____ am / pm

_____:_____ am / pm **to** _____:_____ am / pm

7. 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

Mileage: _________________

Next Shift: ______________

B-6: Bose Seat WBV Measurement Protocol

Subject ID: _________ **Study site:** ____ **Investigator:** ______ **Date:** ____ /____ /____

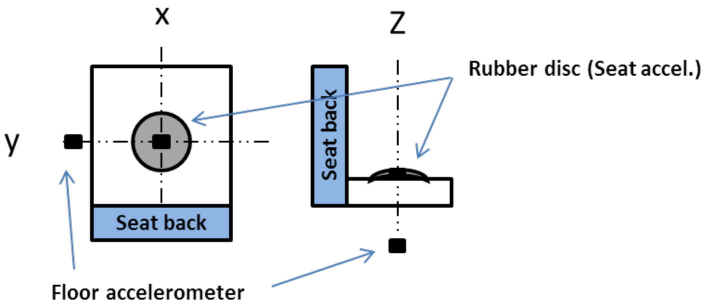
Subject First Name: _______________________________ **Truck#**________ **M#**_______ **Time Point:** ___

Key Location: ________________ **Shift Start Time:** ____________ **Shift End Time (if IM):** ____________

APPARATUS

Vehicle	**Make:** ______________ **Model:** ______________ **Year:** ____________ **Start Odometer**_______________**End Odometer**____________________
Seat	**AR / BR**

Data Collection

	Installation	
		
	Turn on the Rion data logger and check the settings	
	Settings: Range: 3.00 x 10^2 m/s^2 (3V) Input: CCLD, HPF Off, LPF Off, Sens PICK Frequency Range: 500Hz Sampling Freq: x2.56Hz Check Date/Time	
	Seat accelerometer (X, Y, Z) => Ch. 1, 2, 3	
	8-channel logger	**Floor** accelerometer (X, Y, Z) => Ch. 4, 5, 6
	4-channel logger	**Floor** accelerometer (Z) => Ch. 4
	Press record - time (__ __ : __ __)	
	Oscillate all accelerometers (3x X direction – away 1^{st}, 6x Y direction right 1^{st}, 9x Z direction up 1^{st})	
	Post measurement	
	Turn off the Rion data logger and GPS (__ __ : __ __)	
	Away from site	
	Download GPS, save as .csv .gpx and .kml with name RIDE_3M_M000_PDX_T00000_AIR_GPS00_20140131, prntscn of map (paste into paint)	
	Move Rion file and save as RIDE_3M_M000_PDX_T00000_AIR_R0_20140131	
	Check GPS and Rion files for quality, process to power file, and backup on iDrive (ergolab_niosh)	
	Recharge Rion internal batteries (C or AA)	
	Recharge GPS	
	Recharge external batteries	

SHIP WBV HARDWARE

Logger ID	Model	Channel	CF card #	Battery	Seat		Floor		GPS
					Accel. #	Cable #	Accel. #	Cable #	Unit #
#6	RION DA-40	8	6	12	A9	1004	A3	22	6
#7	RION DA-40	8	7	15	A10	17	S1	1000	9
									16
									17

B-7: Feedback Letter

February 27, 2015

Dear [insert participant's name]

Thank you for your involvement in this study entitled ***The effects of Reducing Whole-body Vibration Exposure on Truck Drivers' Vigilance: A Pilot Study.*** The purpose of this pilot research is to learn more about how vibration of the whole body affects a persons' ability to stay alert over a work shift.

The results from this study will help researchers make scientifically-based recommendations to truck drivers and fleet companies who are planning to purchase new truck seats. Your participation in this study is appreciated and the information we learn will be quite valuable. The data will be kept confidential to the research team and will be disposed one year after the data has been analyzed. It will take approximately 4 months to analyze the data and write up the full report. Once all the data are collected and analyzed for this project, I plan on sharing this information with the research community through seminars, conferences, presentations, and journal articles. If you are interested in receiving a summary of your reaction times between the two seats, please provide your email address, and when the study is completed, anticipated by June 30, I will send you the information. You employer will be provided with a summary and the description of individual participants will not be included. A summary of the study results will be shared with Bose Corporation as well.

In the meantime, if you have any questions about the study, please do not hesitate to contact my faculty supervisor, Dr. Philip Bigelow, or myself by email or telephone as noted below. As with all University of Waterloo projects involving human participants, this project was reviewed by, and received ethics clearance through a University of Waterloo Research Ethics Committee. Should you have any comments or concerns resulting from your participation in this study, please contact Dr. Maureen Nummelin, the Director, Office of Research Ethics, at 1-519-888-4567, Ext. 36005 or maureen.nummelin@uwaterloo.ca.

Regards,

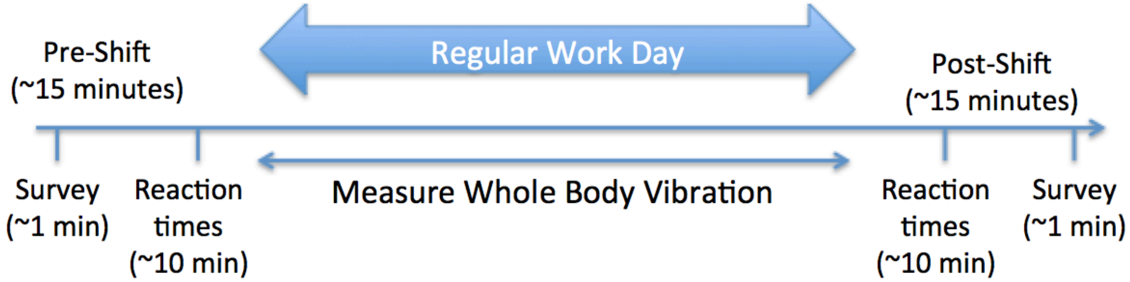
Bronson Du	**Dr. Philip Bigelow**
School of Public Health and Health Studies	School of Public Health and Health Studies
University of Waterloo	University of Waterloo
b2du@uwaterloo.ca	pbigelow@uwaterloo.ca
647 502 5376	1-519-888-4567, Ext. 38491

C-1: Psychomotor Vigilance Task (PVT)

Standard Operations Protocol for BOSE Seat Study

Location and Timing

The PVT is to be performed immediately before the driver leaves for his work-shift and immediately after the driver has returned to the terminal parking. The PVT is performed using a tablet application in the drivers' vehicles. In the pre-shift conditions, the researcher will be meet with the driver by their trucks and the PVT will be administered after the questionnaire. In the post-shift condition, the researcher will administer the PVT immediately after the driver parks his truck in the terminal. The researcher will meet the driver at the parking spot and administer the PVT to the driver.



Set-Up

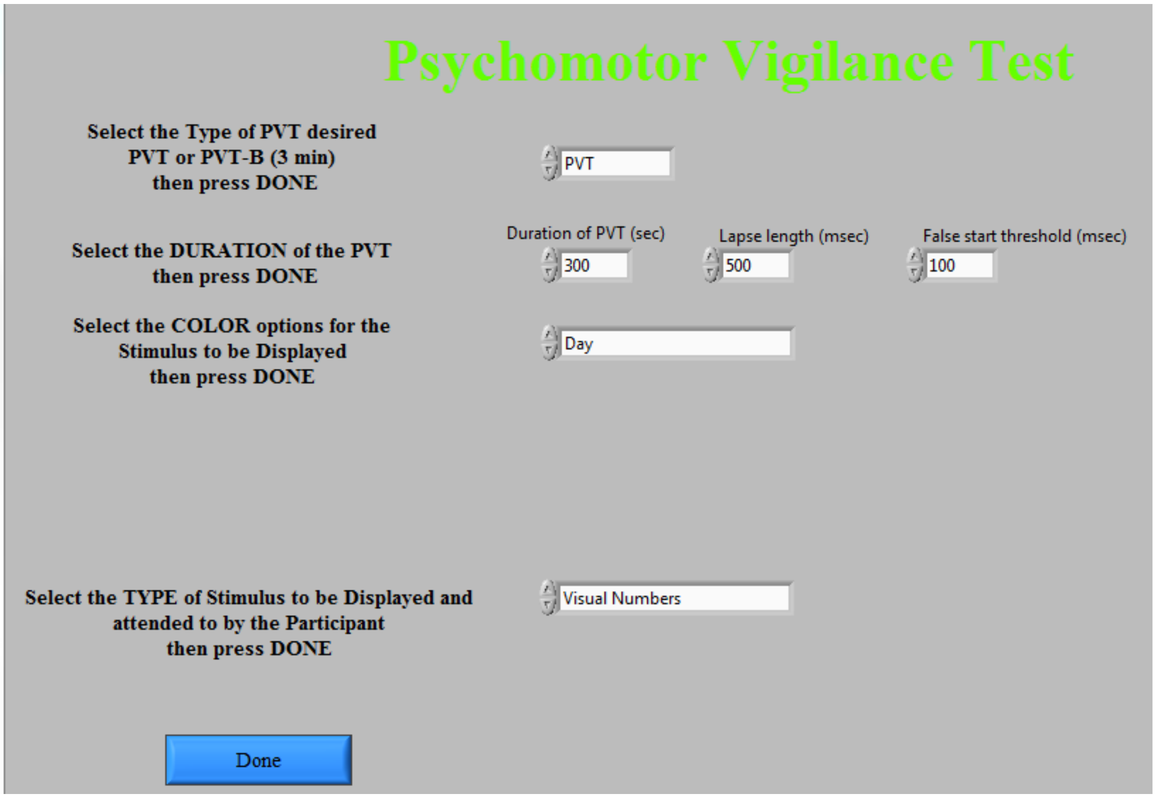
The driver should be seated in the passenger seat of his cabin while performing the test. The tablet should be resting on a steering wheel desk. The driver is asked to use the index finger of their dominant hand to press on the space bar.

Running the PVT

The tablet is placed into a portfolio with an external keyboard. Ensure that the keyboard is plugged into the tablet before starting the PVT application. The set-up of the application should be ready prior to meeting with the driver.

1. To start the PVT app, first unlock the tablet by pressing the button located on the bottom right corner.
2. Swipe left on the touchscreen and select the search icon. Type "PVT app" into the search bar. Launch PVT app once you have found it.

3. Upon running the application, it will ask you where you want to save the output files. Please select “PVTdata” folder on the desktop.
4. Select the appropriate driver number, pre or post shift, and seating condition by using the up and down arrows next to each box. **The time of each loop should remain at 2 ms.** Press “Done” when you have selected all of the appropriate test characteristics.
5. The name of the output files should appear next. If you are satisfied with this file name, press “Done”
6. Next is a page for the set-up of the PVT Task. Below are the PVT settings that you should set for the purpose of this study.



Psychomotor Vigilance Test

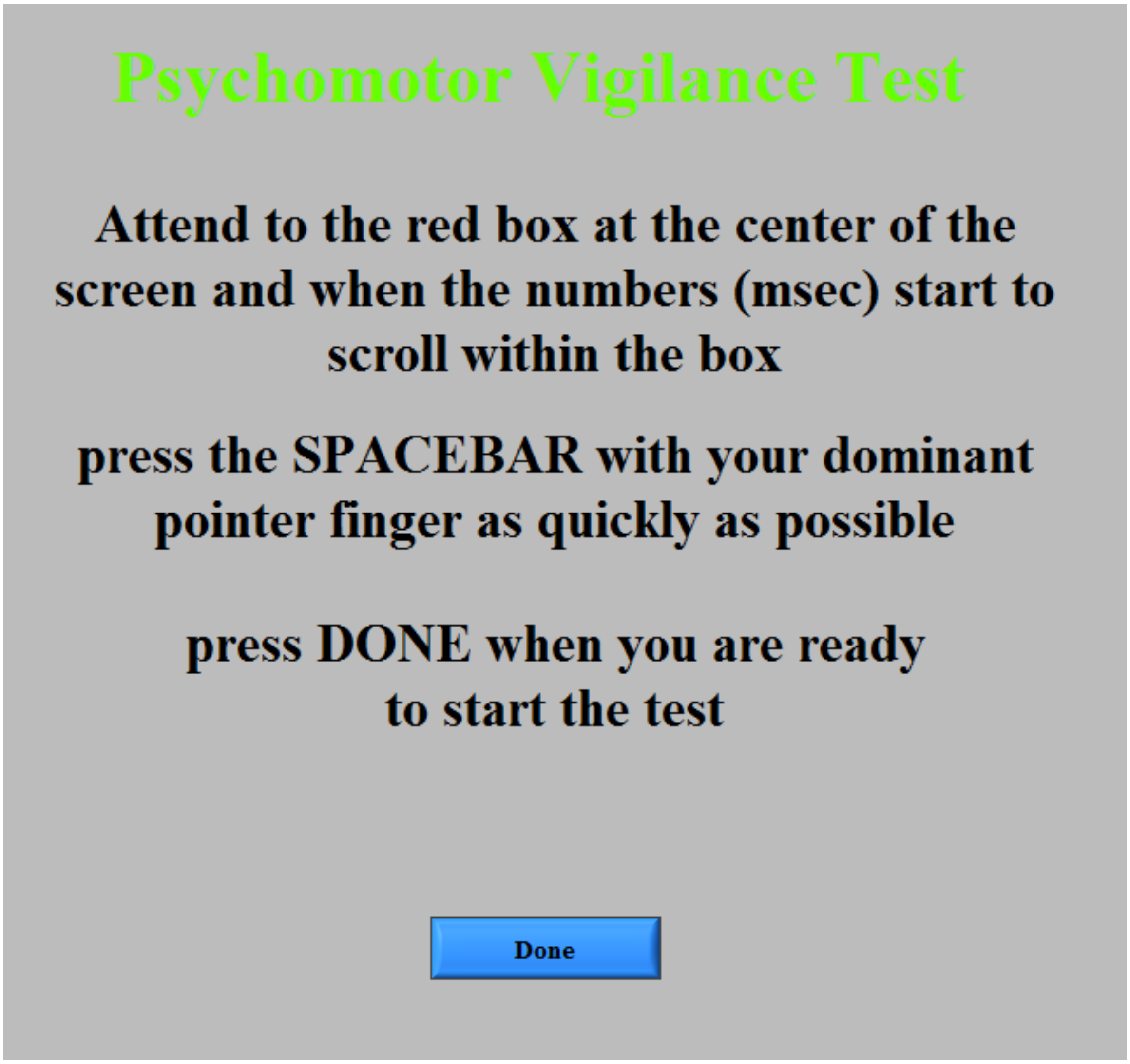
Select the Type of PVT desired
PVT or PVT-B (3 min)
then press DONE: PVT

Select the DURATION of the PVT
then press DONE:
Duration of PVT (sec): 300
Lapse length (msec): 500
False start threshold (msec): 100

Select the COLOR options for the
Stimulus to be Displayed
then press DONE: Day

Select the TYPE of Stimulus to be Displayed and
attended to by the Participant
then press DONE: Visual Numbers

7. Press the “Done” button if all settings are completed.
8. A pop-up will appear to ask if all the settings are correct. If all settings are correct, press the “Correct” button.
9. Once you see the screen shown in the screenshot below, allow the participant to press the “Done” button, this will start the PVT.
10. Notify the driver: “You are going to see a red box in the center. When that red box turns white and a timer starts, I want you to press the space bar as fast as you can. This test will last for a total of 10 minutes. Please let me know when you are done, I will be waiting outside your truck. Try to stay as focused as possible and do your best. Thanks.”



Psychomotor Vigilance Test

Attend to the red box at the center of the screen and when the numbers (msec) start to scroll within the box

press the SPACEBAR with your dominant pointer finger as quickly as possible

press DONE when you are ready to start the test

Data Download

11. Retrieve the tablet once the driver has completed the PVT. Do not allow the driver to hang on to the tablet.
12. Connect the tablet with you computer and locate the PVT data folder from the tablet
13. Drag and Drop the ‘PVT data’ folder the data folder depending on the seat type and driver ID