Research Report

Evaluating the Impact of Whole-Body Vibration (WBV) on Fatigue and the Implications for Driver Safety

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Preface

Driver fatigue is a significant contributor to motor vehicle accidents and fatalities, although the exact share of those events attributable to fatigue is still uncertain. In 2013, accidents involving heavy trucks killed more than 3,944 people in the United States, over 80 percent of whom were not in the truck (National Highway Transportation Safety Administration, 2015). There are numerous factors that contribute to driver fatigue among commercial drivers, including shiftwork schedules; high prevalence of alcohol and substance use; extended hours; comorbid medical conditions, such as pain, and high prevalence of sleep disorders. Many of these factors have been studied extensively in the trucking industry. Whole-body vibration (WBV) is another potential factor that may contribute to driver fatigue, but which has received little attention. Beginning in January 2015, Bose Corporation and AIG commissioned the RAND Corporation to study the link between WBV and driver fatigue. This report summarizes the findings from RAND's systematic review of the literature on WBV and fatigue and also considers appropriate study designs and methodology that will inform new areas of research focused on improving the safety of truckers and those who share the road with them. The literature review identified 24 studies that examined the impact of WBV on fatigue or sleepiness. The majority of studies (n = 18) found a significant association between WBV and fatigue or sleepiness; however, there are several limitations of the existing literature that preclude definitive conclusions regarding the impact of WBV on these outcomes. Thus, this report concludes with recommendations for future studies to strengthen the evidence base.

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Abbreviations

BAC	blood-alcohol content
CDC	Centers for Disease Control and Prevention
EDS	excessive daytime sleepiness
EEG	electro-encephalograpy
ISO	International Organization for Standardization
MFI	Multidimensional Fatigue Inventory
NHTSA	National Highway Transportation and Safety Administration
NTSB	National Transportation Safety Board
PVT	psychomotor vigilance task
RT	reaction time
RMS	root mean square
SD	standard deviation(s)
SSS	Stanford Sleepiness Scale
WBV	whole-body vibration

1. Introduction

There is considerable evidence linking fatigue, and the overlapping but distinct concept of sleepiness, to motor vehicle crashes and fatalities. As described in greater detail below, *fatigue* or *drowsiness* (which, for our purposes, are used interchangeably) refer to the cognitive, affective, or physical state of tiredness or weariness caused by exertion. *Sleepiness*, a related but distinct term, refers to the physiological propensity to fall asleep. The transportation industry has long recognized the critical importance of fatigue on driver safety. In fact, the National Transportation Safety Board (NTSB) has listed fatigue on its "Most Wanted" list of risk factors, since the list was initiated in 1989 (Lerman et al., 2012). Research in the United States and internationally suggests that fatigue is a major risk factor for road accidents, and that fatigue-related accidents are more common among professional drivers than private drivers (Sagberg et al., 2004).

While there is international consensus that fatigue and sleepiness are critical factors contributing to motor vehicle crashes and fatalities, estimates of the risk attributable to these factors vary widely throughout the literature, with estimates ranging from 2 to 50 percent of crashes (Federal Motor Carrier Safety Administration, 2006; Dinges and Maislin, 2006; Centers for Disease Control and Prevention (CDC), 2013, and NTSB, 1995). For instance, the National Highway Transportation and Safety Administration (NHTSA, 2011) estimates that, over the five-year period between 2005 and 2009, on average 83,000 (1.4 percent) out of 5,895,000 total police-reported motor vehicle crashes (including fatalities, injuries, and property damage only) were caused by fatigued driving. Despite variability in prevalence estimates, the evidence is fairly conclusive that fatigue-related crashes disproportionately involve fatalities as opposed to other causes of crashes. More specifically, NHTSA's data suggest that fatigue-related crashes disproportionately contribute to fatalities on the road—2.5 percent (or 1004 deaths) on average during the five-year recording period. In an earlier (1995) study of single-vehicle trucking crashes in which the driver survived and the previous 96 hours could be reconstructed (in order to derive fatigue estimates), the NTSB found that out of 107 crashes, 58 percent were considered to have fatigue as a probable cause, primarily based on the time of day of the accident (occurring between 10:00 p.m. and 8:00 a.m.) (NTSB, 1995).

There are numerous factors that contribute to driver fatigue and sleepiness, particularly among commercial drivers, including shiftwork schedules; high prevalence of alcohol and substance use (Girotto et al., 2013); extended hours; and comorbid medical conditions, such as pain, and high prevalence of sleep disorders, including obstructive sleep apnea (Häkkänen and Summala, 2000; de Mello et al., 2013; Howard et al., 2004; Heaton, 2005; and Sieber et al., 2014). Many of these factors have been studied extensively in the trucking industry (Philip, 2005; Haraldsson and Åkerstedt, 2001; Kales and Straubel, 2014; Adams-Guppy and Guppy, 2003; and Orris et al., 2005). For instance, a study of long-haul truck drivers in the United States found that the following factors were independently associated with self-reported falling asleep at the wheel: daytime sleepiness, limited rest opportunity, older drivers, those with more years of service, night-time drowsy driving, poor sleep on the road, and symptoms of sleep disorders (McCartt et al., 2000).

As these findings suggest, operator fatigue is typically considered a “people management” issue. In recognition of the considerable safety and public health importance of mitigating operator fatigue, particularly among professional road operators, and the limited success of existing people management approaches, however, there has been increased interest in considering operational environmental factors that may contribute to fatigue, as well as the development of technology to mitigate such causes. In particular, whole-body vibration (WBV) is one such operational factor that may contribute to driver fatigue. Simply stated, WBV is a mechanical wave that, in the case of truck drivers, manifests as the energy transfer from the vehicle travelling on the road surface to the human operator who is in contact with the vibrations (Conway et al., 2007). Such vibrations can take the form of sudden and severe jolts (e.g., in the case of potholes) as well as constant but less intense vibrations caused by the vehicle coming into contact with the normal roughness of the road’s surface. Health risks associated with WBV have been evaluated in diverse types of human operators, including truck drivers, and are measured by International Organization for Standardization (ISO) standards 2631-1 and 2631-5. Mitigation of WBV through electromagnetically active vibration-canceling technology, which has been developed by Bose Corporation, has been put forth as an innovative and potentially high-impact approach to reducing driver fatigue and ultimately reducing fatigue-related crashes.

There are several plausible mechanisms that could account for WBV effects on driver fatigue. In particular, the effects of WBV on driver discomfort and lower back pain are well established (Lings and Leboeuf-Yde, 2000; Tiemessen, Hulshof, and Frings-Dresen, 2008; and Bovenzi, 2010). For instance, studies have shown that WBV elevates spinal load (i.e., static pressure on the soft tissues that can lead to discomfort), causes muscle fatigue, and is linked to the thinning of the intervertebral discs and subsequent disc herniation. Given that pain can increase fatigue, both directly and indirectly, by reducing sleep quality and duration and by exacerbating muscle exertion, WBV may be an important, understudied risk factor for driver fatigue (Moldofsky, 2001, and Lautenbacher, Kundermann, and Krieg, 2006). Moreover, WBV could have a direct impact on driver fatigue by increasing physical stress on the driver and leading to both cognitive and physical exertion, which could impair performance (Conway, Szalma, and Hancock, 2007). On the other hand, some researchers have cautioned that modern technology that reduces noise and vibration in vehicles to enhance driver comfort may have inadvertent consequences for driver safety by contributing to increased monotony, which can contribute to decreased awareness and vigilance, and ultimately increased risk of driver errors and crashes (Sagberg et al., 2004).

In light of these conflicting perspectives, it is essential to synthesize the existing knowledge base to inform evidence-based decisions concerning the potential benefits or consequences of reducing WBV as it relates to driver fatigue and fatigue-related crashes and fatalities in the trucking industry. To our knowledge, however, there has not been a systematic review of the literature focused on the impact of WBV on fatigue.

Organization of Report

Given the importance of identifying novel efforts to mitigate driver fatigue in order to improve driver safety, a critical next step is to develop a more rigorous evidence base to examine possible causal links between WBV and fatigue/sleepiness[1]. The development of such an evidence base would then lead to the next logical step, which would be to examine whether a device designed to reduce driver fatigue/sleepiness could have a measurable, positive impact on driver safety.

Toward this aim and to address knowledge gaps, we conducted a study with three primary goals, which are discussed in each of the chapters in this report. Chapter Two, "Literature Review," reports the results from a systematic review and evaluation of the literature on WBV and fatigue/sleepiness. Chapter Three, "Modeling Estimates provides statistical estimates of the potential impact of reducing vibration on sleepiness and fatigue, and in turn, the effects of reducing fatigue/sleepiness on truck-driver crashes. Chapter Four, "Proposed Research Designs" provides several potential design options for evaluating the relationship between WBV and fatigue/sleepiness or driver safety, with a specific focus on relatively short-term studies (for pragmatic reasons) using appropriate intermediate outcomes that are linked with sleepiness, fatigue, and driver performance. Finally, Chapter 5, "Summary and Implications," synthesizes the findings across the prior chapters in relation to the study aims.

[1] Except where specifically noted throughout the document, and in the definitions that can be found in the methodology section of this report, these terms are used collectively to ensure that our review was inclusive of both of these factors that are directly implicated in driver safety.

2. Literature Review

Methodology

We conducted a systematic review of the literature on WBV and fatigue/sleepiness. A *systematic review* is a critical assessment and evaluation of research studies that address a particular clinical issue. The researchers use an organized method of locating, assembling, and evaluating a body of literature on a particular topic using a set of specific criteria. In the next section, we describe the methodology used to conduct the systematic literature review, including databases used, inclusion/exclusion criteria, and screening process.

Operational Definition of Key Exposure: Whole Body Vibration (WBV)

Before considering how WBV can affect fatigue, sleepiness, and performance, it is useful to first define the parameters for WBV exposure. In general, *vibration* refers to an oscillatory motion around an equilibrium point. It can be studied as a mechanical wave and has five defining characteristics: amplitude, frequency, direction, waveform, and duration. Basic physics background about each of these characteristics is described in Box 1.

Occupational exposure to vibration can be *whole body* and/or *local*. WBV is vibration transmitted from a vibrating surface *on which the body rests,* e.g., a driver's seat or a vibrating floor (Kjellberg, 1990). It is distinct from *local vibration*, in which vibration is applied to a specific part of the body, e.g., hand/arm through vibrating hand tools. The present review focuses on WBV, not local vibration.

Box 1: Parameters Defining Vibrations

The magnitude or amplitude of a vibration can be quantified by its displacement, velocity, or more commonly, its **acceleration**. When a body or object oscillates about a point, it alternately moves and gains velocity in one direction, slows down and comes to a stop at maximum displacement, and then moves and gains velocity in the opposite direction, and so on and so forth. This means that the object is accelerating and decelerating, first in one direction and then in the opposite direction. The unit for acceleration is meter per second per second (m/s^2).

Frequency refers to the number of complete oscillation cycles in a given amount of time. The unit for frequency is hertz (Hz) (cycles per second). The effects of whole-body vibration are known to be greatest at lower frequencies, from 0.5 to 100 Hz (Griffin, 2011). As points of comparison, vibration frequencies below about 0.5 Hz can cause motion sickness; and occupational exposure to hand-held power tools, which produce vibration as high as 1,000 Hz, can be a health hazard.

The oscillatory motion can take place in three translational **directions** and three rotational directions (i.e., there are six degrees of freedom). For a seated person, the translational axes are front and back (*x*), side to side (*y*), and up and down (*z*). Rotations around the *x*-, *y*- and *z*-axes are known as roll, pitch, and yaw, respectively. In truck driving, the up-and-down movement tends to dominate.

On other vehicles, such as ships and aircrafts, vibration could be in many directions at once.

Waveform refers to the shape of the motion. A common vibration waveform is continuous sinusoidal vibration, i.e., a wave in the shape of the sine function, although real-life vibrations tend to be random (noncontinuous, and/or non-periodical). Furthermore, shock/transient WBV may also occur when the vehicle travels over, for example, bumpy roads or potholes.

Finally, the fifth characteristic of the vibration stimulus is exposure **duration**. Generally, the longer the exposure, the more impact on performance.

Operational Definition of Key Outcomes: Fatigue and Sleepiness

As mentioned, fatigue and sleepiness are overlapping but distinct constructs that are both associated with increased risk of motor vehicle crashes. A critical first step in conducting the literature review, as well as for informing operational strategies and policymaking, is to operationally define the key outcomes (fatigue/sleepiness), particularly given that there is considerable ongoing debate in the literature concerning the definition of fatigue and the relative importance of fatigue versus sleepiness for driver safety (Phillips, Nævestad, and Bjørnskau, 2015). *Fatigue* can be defined as the cognitive, affective, or physical state of tiredness or weariness caused by exertion. *Sleepiness,* on the other hand, is operationally defined as the propensity to fall asleep and is largely an involuntary process governed by two physiological processes: circadian processes (i.e., time of day effects) and homeostatic processes (i.e., the balance between the amount of sleep a person has had and how long they have been awake). *Circadian rhythms*, or “body clocks,” are 24-hour rhythms that control humans’ (and other species) sleep-wake cycles and have a direct influence on the propensity to fall asleep (Åkerstedt, 1995). The peaks in circadian-driven sleepiness occur between 2:00 a.m. and 6:00 a.m. and 2:00 p.m. and 4:00 p.m. In fact, fatigue-related traffic crashes align closely with these circadian-driven peaks in sleepiness. Given that the peak in crashes actually occurs around midnight, somewhat earlier than that which would be expected by circadian effects alone, however, homeostatic processes (i.e., extended wakefulness) also contribute to fatigue-related road crashes.

Given the clear importance of sleepiness to driver safety, some researchers have argued that sleepiness is the most important contributor to fatigue-related motor vehicle crashes (Dawson and McCulloch, 2005), and subjective measures of sleepiness may be the most salient for evaluating driver safety. Others however, particularly within the U.S. transportation system, have advocated for a broader definition of fatigue (which includes, but is not limited to, sleepiness), given that both fatigue and sleepiness are implicated in driver performance and wakefulness. Recognizing these inconsistencies in the terminology and with the goal of evaluating the literature on WBV’s effects on driver fatigue and ultimately risk of fatigue-related crashes, our review focuses on this broader definition, which incorporates measures of fatigue and sleepiness.

Both fatigue and sleepiness can be measured subjectively by directly inquiring about these subjective states or objectively via performance measures (e.g., reaction times) or other physiological assessments (e.g., brain-wave activity as measured by electro-encephalography; EEG). Fatigue can be measured subjectively by the individual's report that "I am tired" or by endorsing high levels on a fatigue scale (e.g., the Multidimensional Fatigue Inventory [MFI]) (Smets et al., 1995). Objectively, fatigue is generally defined by degraded performance on various tasks that require sustained attention and/or vigilance. Among the objective fatigue measures, the psychomotor vigilance task (PVT) (Basner and Dinges, 2012) is one of the most widely used and well-validated performance metrics. The PVT requires pressing a button in response to the presentation of a visual stimulus as soon as the stimulus appears. Robust research demonstrates that extended wakefulness and cumulative sleep restriction results in an increase in reaction time (the time, measured in milliseconds, taken to respond to the stimulus), a decrease in response speed, and an increase in lapses (Van Dongen et al., 2003, and Dinges and Maislin, 2006). For pragmatic reasons, the PVT is particularly favored because it is relatively short (as compared to driving simulator tasks), simple to perform, and has only minor practice effects. Other performance measures (e.g., lane drifting assessed via driving simulator tasks) are arguably the most relevant for considering factors that influence driver safety, as they more closely capture the complex task of driving (Baulk et al., 2008).

Sleepiness can also be measured subjectively (which assesses the individual's propensity to fall asleep in a variety of situations, e.g., Epworth Sleepiness Scale; Johns, 1991); objectively through polysomnography[2] (i.e., a "sleep study"); or behaviorally through measures such as wrist actigraphy, which provides a behavioral measure of sleep as indicated by inactivity[3].

Data Sources for Literature Review

Five electronic databases were searched: Scopus, MEDLINE, PsycINFO, Military & Government Collection, and the Transportation Research Board's integrated database (TRID). The search was executed on January 23, 2015. We did not apply a limit on publication year, so theoretically the search went back to 1806 for MEDLINE, 1887 for PyscINFO, and 1956 for Military & Government Collection. In practice, the oldest paper that was identified was from 1958. Reference lists of included studies were also used to identify additional studies.

To ensure the list of articles we collected was comprehensive, we also consulted with subject-matter experts for relevant sources that were independent from our database search. We also reviewed the reference list of a scholarly thesis from the University of Waterloo (provided to us by the sponsor, with permission from the primary author) on the topic of "Effects of

[2] *Polysomnography*, also called a sleep study, is used to diagnose sleep disorders and includes a combination of recordings of brain-wave activity, eye-muscle movements, and peripheral-limb movements as measured by electroencephalographic (EEG), electrooculographic (EOG), and electromyographic (EMG) activity, respectively.

[3] Actigraphy is a noninvasive for monitoring human rest/activity cycles. For the measurement of sleep, actigraphy involves a wristwatch-sized device, called an *actigraph*, which is worn on the wrist, for a period of days and up to a number of weeks. Actigraphs measure gross motor activity, which can be used to derive behavioral measures of sleep.

Whole-body Vibration on Driver Vigilance" to ensure that our search was inclusive of articles covered in this recent literature review.

Inclusion Criteria

This review focused on the link between WBV and driver fatigue/sleepiness, as operationally defined above. Only English-language, published, and peer-reviewed manuscripts or government reports were included. To be inclusive of constructs that are related to fatigue/sleepiness, we also included search terms for opposing constructs, such as "alertness"/"wakefulness". Papers that examined the relationship between WBV exposure and at least one fatigue or sleepiness-related outcome were included. Outcomes included subjective measures of fatigue/sleepiness or alertness, as well as objective measures of these constructs, including cognitive or visual performance or other physiological indicators of fatigue/sleepiness.

Exclusion Criteria

Dissertations, book chapters, and conference abstracts were not included, in order to ensure a minimal threshold for quality based on peer review. Studies about hand vibration specifically (e.g., in construction workers) were also excluded, as this is considered a physiologically different type of vibration exposure. Similarly, studies from the sports-conditioning literature, which focuses on the impact of vibration on athletic performance, were also excluded, as this is also a physiologically different exposure. Finally, articles that examined shocks or acute and transient WBV (e.g., when driving over rumble strips) were excluded. Severe shocks or transient WBV has been shown to increase wakefulness (e.g., Hattori et al., 1987) and are unrepresentative of the more monotonous and constant vibrations that are the focus of the current report.

Search Terms

The search string we used had two main parts: The first part is used to pinpoint studies related to WBV (the search term used was simply "whole body vibration*")[4], and the second part is used to identify studies related to the outcome of interests (fatigue or sleep* or alert* or wake* or tired* or "reaction time" or "performance"). The two parts were connected together in a search string using "AND," while the terms within the second part were connected together in a search string using "OR." The search string was applied to "all text," which includes title, abstracts,

[4] This search string was designed to yield articles that included the keywords "whole body vibration" as well as the hyphenated phrase "whole-body vibration." Search terms with less specificity, such as "vibration*," were considered, but ultimately not used because too many irrelevant hits were returned as a result. The term "whole body vibration" is widely used in relevant literature, and therefore the research team judged that it was unnecessary to use a more general term.

medical subjects headings (MeSH), and other text that the record has in the database (but "all text" in this context does not mean a "full text" search of each of the article).

Article Screening Process

The research resulted in 652 titles and abstracts for screening. Of these, 24 articles met our inclusion/exclusion criteria and were included in the review as *core papers*. While our search strategy was designed to target relevant studies, it is designed to err on the side on of inclusiveness to ensure we did not miss any important studies. A number of irrelevant studies were yielded from the search and were manually dropped at the title and abstract-screening step. Primary reasons for exclusion at the screening phase were because the excluded study focused only on WBV exposure without including a fatigue-related outcome or focused solely on WBV exposure and discomfort.

Dropping a large number of papers at the title- and abstract-screening stage is common in systematic review processes. For example, in a review on a similar topic (WBV and performance) by Conway, Szalma, and Hancock (2007), their search resulted in 224 articles, reports, dissertations, and theses; however, only 13 studies were retained after the screening procedure in their review.

Upon screening of the abstracts, articles that focused on WBV's effects on visual acuity were excluded from the core set of reviewed articles, as visual acuity is not considered a measure of fatigue or sleepiness. A number of these articles are suggestive of relationships between WBV and decreased visual performance (see, for example, Ishitake et al., 1998; McLeod and Griffin, 1990; McLeod and Griffin, 1988; and Dennis, 1965); however, these articles are only considered *supplementary*, as visual acuity is not considered a measure of fatigue/sleepiness and was thus not incorporated into the systematic review of "core" articles. A sample of articles on visual acuity and WBV exposure (a total of 12) are summarized in Appendix A-1.

Additionally, our search identified five *review articles* that were judged to be directly relevant to the topic of WBV and fatigue (Conway, Szalma, and Hancock, 2007; Kjellberg, 1990; Mabbott, Foster, and McPhee, 2001; Oborne, 1986; and Kjellberg and Wilkström, 1985). They were not included in the count of the number of "articles yielded" because the reviews themselves did not offer primary evidence. Nevertheless, their full text (including reference lists) were read completely by our research team, and their findings will be taken into account in our review.

Literature Review Results

Overall Findings

Out of the 24 "core" papers, the majority (*n* =18; or 75 percent of the papers) found that WBV increases fatigue or sleepiness (or lowers performance), whereas seven studies found no relationship between WBV exposure and fatigue/sleepiness-related outcome. A brief summary of the 24 core papers is provided in Table 1.

Table 1. Summary of the 24 Core Papers

Articles	Findings On		Exposure Conditions	
	Objective Outcomes	Subjective Outcomes	Frequency Hz)	Acceleration*
Zamanian et al., 2014	↘	n/a	3–7 Hz	0.53, 0.81, 1.21 m/s^2
Stamenković, Popović, and Tirović, 2014	↘	n/a	1, 5, 20, 50 Hz	2.4 m/s^2
Costa, Arezes, and Melo, 2014	↘	n/a	not specified	0.20 to 0.54 m/s^2
Paddan et al., 2012	↘	↘	four bands of frequencies: 2–8 Hz, 8–14 Hz, and 14–20 Hz, plus a stationary control condition	2 m/s^2
Costa, Arezesa, and Melo, 2012	↘	n/a	not specified	0.17–0.23 m/s^2 (mean of 0.20±0.01 m/s^2) for asphalt; 0.43–0.68 m/s^2 (mean of 0.54±0.05 m/s^2) for cobblestone
Satou et al., 2009	↘	○	none, 10, or 20 Hz	0.3 m/s^2
Newell and Mansfield, 2008	↘	↘	1–20 Hz	1.4m/s^2 in the *x* direction, and 1.1 m/s^2 in the *z* direction
Satou et al., 2007	↘	○	10 Hz	0.6 m/s^2
Ljungberg and Neely, 2007	↘	⬀	2 Hz in the *x* direction, 3.15 Hz in the *y* direction, and 4 Hz in the *z* direction	1.1 m/s^2
Ljungberg, 2007	○	↘	dominant range between 1 Hz and 20 Hz (recorded from a forwarder)	0.87 m/s^2
Schust, Blüthner, and Seidel, 2006	○	n/a	a dominant frequency content from 1 to 3 and 7 to 12 Hz in the *x* axis and from 1 to 4 Hz in the *y* axis	0.55 m/s^2
Abbate et al., 2004	n/a	↘	n/a	n/a
Ljungberg, Neely, and Lundström, 2004	○	n/a	16 Hz	n/a
Lindberg et al., 2001	○	n/a	n/a	n/a
McLeod and Griffin, 1993	○	n/a	4 Hz	1.4 m/s^2
Lundström, Landström, and Kjellberg, 1990	○	○	3 Hz	0.3 m/s^2
Landström and Lundström, 1985	↘	n/a	sinusoidal at 3 Hz and random WBV at 2–20 Hz	0.3 m/s^2
Webb et al., 1981	↘	n/a	sinusoidal (6 Hz) and random (0–5 Hz)	0.21, 0.28, and 0.35 g
Seidel et al., 1980	↘	↘	4 and 8 Hz	1 m/s^2

Articles	Findings On		Exposure Conditions	
	Objective Outcomes	Subjective Outcomes	Frequency Hz)	Acceleration*
Lewis and Griffin, 1979	➘	n/a	4–64 Hz	n/a
Lewis and Griffin, 1978	➘	n/a	3.15–5 Hz	n/a
Cohen, Wasserman, and Hornung, 1977	➘	n/a	2.5–5.0 Hz	0.69 m/s^2
Hornick, 1962	➘	n/a	1.5, 2.5, 3.5, 4.5, 5.5 Hz	0.15, 0.25, and 0.35 g peak acceleration
Mozell and White, 1958	○	n/a	0–50 Hz	0.05, 0.1, and 0.16 inches

NOTE: Studies are listed in reverse chronological order (i.e., most recent publication to oldest).
*The unit m/s^2 refers to *meter per second squared*, the standard unit for acceleration; the unit *g* refers to the acceleration of gravity.

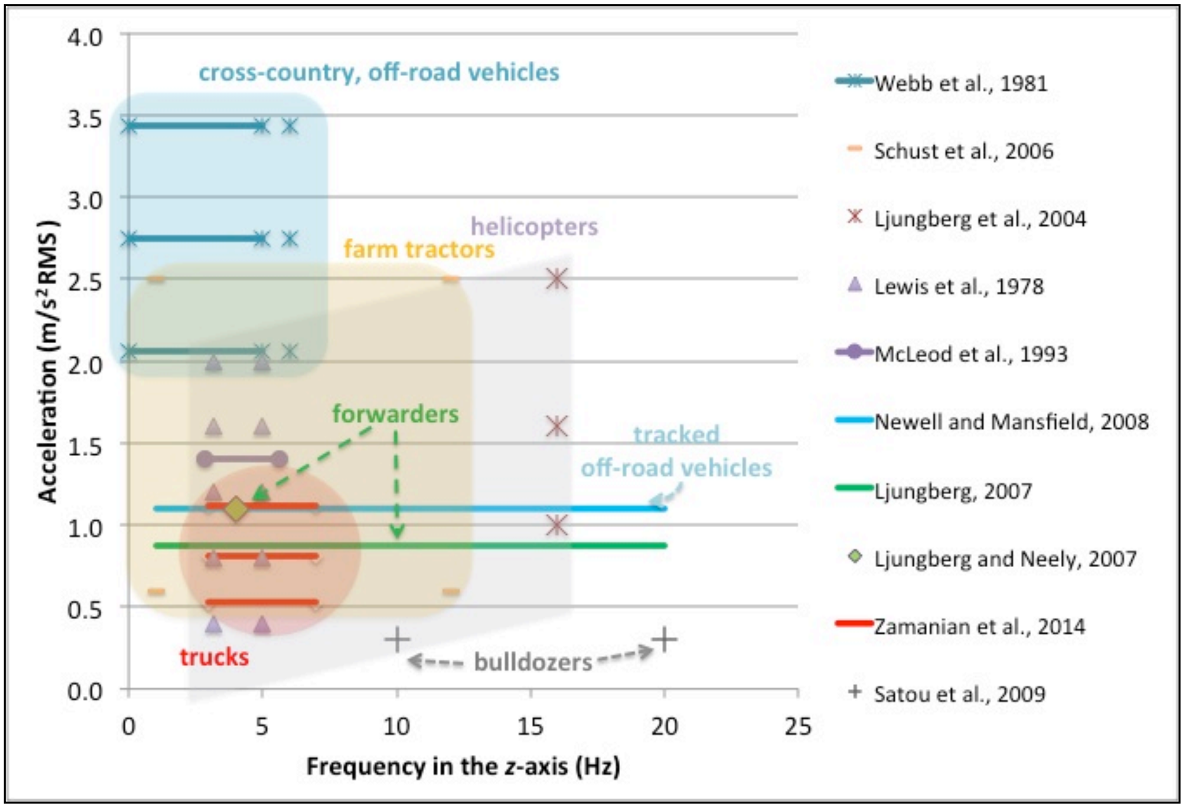
Legend	
➘	WBV impairs performance/increases fatigue
⬀	WBV improves performance/decreases fatigue
○	WBV has no impact
n/a	not applicable/not investigated

WBV Exposure Conditions

Only two studies examined the impact of WBV exposure under field conditions, which may limit the generalizability of the results to real-world truck-driving conditions. Moreover, of the two field tests, both involved a van drive over asphalt and cobblestones as tests of performance were conducted. Thus, the representativeness of real driving conditions are still limited, as both studies used van speeds that were considerably slower than typical driving conditions; i.e., 10 km/h (Costa, Arezesa, and Melo, 2012) and 20 km/h and 30 km/h (Costa, Arezes, and Melo, 2014).

Figure 1 summarizes the acceleration-frequency combinations used in the core studies. The colored shapes represent the vehicle type the studies sought to simulate. In this figure, we only include studies where information on acceleration, frequency, and the type of vehicle that the study was simulating was included. Additional information of the exposure conditions of all core articles, even when the information is incomplete, e.g., frequency or acceleration information is missing in some papers, are presented in Table 1.

Figure 1: The Acceleration-Frequency Combinations Investigated in the Core Studies



Note: Studies that did not provide full information on acceleration, frequency, and type of vehicle are not shown in this graph. Exposure conditions in the different studies are simulated conditions, i.e. not the real condition in the mentioned types of vehicles. Points are used to indicate where a specific acceleration/frequency level was investigated; lines are used to indicate where a range of accelerations/frequencies was investigated.

The WBV exposure conditions in the studies reviewed varied greatly, as previous researchers sought to represent different types of vehicles in their studies. Only one article (out of 24) explicitly stated that it aimed to simulate the environment of truck driving (Zamanian et al., 2014). In this study, WBV were regulated in a range of frequency from 3 to 7 Hz with acceleration rates of 0.53, 0.81, and 1.12 m/s^2. This is broadly consistent with the acceleration rates and frequencies suggested in a review paper by Mabbott, Foster, and McPhee (2001), which found that typical WBV of heavy vehicles in operating conditions are in the range of 0.4–2.0 m/s^2 in the vertical direction, with a mean value of 0.7 m/s^2. Studies that created WBV conditions somewhat similar to that of the truck-driving conditions reported in Zamanian et al. (2014) include: A study by Ljungberg and Neely (2007) that sought to simulate the conditions of a forwarder (i.e. 1.1 m/s^2 and 4 Hz in the *z* direction) and two studies that sought to simulate conditions of a helicopter (0.4–2.0 m/s^2 and 3–5 Hz) (McLeod and Griffin, 1993, and Lewis and Griffin, 1978).

Other vehicle types that studies simulated in laboratory conditions include: helicopters (Ljungberg, Neely, and Lundström, 2004; McLeod and Griffin, 1993; and Lewis and Griffin, 1978), off-road vehicles on rough terrains (Newell and Mansfield, 2008, and Webb et al., 1981), bulldozers (Satou et al., 2009), farm tractor (Schust, Blüthner, and Seidel, 2006), and forwarders (a fast-moving forestry vehicles for picking up logs) (Ljungberg and Neely, 2007, and Ljungberg, 2007).

In lab-based studies (n = 20), participants were typically seated on a chair (often a car seat) mounted on a vibrating platform, and an accelerometer was used to measure the vibration. It is worth noting that some lab experiments represented the real-world environment better than others. Real-world vibrations are random, oscillating in a range of frequencies and accelerations simultaneously, and multidirectional. Many studies (n = 12), however, used an experimental setup with a constant frequency; or if a random vibration was used in the experimental setup, only a single direction was examined (Landström and Lundström, 1985; Webb et al., 1981; and Mozell and White, 1958). In more recent studies—e.g., Costa, Arezesa, and Melo, 2012; Costa, Arezes, and Melo, 2014; and Zamanian et al., 2014—a stronger emphasis has been placed on mimicking the real driving environment. For instance, in Zamanian et al. (2014), experiments were conducted using a vibration simulator that produced vibration as sinusoidal/random waves in three directions (x, y, and z axes) and different acceleration rates and frequencies. Using such real-world exposures, Zamanian et al. found that the effects of WBV on reaction time and accuracy are mixed (could be positive, negative, or none) depending on the difficulty of the tasks. Further discussion of the results of this paper is presented in later sections.

Another significant limitation of the majority of existing studies in terms of extrapolating to real-world driving conditions is that they tend to focus on short-term exposure rather than prolonged exposure, which is more characteristic of truck-driver operating conditions. In most of the reviewed studies, participants were exposed to WBV for 15 to 20 minutes; but in a few studies, WBV exposure was tested for under three minutes (Zamanian et al., 2014; Newell and Mansfield, 2008; and Mozell and White, 1958). Experiments of very short duration have limited relevance for professional truck drivers, whose typical workdays are at least eight hours long, and may underestimate the actual impact of WBV on driver fatigue.

Finally, two out of the 24 studies examined the effects of long-term occupational WBV exposure on fatigue/sleepiness using observational methods (i.e., WBV was not experimentally manipulated or objectively measured; Lindberg et al., 2001, and Abbate et al., 2004). Rather, WBV exposure was defined by self-reported experience of occupational WBV exposure (Lindberg et al., 2001) or based on the population characteristics (i.e., drivers of mechanical trolleys; Abbate et al., 2004). The Lindberg et al. (2001) study is noteworthy because it sought to understand the direct relationship between WBV and the number of occupational accidents; however, the measure of WBV was a retrospective report of exposure to any type of work-related vibration in the past year, and accidents were inclusive of any occupational accident, rather than being specifically driver related. As such, the generalizability of these findings to WBV exposure in truck drivers specifically, or the risk of fatigue-related trucking crashes, is limited. Further discussion of the Lindberg et al. (2001) study is presented in the section about moderating influences. Abbate et al. (2004) found that drivers of mechanical trolleys reported more fatigue compared to a group of nondrivers, and that there was an association between duration of occupational exposure and fatigue. Given the lack of controlled conditions in this study and that WBV was not directly measured, however, these findings cannot rule out the possibility that other factors were associated with increased fatigue.

Variability in Measurement of Fatigue/ Sleepiness Across Studies

To measure fatigue, sleepiness, and performance, researchers have used a diverse range of tests and metrics (and typically multiple tests/metrics were used in a single study). We discuss them here in three broad categories: objective physiological outcomes, objective performance outcomes, and subjective outcomes.

Objective Physiological Outcomes

Objective sleepiness (or the opposing state of wakefulness/alertness) can be measured by monitoring changes in the brain's alpha and theta activity through EEG. Four out of 24 core papers used EEG to assess whether WBV reduces wakefulness/alertness. Of the four studies, three found that WBV reduced wakefulness (Satou et al., 2009; Satou et al., 2007; and Landström and Lundström, 1985), as indicated by changes in brain activity, with relatively large effect sizes. In contrast, Lundström, Landström, and Kjellberg (1990) found a small and non-statistically significant difference in EEG-assessed wakefulness.

Other physiological measures of fatigue and sleepiness (e.g., heart rate, eye movement, oxygen uptake) were used infrequently, and findings concerning the effects of WBV on these outcomes were mixed. This may have been due to differences in the complexity of the tasks used, differences in WBV exposure, and that these other indicators are more general indicators of attention/alertness, which may reflect influences other than fatigue/sleepiness. In general, as alertness level is lowered, heart rate decreases, blinks have longer eye-closed durations, horizontal eye movement reduces, and oxygen uptake drops. Lundström, Landström, and Kjellberg (1990) observed that WBV had minor and non-statistically significant changes in participants' heart rate, whereas Landström and Lundström (1985) found that WBV decreased heart rate. Another study, Webb et al. (1981), found that WBV increased heart rate, but when WBV was terminated, heart rate fell to below pre-vibration levels.

Objective Performance Outcomes

The effect of WBV on fatigue and sleepiness may manifest as changes in operator performance, although it is important to note that factors other than fatigue/sleepiness may also contribute to performance decrements (e.g., time of day, practice effects, task difficulty). Two kinds of objective performance outcomes were used in the existing studies, namely reaction-time tasks and tracking tasks. This section discusses each of these in turn.

Reaction-Time Tasks

The most commonly used performance outcome is reaction time. Over half of the core studies (13 out of 24) examined the effect of WBV on reaction-time tasks. Although there is considerable variability in the types of reaction tasks used across studies, typically, participants are asked to press a button or a pedal as quickly as possible after a stimulus (often the stimulus is visual, but it could be auditory as well). Reaction time and task accuracy (number of correct answers) are measured and reported as outcomes. The full list of reaction-time tasks employed in the core articles is summarized in Table A.2 in Appendix A, along with their findings.

Figure 2 summarizes the findings on the effect of WBV on reaction time as well as task accuracy. Reaction-time outcomes (i.e., slower, no change, not measured, and faster) are presented as the horizontal axis, and task-accuracy outcomes (i.e., poorer, no change, not measured, and better) are presented as the vertical axis. These form a four-by-four grid. The color coding indicates the classification of the studies' findings: "worse overall," "better overall," or "no change overall." Since *either* slower reaction time *or* poorer accuracy is undesirable, the entire leftmost column and the entire bottom row represent "worse overall" (colored in red).

While there were 13 studies that employed reaction-time tasks, some of these studies have multiple findings (Seidel et al., 1980; Webb et al., 1981; Newell and Mansfield, 2008; and Zamanian et al., 2014). Therefore, the 13 studies provided 17 data points for analysis.

As shown in Figure 2, nine out of 17 findings were classified as "worse overall"—these studies found that WBV resulted in impairments in either reaction time or poorer accuracy, or both. In particular, three out of nine showed decrements in both reaction time and accuracy (the visual motor test in Seidel et al., 1980; the no armrest condition in Newell and Mansfield, 2008, and Costa, Arezes, and Melo, 2014). Additionally, it is noteworthy that the performance decrements observed in Costa, Arezes, and Melo (2014) was substantial—the amount of time the subjects took to correct their own errors was tripled when exposed to a higher acceleration levels (from 0.20 to 0.54 m/s^2). It is possible, however, that the performance impairment was, at least in part, due to the fact that increased acceleration level makes the task more difficult, and the effect observed may not be solely attributable to the effect of fatigue.

Another notable finding is that WBV can result in faster reaction time at the expense of accuracy (Ljungberg and Neely, 2007). It is possible that the WBV causes participants to be annoyed or less patient, and they worked faster at the expense of precision.

Task difficulty is an important factor affecting the findings. In another study, *faster* reaction time and *increased* accuracy were observed during WBV exposure during a more complex, sustained attention task—perhaps because participants exercised extra care when the task became difficult (the divided-attention test in Zamanian et al., 2014). In fact, in this same study, participants had slower reaction times and more errors in the less cognitively demanding (selective-attention tasks). The study authors suggest that the performance decrements associated with the less cognitively demanding task (i.e., selective-attention task) may be more consistent with monotonous driving conditions, particularly for commercial drivers.

Even seemingly minor modifications of a reaction-time task can lead to different results. For example, Ljungberg and Neely (2007) and Ljungberg (2007) implemented essentially the same tasks (a “search-and-memory task”). The former study observed that WBV impaired performance in the minutes after exposure, while the latter did not. Ljungberg (2007) attributed the difference in results to the fact that the participants in the former study were more active during exposure, whereas those in the latter study were more passive (they watched a film of the driver’s view from the cabin of a truck that was driven slowly on a lightly trafficked rural road). Another plausible explanation for the difference in results, however, is that Ljungberg and Neely (2007) used a monotonous WBV (one that was periodic and has no variation in frequency or acceleration), whereas Ljungberg (2007) used WBV recorded from a forwarder, thus providing an exposure that is unpredictable and less repetitive. Thus, it is possible that performance decrements are related to the monotonicity of a WBV.

Figure 2: Summary of Findings on WBV Effects on Reaction Time and/or Task Accuracy

TASK ACCURACY	REACTION TIME: Slower	Not measured	No change	Faster
Better				Zamanian et al., 2014, divided attention test
No change	Newell and Mansfield, 2008, with armrest		Ljungberg, 2007	
Not measured	Hornick, 1962, post exposure Stamenković, Popović, and Tirović, 2014 Webb et al., 1981, at 3.43m/s2		Hornick, 1962, during exposure Webb et al., 1981, at 2.75 and 2.06m/s2 Schust, Blüthner and Seidel, 2006 Ljungberg, Neely, and Lundström, 2004	
Poorer	Seidel et al., 1980, visual-motor test Newell and Mansfield, 2008, no armrest Costa, Arezes, and Melo, 2014	Cohen, Wasserman, and Hornung, 1977	Seidel et al., 1980, auditory-motor test Zamanian et al., 2014, selective attention test	Ljungberg and Neely, 2007

Color Key	
Better overall	(green)
Worse overall	(red)
No change overall	(blue)

Notes: Either degradation in reaction time or task accuracy is presented as “worse overall” in this color-coded scheme. Hence all of column 1 and row 4 are red. If a study has different findings under different exposure conditions, it appears more than once in the figure. For example, Newell and Mansfield (2008) found that task accuracy impaired performance in the “no armrest,” but had no impact in the “with armrest condition.” It appears twice in the figure (column 1, row 2; and column 1, row 4).

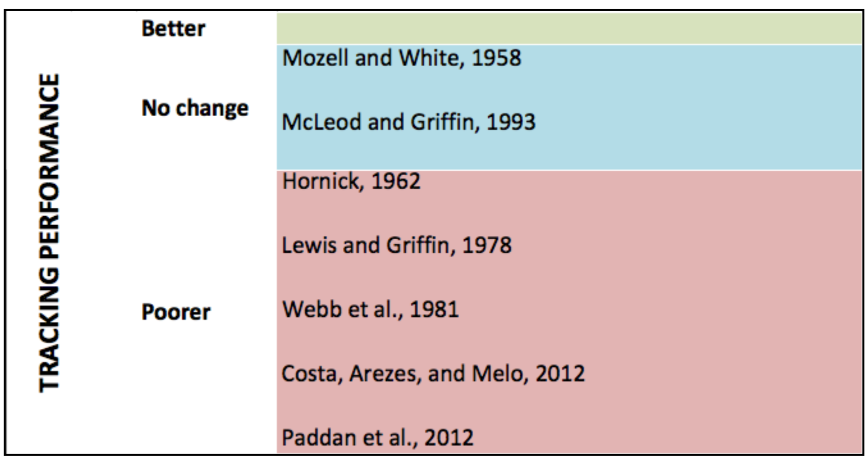
Tracking

Seven out of 24 core studies employed a tracking task to measure performance. Tracking tasks used in the current studies typically involved a simulated driving (or piloting) task, in which participants were instructed to maintain an indicator or an object at an equilibrium point using a steering wheel or a joystick, while being exposed to WBV. Tracking errors are measured and reported. The variety of experimental setups and their findings are summarized in Table A.3 in Appendix A.

Overall, the studies reviewed suggest that WBV impairs tracking performance. Out of the seven existing studies that employed a tracking task, five showed that tracking errors were greater in the presence of WBV (Hornick, 1962; Webb et al., 1981; Costa, Arezesa, and Melo, 2012; Paddan et al., 2012; and Lewis and Griffin, 1978). Only two studies found no significant effect of WBV on number of errors (Mozell and White, 1958; McLeod and Griffin, 1993).

The overall findings about WBV and tracking performance are summarized in Figure 3.

Figure 3: Summary of Findings on Tracking Performance



Subjective Rating of Alertness and Performance

Nine out of the 24 core studies examined subjective ratings of fatigue or sleepiness. Typically, participants were asked to complete a questionnaire as part of the experiment, in which they had to rate their perceived fatigue/sleepiness or alternatively, the opposing state of alertness, or performance on a graded point scale or a slider. Out of the nine studies using subjective measures, five found that, after WBV exposure, participants rated themselves as more fatigued or perceived that their performance was diminished relative to the control condition (Abbate et al., 2004; Ljungberg, 2007; Seidel et al., 1980; Newell and Mansfield, 2008; and Paddan et al., 2012); three studies found that WBV had no significant effects on subjective alertness (Lundström, Landström, and Kjellberg, 1990; Satou et al., 2009; and Satou et al., 2007); and one study found that WBV increased subjective alertness (Ljungberg and Neely, 2007). Importantly, in the one study that found that WBV resulted in increases in subjective alertness, those same participants showed greater objective-performance decrements on a search-and-memory task (Ljungberg and Neely, 2007). As pointed out by the authors, "in applied situations, this combination of perceived alertness while at the same time exhibiting degraded performance could be a dangerous combination." These findings highlight the frequent discrepancy between objective and subjective ratings of fatigue and the importance of including objective measures as well as subjective ratings. In fact, substantial research confirms that humans are poor at judging the impact of fatigue on their own performance (Van Dongen et al., 2003).

The findings on subjective rating of alertness and performance are summarized in Figure 4.

Figure 4: Summary of Findings on Subjective Outcomes

SUBJECTIVE OUTCOMES	**More alert**	Ljungberg and Neely, 2007
	No change	Lundström, Landström, and Kjellberg, 1990 Satou et al., 2009 Satou et al., 2007
	More fatigue	Abbate et al., 2004 Ljungberg, 2007 Seidel et al., 1980 Newell and Mansfield, 2008 Paddan et al., 2012

Moderating Influences

The degree to which WBV affects fatigue, sleepiness, and performance has been shown to be influenced by moderating variables, such as the driver's alcohol consumption (Stamenković, Popović, and Tirović, 2014), noisy environment (Lundström, Landström, and Kjellberg, 1990; Ljungberg and Neely, 2007; Ljungberg, 2007; and Ljungberg, Neely, and Lundström, 2004), and seat-backrest angle or posture (Paddan et al., 2012, and Newell and Mansfield, 2008) as well as other driver characteristics and environmental influences (Webb et al., 1981). Noise is an important moderating influence to be considered for the trucking industry, as it often coexists with WBV in real driving environments, whereas seat-backrest angle and posture are of more relevance to military vehicles than trucks.

From a broader perspective, other factors that are known to affect truck driver fatigue (e.g., nighttime driving, shiftwork, sleep disorder) are also critically important to consider as potential moderating factors that could potentiate the impact of WBV on fatigue/sleepiness. Mabbott, Foster, and McPhee (2001) identified a long list of such factors, including temporal characteristics of the driving conditions (e.g., time of shift), driver characteristics (e.g., age), environmental conditions (e.g., remote areas), and sleep factors (e.g., presence of sleep apnea). One moderating factor that is not included in Mabbott, Foster, and McPhee's review but would also be critical to consider is lower back pain, given that there is strong evidence that lower back pain is prevalent among professional drivers (Bovenzi et al., 2006) and is related to both WBV as well as fatigue and sleep disturbances.

Of particular relevance to this broader perspective, Lindberg et al. (2001) considered a large set of moderating variables in a ten-year prospective study. In the study, 2,874 participants (males, aged 30–64) answered questions on snoring and excessive daytime sleepiness (EDS) in 1984; ten years later, 2,009 of the participants (73.8 percent of the "survivors") responded to a follow-up questionnaire. The questionnaire covered a large set of risk factors for work-related accidents (age; body mass index; smoking; alcohol dependence; years at work; blue-collar job; shift work; and exposure to noise, organic solvents, exhaust fumes, and WBV). A total of 345 worked-related accidents were reported by 247 of the participants (12.3 percent). Multivariate analysis was conducted to identify risk factors that had a significant association with work-related accidents, and WBV was found *not* to be one of the significant risk factors. The multivariate approach used in Lindberg et al. (2001) has its merits; however, a caveat of the study is data quality, particularly the measurement of WBV, which was assessed via retrospective self-report (i.e., "exposure during one year"). Moreover, this study was focused on occupational accidents in general, rather than focusing on driver safety specifically.

Discussion

Overall, the results of the systematic literature review demonstrate a positive association between WBV and fatigue/sleepiness; however, there are significant limitations of the existing literature, including the lack of generalizability to truck driver populations, which preclude definitive conclusions regarding the degree to which WBV serves as an independent risk factor for driver fatigue/sleepiness. In general, the existing literature on WBV and fatigue is small (24 studies identified in the systematic review), which highlights the need for further research in this area. Of the 24 studies, 18 showed that exposure to low-frequency WBV was associated with increased fatigue/sleepiness, as measured by objective or subjective indicators of these outcomes. There were also a handful of studies showing no significant association and isolated cases, where WBV had the opposite effect on fatigue/sleepiness. This discussion section summarizes the insights drawn from assessing and comparing these 24 studies.

A notable limitation in the existing studies is that field tests are rare (only two out of 24), and those three field tests were still limited representations of the real driving environment for other reasons. Another limitation of the existing studies is that the durations of exposure were very short (a number of studies tested a duration shorter than three minutes) and not at all representative of typical driving conditions.

The WBV exposure conditions, in terms of duration, frequency, and intensity, also clearly contribute to variability in the effects observed. Monotonous low-frequency vibration may cause a reduction in alertness, but acute and irregular WBV may actually increase alertness (for example, in Hattori et al., 1987,WBV was studied as a stimulating agent). Future research should take these considerations into account.

The key fatigue/sleepiness/performance outcomes that were analyzed in the existing studies include: EEG (an objective physiological outcome), reaction and tracking (objective performance outcomes), and subjective alertness/performance ratings. Some of the variability in results across studies may be due, at least in part, to the diversity of methods and metrics used to assess performance. Notably, within the broad class of "reaction-time tasks," a variety of tests were used, and the results were sensitive to even minor changes in the tests (as illustrated by Ljungberg and Neely, 2007, and Ljungberg, 2007). As such, the set of results reviewed here could only be interpreted according to the nature of the tasks as well as exposure conditions. Future research for informing the trucking industry should be designed specifically for vehicle-control performance (such as steering, lane drifting, speed choice, and following behavior) or should use standardized and validated performance assessments, such as the PVT (described in Chapter 2), which has been used in other operational settings, including the military.

The degree to which WBV affects fatigue, sleepiness, and performance has been shown to be moderated by many variables. Multivariate analysis that evaluates WBV as one of many risk factors for occupational accidents—along the lines of (Lindberg et al., 2001)—shows a useful framework for future analysis. In summary, the existing literature on WBV and fatigue/sleepiness is suggestive of a positive relationship; however, there are clear limitations in the current methodologies that preclude definitive conclusions regarding the impact of WBV on driver fatigue/sleepiness. Recognizing these limitations, in the subsequent sections of this report, we draw from the reviewed literature to provide modeling estimates of the relationship between WBV exposure and driver fatigue and ultimately accident risks, and provide recommendations for future studies to strengthen the evidence base.

3. Modeling Estimates of the Impact of WBV on Fatigue-Related Crashes

The question underlying this research effort is: How does exposure to WBV impact the frequency of trucking crashes? While the literature discussed in the previous section highlights some of the adverse impacts of exposure to WBV, to the best of our knowledge, there have not been any studies looking directly at the relationship between WBV and road crashes. As an attempt to bridge this gap in the literature, we have integrated data from various sources to produce an order-of-magnitude estimate of the impact of WBV on traffic crashes. The research papers cited below provide data that are relevant to slightly different parts of the problem, as none of the papers directly included all relevant data to model the effects of WBV on fatigue-related crashes. Therefore, we have used the collective data available and made some assumptions about the channels through which WBV may impact trucking crashes. Specifically, given the state of the literature on the effects of WBV, a primary channel is likely to be through fatigue induced by WBV, which in turn is associated with a higher risk of crashes.

Our underlying model works on the assumption that different levels of WBV induce different levels of fatigue and therefore road crashes. That is to say, based on the available evidence, we assume that a high-acceleration WBV induces a certain level of fatigue on average, while lower acceleration exposure induces a different (presumably lower) level of fatigue. The exact threshold for the difference between high and low acceleration varies within the literature, but we will consider the threshold to be 0.7 m/s^2 based on Conway et al.'s (2007) meta-analysis, described below. We assume that WBV with a lower acceleration induces less fatigue and therefore will have less decrement on performance. We can think of estimating the number of crashes due to high-acceleration WBV compared to low acceleration using the following relationship:

$$\Delta\ Crash\ Rate = \beta\ (Fatigue\ (WBV_{high}) - Fatigue\ (WBV_{low})).$$

In this equation, *Fatigue (WBV)* is the level of fatigue induced by a given level of WBV. The increase in the probability of an accident per hour associated with an incremental increase in the level of fatigue is β. The expected change in the frequency of crashes when reducing the WBV from high to low acceleration is Δ *Crash Rate*.

Conway et al. (2007) conducted a meta-analysis of the literature on various characteristics of WBV exposure (acceleration or amplitude, duration, and frequency) and performance. Collectively, the results suggest that there is an apparent gap in the literature of studies of the fatigue-inducing effects of high acceleration WBV (more than 0.07 RMS_g, which is about 0.7

m/s^2 for a long duration (more than 30 minutes). Thus, for estimates relevant to professional drivers, we will need to scale the effect of long exposure to WBV based on short duration exposures from low and high accelerations. Specifically, Conway and colleagues report a pair of observations for low-duration exposure, showing a 46-percent performance reduction between low- and high-acceleration WBV. Another comparison of high- and low-acceleration WBV in Conway (2007) showed a higher-percent performance reduction but, because of the high degree of uncertainty in our analysis, we selected the more conservative of the two values for estimating the impacts.

From Conway et al. (2007), we know that, for long exposure to low acceleration WBV, there is a 3.04 standard-deviation (SD) decline in performance relative to baseline. We also know that, for short-duration exposures, there is a 46 percent decline in performance from low acceleration to high acceleration WBV. The literature, however, does not give estimates for high acceleration WBV for long-duration exposure. We consequently make an assumption that change in performance from high to low acceleration is the same for both short- and long-duration exposure. Given that low-acceleration WBV under long exposure impairs performance by 3.04 SD, estimating performance decrement for long-duration exposure under high acceleration would require that we multiply 3.04 SD by 46 percent. We consequently estimate that long exposure to high acceleration vibrations would decrease performance by 4.4 (3.04 + 3.04 * 46 percent) SD. Thus, over long durations, we expect that a subject exposed to high-acceleration WBV might perform 1.4 (3.04 * 46 percent) SD worse on average than someone exposed to only low-acceleration WBV. The value of 1.4 SD represents the $(Fatigue\ (WBV_{high}) - Fatigue\ (WBV_{low})$ term in the equation above. This estimate of an effect size, while our best estimate, is still an extrapolation based on fewer data than would be needed for a high-confidence estimate.

While sleepiness and fatigue are conceptually related, the literature on motor vehicle crashes puts more emphasis on sleepiness as a risk factor than fatigue, and it is very difficult to determine the independent effect of either fatigue or sleepiness on crash risk, over and above the effects of other influences. As an alternative for considering the impact on crashes, we use a recognized indicator of driver impairment (i.e., blood-alcohol content or BAC) to provide a benchmark for considering the impact of fatigue/sleepiness. Specifically, we compare the performance decrement from WBV (in terms of the SD calculated above) to the performance decrement associated with the other risk factors (e.g., extended wakefulness, BAC) that have known safety consequences. Maruff et al. (2004) experimentally compared the performance impact of different fatigue levels, based upon experimentally manipulated extended wakefulness in comparison to BAC. Their experimental design allowed them to directly compare performance declines due to extended wakefulness and to identify the BAC that produced the same decline in performance. From this work, we can make comparisons with the performance decrement associated with exposures to low- versus high-acceleration WBV. Specifically, we estimated the β value by assuming that a 1.4 SD reduction in performance stemming from WBV-induced fatigue is equivalent to a 1.4 SD reduction in performance stemming from wakefulness. Using data on reaction-time decrements and variability in reaction time reported in Maruff et al. (2004), a decrease in performance of 1.4 SD for someone who had been awake for ten hours would be comparable to having been awake for 22 hours. In other words, we estimate that the average performance of individuals exposed to high-acceleration WBV who had been awake for ten hours would closely resemble performance decrements for people exposed to low-acceleration WBV who had been awake for 22 hours.

Under the conditions discussed above, the performance decrement for reaction time associated with long-duration exposure to high-acceleration WBV appears to be roughly similar to a BAC between 0.03 percent and 0.05 percent, while exposure to low-acceleration WBV appears to result in an equivalent performance to a BAC between 0.02 percent and 0.03 percent based on the calculations above. For context, the legal threshold for BAC is 0.08 percent in all the U.S. states.[5] Other studies suggest that, after periods as short as 17–19 hours of extended wakefulness, subjects show impairments on other performance measures that are the equivalent to BAC levels above 0.05 percent and as high as 0.10 percent (Williamson and Feyer, 2000; Dawson and Reid, 1997; and Lamond and Dawson, 1998). Thus, the impact of WBV-induced fatigue may vary depending on which performance characteristic is measured, and more work will be required to assess the specific risks relevant to safety.

In another literature survey, Zhang et al. (2014) examined the impact of sleepiness on the risk of collisions in professional drivers. Sleepiness is not a direct analog to fatigue, but acute sleepiness was associated with between two and 14 times the risk of a collision for the general population of drivers. Their review of the literature also notes that acute sleepiness is also associated with an increase in the severity of crashes for professional drivers. Thus, the literature indicates that sleepiness can both significantly increase the frequency and severity of crashes.

The literature does not provide a direct path to estimate the impact of WBV on traffic crashes. Thus, these results are speculative because the studies used to draw the connections do not provide direct data on the links between WBV and crashes. This work should be thought of as indicative of the importance of considering WBV rather than accurate estimates of the performance decrement associated with exposure to high levels of WBV for long durations.

Furthermore, there is considerable variability in individuals' performance decrements in response to extended wakefulness, and many other unmeasured factors may contribute to observed associations. Therefore, while the findings from the literature may be true on average, there may be subpopulations in which there is much more or much less impact. Furthermore, as the inconsistencies in the literature suggest, effects also may vary greatly depending upon the nature of the task or under real-world driving conditions. Nevertheless, the scale of WBV's impact on fatigue and the higher crash risks associated with fatigue highlight that this is a subject that warrants further study.

[5] Insurance Institute for Highway Safety, Highway Loss Data Institute, "Alcohol-Impaired Driving," September 2015. Accessed on September 16, 2015: http://www.iihs.org/iihs/topics/laws/dui.

4. Proposed Research Designs

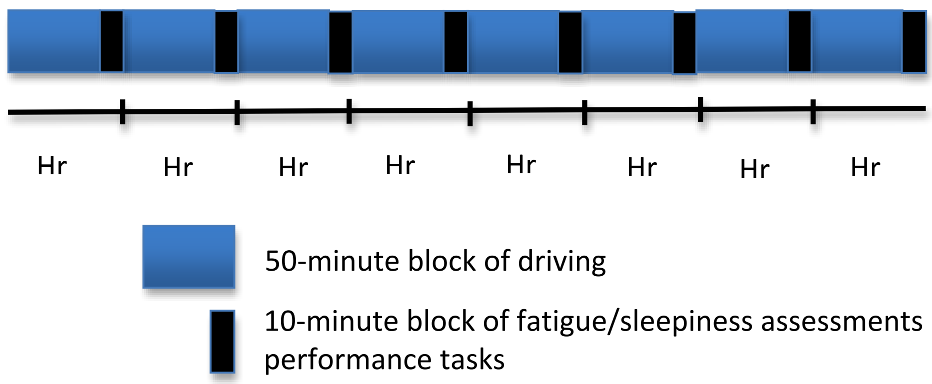
As part of this study, we identified several potential follow-on studies that could more effectively discern the relationship between truck-generated WBV and fatigue. Our recommendations are derived from our review and critique of the existing literature, with the aim of strengthening the evidence base concerning the impact of WBV on fatigue. In particular, studies are needed that use doses of vibration that are similar to those experienced by the trucking industry. As previously noted, Mabbott, Foster, and McPhee. (2001) estimate that typical acceleration rates for heavy vehicles range from 0.4 to 2.0 m/s^2. In addition, the duration of exposure for WBV should be increased to better reflect the four- to eight-hour driving shifts that are likely common in the trucking industry. Finally, researchers should use more standardized and validated performance assessments, such as the PVT, in conjunction with established subjective sleepiness or fatigue scales, as both sources of information can yield meaningful insights into the driver's experience and safety risk. Addressing these significant limitations in the literature is critical to inform evidence-based decisions to reduce driver fatigue and ultimately reduce driver crashes and fatalities. Obviously, there is no single study that could provide a definitive examination of WBV and fatigue, as even the best studies will yield additional hypotheses that merit future examination. That said, we offer two potential strategies, both a laboratory and field investigation, for addressing current research gaps.

Laboratory Investigation

Laboratory studies have the advantage of allowing for experimental control and precise measurement of key study variables (e.g., WBV, fatigue/sleepiness). They also offer several pragmatic advantages in terms of duration of the study and sample size, compared to field studies. As discussed in the literature review, however, there were several limitations of the existing studies that limit the generalizability of the laboratory-based findings. Thus, we recommend a laboratory-based study that investigates the impact of WBV on prolonged periods of performance in a driving simulator. More specifically, we recommend that investigators test four levels of WBV: 0, 0.5, 0.8, and 1.1 m/s^2, based on ISO standards on occupational exposure to WBV. These levels are consistent with data from Zamanian et al. (2014), who sought to ensure that WBV administrations were similar to that of big-rig trucks. Similarly, we recommend using a vibration as sinusoidal/random waves in three directions (x, y, and z axes) and frequencies that range from 3 to 20 Hz (to be inclusive of the range of frequencies likely to be experienced in a truck driver's cab).

Each level would be tested in an eight-hour driving simulator procedure. Drawing on a prior study that employed an eight-hour exposure to a driving simulator (Ranney et al., 1999), participants would engage in the driving-performance task for 50 minutes of every hour for eight consecutive hours. In the remaining ten minutes of each hour, participants would complete a five-minute PVT and complete self-report measure of sleepiness (Stanford Sleepiness Scale) and fatigue (Multidimensional Fatigue Inventory).[6] See Figure 5 for a schematic view of the design.

Figure 5: Schematic View of the Proposed Laboratory Investigation



Note: Adapted from Ranney et al., 1999.

Dependent variables would include reaction time for the PVT and scores of the Stanford Sleepiness Scale (SSS) and Multidimensional Fatigue Inventory (MFI). The SSS contains a seven-point Likert scale, which ranges from one for "very alert" to seven for "very sleepy." It has been shown to be a valid and reliable measure of sleepiness (Hoddes et al., 1973). The MFI is a 20-item self-report measure designed to measure fatigue. It provides subscales for the following dimensions: General Fatigue, Physical Fatigue, Mental Fatigue, Reduced Motivation, and Reduced Activity (Smets, et al., 1995). Standard-outcome measures for driving simulator would include: SD of car speed, SD of the lateral position, frequency of extremely large steering-wheel movements (> 10 degrees), and frequency of edge-line crossings for the two sides of the road. These measures have been shown to be correlated to physical and objective levels of sleepiness (see Liu, Hosking, and Lenne, 2009, for a review). In studies testing prolonged exposure to a driving simulator, these outcome variables also show degradation as a function of time on task and so appear to represent a valid indicator of fatigue (Ranney et al., 1999; Ting et al., 2008; and Nilsson, Nelson, and Carlson, 1997). Depending on the driving simulator used for this investigation, it may also be possible to include reaction time to a stimulus (often pictured as a pedestrian) presented in the driver's field of vision. The introduction of a simulated wind shear would require participants to make constant adjustments to the steering wheel to maintain vehicle position.

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[6] If one assumes that the effect size is 1.4 SD, then with a 95-percent confidence interval, the necessary sample size would be 12 per group. If the effect-size assumption is changed to 0.7 SD, then with a 95 percent confidence interval, the sample size would increase to 45 per group. A reduction in the confidence interval to 90 percent would require a sample size of eight per group for an effect size of 1.4 SD, and 28 per group for an effect size of 0.7 SD.

To enhance the quality of this study, participants would undergo an initial screening to rule out those reporting chronic back pain or the presence of sleep disorder to include sleep apnea and insomnia. Administration of Epworth Sleepiness Scale, a reliable and valid measure of daytime sleepiness, could be used to screen out participants with EDS (e.g., those scoring greater than or equal to ten on the Epworth). Finally, to help control for baseline levels of sleepiness, investigators should also require participants to spend eight hours in bed prior to each session. Adherence could be monitored with a sleep-actigraph sensor. Actigraphs are small sensors worn by participants on their wrist when they sleep, which provide a behavioral assessment of sleep.

Field Investigation

An alternative approach would be a field investigation of WBV effects on driver fatigue and alertness. Bose Corporation's development of anti-WBV technology, which reduces cab vibrations in trucks, offers an opportunity to examine the impact of WBV and its mitigation on fatigue and driver safety in field settings. Specifically, it may be possible to randomly assign truck drivers, in a double-blind, placebo-controlled fashion, to trucking rigs outfitted with the Bose anti-WBV technology. For the placebo condition, trucks would be outfitted with the Bose technology, but the technology would not be activated. Neither participants nor frontline research staff would be informed of their group assignment. According to data from Bose, at 2 Hz, vehicles outfitted with Bose will likely experience a reduction from 0.3 to 0.15 m/s^2. After an orientation period, in which Bose would train participants on operating vehicles with the anti-vibration technology, truckers assigned to both conditions could operate the trucks, in a commercial capacity, for a period of several weeks. Key to such a design would be instituting a systematic approach to measuring sleepiness and alertness, including objective and validated subjective measures. Participants, for example, could be asked to complete self-report measures of sleepiness and fatigue at regularly controlled time points. Ensuring administration of sleepiness measures at specific and regular time points is critical, given that variations in circadian rhythm have systematic effects on sleep drive. Both the SSS and MFI would be appropriate assessments. During these time points, participants should also complete a handheld version of the PVT, which provides exposure to a five-minute sustained vigilance task (Lamond, Dawson, and Roach, 2005)—tasks that are critically important to driver safety. Given the potential for anti-vibration technology to alleviate the symptoms of chronic back pain, it would also be wise to incorporate subjective pain measures.

Importantly, such a study should attempt to incorporate more advanced methods of measuring driver fatigue. First, investigators should incorporate vehicle measures to include variation in steering-wheel movement, variation in speed, and the presence of lane departures. As previously noted, such measures have been shown in simulators to be correlated with changes in sleepiness. Second, newer technologies have recently been developed to measure slow eyelid closure—which can provide an objective assessment of propensity to doze at the wheel. These technologies typically involve installation of a specialized camera on the driver's dashboard. The camera is able to detect eyelid movements, and the system calculates the proportion of time the eyes are closed 80 percent or more over a specified interval of time (Barr et al., date unknown). This outcome has been shown to be a valid measure of sleepiness in both driving and non-driving tasks (Sahayadhas et al., 2012).

It is critical that any study use a careful screening regimen. Prospective participants should be evaluated for the presence of sleep apnea, insomnia, and drug or alcohol abuse/dependence. Participants should also be screened for the presence of EDS via a validated instrument, such as the Epworth Sleepiness Scale. For reasons of safety, participants with drug and alcohol dependence should be excluded from participation. An argument also may be made for screening out those with sleep disorders or EDS; however, given the high prevalence of these conditions in trucking populations, it may be wise to include these individuals in the study and include such factors as covariates in order to increase generalizability of the findings. Participants should also wear a sleep actigraph throughout the duration of the study, so that the impact of varying sleep times can be accounted for in the analysis. The presence of sleep disorders, if included in the study, as well as variations in baseline time in bed should be randomly assigned to conditions in a stratified manner.

Two additional issues are worth noting regarding the laboratory investigation. First, it is useful to note that one additional and potential outcome variable is crash rate. As previously noted, we were unable to identify a direct link between WBV and vehicle crashes and were required to instead develop a model of WBV accident risk by examining the WBV link to sleepiness and fatigue measures. A field test of the Bose Ride system could have the potential to fill this gap in the literature if crash rates are shown to be reduced by the Bose Ride in comparison to a control condition. The key challenge, however, is the low base rate of vehicle crashes. Specifically, for 2013, the last year that data is available, the accident rate fell at 27 crashes for every 100 million miles travelled.[7] Testing the impact of Bose Ride on vehicle crashes would thus require a relatively large sample tested over an extended period of time.[8] Given the time and costs that would be involved in such an evaluation, we think it would be preferable to demonstrate that the Bose Ride device is able to significantly impact putative measures of accident risk to include sleepiness and fatigue measures as well as reaction time and the various vehicle-born measures described above. Demonstration of significant effects across many of these measures would help justify longer-term field trials of the Bose device, which in turn may be used to test the impact on accident rates.

A second issue pertains to how both the proposed laboratory and field investigations should be prioritized for funding. Typically, laboratory experiments should precede field trials of a

[7] See National Highway Traffic Safety Administration, 2013.

[8] It may alternatively be possible to craft an "almost" accident measure, where drivers self-report crashes that "almost" happen. It remains unclear, however, if such a measure exists and if it reliably and validly measures accident risk.

commercial device, such as Bose Ride, because the lab experiments would provide enhanced justification for the development and refinement of the commercial device and offer experimental control of the key constructs under investigation. In particular, the value of the laboratory study is its ability to test the relative impact of different WBV levels on fatigue/sleepiness. Consequently, it may identify the specific reductions in WBV that would be necessary to significantly reduce fatigue/sleepiness and enhance driver performance. A further issue to consider is cost and feasibility of the study. The nature of the costs associated with field-versus-laboratory studies varies considerably and depends on the scope and outcomes of the project. For instance, the equipment required to perform a laboratory-based driver simulation study is very costly. On the other hand, given the experimental control afforded in laboratory studies, which can enhance statistical power, the sample size required should be smaller than in a field-based study, and the duration of the study can also be considerably more constrained than in a field-based study (which is cost effective in terms of research labor). The ultimate decision of whether to prioritize the proposed field study versus laboratory study must carefully weigh the pros and cons of each approach and find a balance between choosing the most rigorous methodological approach to address the scientific question and issues of feasibility.

5. Summary and Implications

Driver fatigue is a significant contributor to motor vehicle crashes and fatalities, although the exact share of those events attributable to fatigue is still uncertain. We do know that, in 2012, crashes involving heavy trucks killed over 3,944 people in the United States, over 80 percent of who were not in the truck (National Highway and Transportation Safety Administration, 2015). Thus, fatigue is a critical issue not only for driver safety, but for public safety in general. There are numerous factors that contribute to driver fatigue among commercial drivers, including shiftwork schedules; high prevalence of alcohol and substance use; extended hours; comorbid medical conditions, such as pain; and high prevalence of sleep disorders (Filiatrault et al., 1999; Lal and Craig, 2001; Sieber et al., 2014; and Teran-Santos et al., 1999). Many of these factors have been studied extensively in the trucking industry (Crum and Morrow, 2002, and Adams-Guppy and Guppy, 2003). Another potential factor that may contribute to driver fatigue that has received little attention is WBV. Given the importance of identifying practicable efforts to mitigate driver fatigue in order to reduce accidents and injuries, a critical next step is to develop a more rigorous evidence base to examine possible causal links between WBV and fatigue. The development of such an evidence base would then lead to the next logical step, which would be to examine whether a device designed to reduce driver fatigue could have a measurable impact on truck-related crashes and fatalities.

This report summarizes the findings of a study conducted by the RAND Corporation that was commissioned jointly by AIG and Bose Corporation and had three primary aims: (1) to review and evaluate the literature on WBV and fatigue, (2) to provide modeling estimates of the association between WBV and fatigue and ultimately accident risk, and (3) to highlight future research directions in order to strengthen the evidence base concerning a causal role of WBV on fatigue and driver safety. A brief summary of findings pertinent to each aim is summarized herein.

The results of the literature review elucidated a number of important findings and limitations. Overall, the studies suggest that there is an association between exposure to WBV and increased fatigue or sleepiness; however, methodological limitations in the existing literature preclude definitive conclusions concerning the impact of WBV on driver fatigue/sleepiness. Out of 24 studies reviewed for this report, 18 show that exposure to WBV results in decrements in psychomotor performance or increases in sleepiness or fatigue. There were several important methodological limitations, however, that limit the generalizability of findings to real-world truck-driving conditions and that temper conclusions regarding a causal association between WBV and fatigue/sleepiness. In general, the reviewed literature is also limited by duration of WBV exposure; small participant samples that may not be representative of commercial truck drivers; and failure to consider other moderating influences that may potentiate the effects of

WBV on fatigue, such as the presence of sleep disorders or pain. Furthermore, the reviewed studies primarily focused on performance metrics, rather than fatigue/sleepiness indicators specifically. Although these measures are clearly related, future research is needed that incorporates performance measures as well as subjective measures of fatigue/sleepiness and ideally objective measures of sleepiness as well, as these measures are ostensibly most closely linked with driver accidents.

Our efforts at modeling the relationship between WBV and fatigue-related vehicle crashes were somewhat limited, based on lack of existing data that connects WBV with crashes. Nevertheless, based on the available data and specific modeling assumptions (e.g., performance declines from fatigue induced by high acceleration WBV scale in time such as low acceleration WBV), model estimates suggest that the performance decrements associated with WBV exposure may be comparable to 22 hours of sleep restriction. In turn, prior work has shown that under sleep-deprived conditions, participants show performance decrements that are equivalent to being legally impaired, based on a blood-alcohol content exceeding the legal limit. Importantly, this latter observation is extremely tentative, given its reliance on several modeling assumptions and limited data to inform the models, and it merits additional study.

Finally, to address limitations in the existing literature, we also provide several suggestions for future research studies, including a laboratory design as well as a field-study design that could strengthen the evidence base. There are clearly advantages and disadvantages of both types of studies, including the trade-offs between generalizability of the findings (i.e., in a field study) versus experimental control to rule out confounding factors in a laboratory study. Pragmatic factors, including cost and duration of the study, are also crucial to consider.

In summary, although there was some inconsistency in the reviewed results and several methodological limitations in the existing literature, the results of this review and the preliminary (though suggestive) modeling estimates suggest that reducing WBV among commercial truck drivers is a modifiable target that may reduce fatigue and ultimately reduce the public-health burden and societal costs of trucking accidents. More methodologically rigorous examinations of the impact of WBV on fatigue/sleepiness, however, are needed to establish a causal relationship.

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Appendix

Table A.1. Supplemental Articles on WBV Exposure and Visual Acuity

	Exposure	Outcomes Measured	Results
Ishimatsu, et al., 2009	Frequencies: 0 Hz, 5 Hz, and 16 Hz; sinusoidal direction: vertical vibration; magnitude: 1.0 m/s^2 (root mean square, or RMS)	Target color discrimination target detection performance (Reaction times (RTs) as a function of inter-stimulus intervals (ISIs) between a fixation display and a target display)	In the target discrimination tasks, the RTs during shorter interstimulus intervals in the 5 Hz block were significantly briefer than during the 0 Hz and 16 Hz blocks. For target detection, on the other hand, no significant difference was found between the three experimental blocks. These results suggested that visual information processing (i.e., target-color discrimination) **could be improved during** exposure to 5 Hz sinusoidal vertical WBV.
Ishitake et al.,1998	Frequencies: 8, 10, 12.5, 16, 20, 25, 31.5, 40, 63.5, and 80 Hz Magnitude: 2.5 m/s^2 (RMS). Duration: 20 seconds	A standard visual-acuity test and a self-rated assessment for difficulties in visible perception	The disturbances of visual performance were dependent on the vibration frequency ($p < 0.01$, analysis of variance), with a maximum reduction of visual acuity at a frequency of 12.5 Hz. The disruption of the visual performance was more severe with the erect posture than with the muscle-relaxed posture.
McLeod and Griffin, 1990	Sinusoidal and random vibration at 0.5–20 Hz Direction: vertical	A combined continuous and discrete tracking task One group performed the task with the display collimated by (i.e., accurately aligned with) a convex lens.	Results show that continuous control performance was disrupted by visual interference at frequencies above 1.6 Hz; closed-loop system-transfer functions showed that visual interference increased the phase lags that impaired control performance. Possible mechanisms explaining the disruption in performance at lower frequencies are discussed.
McLeod and Griffin, 1988	Between 0.5 and 5.0 Hz Vertical, *z*-axis, whole-body sinusoidal vibration was presented in three separate sessions.	A complex, first-order manual-control task	Disruption was independent of vibration frequency below 3.15 Hz and increased at 4.0 and 5.0 Hz. A visual mechanism was assumed to account for the increased disruption at these higher frequencies.

	Exposure	Outcomes Measured	Results
Moseley and Griffin, 1987	Vertical sinusoidal WBV	Alphanumeric reading performance and contrast thresholds	A large variation was found in the effect of WBV on performance, with the higher spatial frequency both during and after WBV exposure. Data suggest that time-dependent changes in seat-to-head transmissibility were partly responsible for the results. Other time-dependent changes were found with the high spatial frequency.
Moseley and Griffin, 1986	Three possible viewing conditions (WBV, display vibration, and simultaneous vibration of both display and observer) Sinusoidal motion at 11 frequencies (0.5–5.0 Hz) was presented at five acceleration magnitudes (1.0–2.5 m/s^2 RMS)	A numeral reading task	Measures of reading time and reading error showed that for all except the highest frequencies, vibration of the display resulted in the poorest performance. Simultaneous WBV and display vibration produced least performance decrement. The effects of both the viewing conditions and the vibration frequency are discussed in relation to known characteristics of the visual system. Results suggest that any eye movement that compensates for translational head motion must depend on the viewing distance. It is suggested that any such eye movement is primarily controlled by visual feedback but assisted by other dynamic sensory information.
Moseley et al., 1982	One-third octave-band random vibration	A display reading task	Findings indicate that the octave-band random vibration had significantly less effect on performance. Subsequent measurements of rotational head motion demonstrated that this finding may have been due to differences in the velocity-probability density distributions produced by the different motions. Subjects also performed the visual task during exposure to several broadband random motions. Predicted error values were obtained by averaging the frequency-weighted time histories of these motions. It was found that both RMS- and root mean–quotient averaging procedures applied to the broadband-frequency weighted-time histories gave accurate error predictions when compared with the measured error scores.

	Exposure	Outcomes Measured	Results
Lewis and Griffin, 1980	Five levels of sinusoidal whole-body vibration (2.8–63 Hz), three translational axes, and two seating conditions (hard, flat seat with fixed footrest, and simulated helicopter seat with moving footrest)	A numeral reading task	Results, presented in the form of equal performance contours, show that seating conditions, as well as the use of personal equipment, such as flying helmets, interact with the effects of vibration on reading performance by affecting the transmission of vibration to the head. The possibility that predictions about the relationship between seat motion and decrements in reading performance can be made from measures of rotational head motion and seat-to-head vibration transmission is noted, along with the need to extend the previous data to situations in which both the body and the display vibrate.
Griffin, 1976	Vibration frequencies of 7, 15, 30, and 60 Hz.	The minimum levels of vibration required to produce a perceptible blur of stationary point sources of light	It was found that the levels of vertical vibration on the seat and vertical and pitch vibration at the head were independent of viewing distance. It is concluded that the minimum levels of vertical vibration required to produce blur cause angular motion of the eye. In some vibration environments, a reduction in viewing distance will, therefore, often improve vision, since it will increase the size of the retinal image of an object without significantly increasing the retinal image displacement due to WBV.
Griffin, 1975	Vibration frequency (from 7 to 75 Hz)	A visual task This task was the perception of the blur—due to eye motion—of an image of a stationary point source of light	Minimum levels of sinusoidal vertical vibration required to produce blur have been determined in a group of 12 subjects seated in a posture that maximized the sensation of vibration at their heads. The effect of vibration frequency (from 7 to 75 Hz) differed between subjects, and there was a large individual variability in the levels of both head and seat vibration required to produce blur at any frequency. This intersubject variability has been compared with the potentially large intra-subject variability due to changes in body posture. The experimental results have led to the tentative recommendation of vibration levels below which vibration is not normally expected to reduce visual acuity.

	Exposure	Outcomes Measured	Results
Dennis, 1965	Levels of peak-to-peak acceleration of half gravity and 1 gravity over a frequency range of 5 to 37 Hz	A task requiring the reading of printed numbers	Head movement in the vertical plane was measured during performance of the visual task. Movement of the head showed progressive attenuation as frequency of vibration was increased, the transmission factor being approximately 100% at 5 Hz and 10% at 37 Hz. Changes in frequency of vibration had considerable effects on visual performance, e.g. similar amounts of deterioration in visual performance being produced at head movements of 0.2 inches and 0.0006 inches at 5 and 37 Hz, respectively. These results support previous theories of resonance of eyeball and/or facial tissue to account for the impairment of vision found with very small head movements in the upper frequencies. Changes in amplitude of head movement appeared to have more effect at the lower and middle frequencies (7–19 Hz) than at 27 Hz. This also was in accordance with the previous theory.
Dennis, 1965	6, 14, 19, and 27 Hz	Impairment of vision	Experiments have been carried out in which the effects on visual performance of WBV have been compared with the effects of vibrating the visual object itself. At 6 Hz, using similar angular displacements, vibration of the visual object was found to result in higher impairment of vision than vibration of the human subject. At 14, 19, and 27 Hz, the converse was found to be the case; results that support previous theories of resonance of eyeball or facial tissue to account for the sensitivity of visual performance to WBV at these higher frequencies.

Table A.2. Reaction-Time Tasks Summary

Study	Reaction-Time Task	Findings About the Effects of WBV
Hornick, 1962	The reaction-time task involved the participant responding to colored-light patterns by pressing a simulated brake pedal accordingly.	No significant change in reaction time during exposure Slower reaction post exposure
Cohen, Wasserman, and Hornung, 1977	A display showed various colored light representing movements of all four limbs. Participants were asked to correctly respond in five seconds to four-limb coordination task.	Reduced accuracy relative to control
Seidel et al., 1980	One visual-motor and one auditory-motor test were employed. The visual test involved exposing the participant to 60 circularly arranged small lamps. The 60 lamps flashed successively, but at random intervals one lamp was omitted. An omission is the “critical stimulus,” and the participant was expected to react by pressing down a button. In the auditory-motor test, the participant was asked to detect a special tone in a background of white noise and react by pressing a button.	In the visual-motor test: Slower reaction Poorer accuracy (with longer exposure) In the auditory-motor test: No significant change in reaction time Poorer accuracy (with longer exposure)
Webb et al., 1981	Participants were asked to respond to light stimuli—a set of six red lights placed symmetrically around the participants—by pressing the appropriate button on a panel on their laps.	Slower reaction at one out of three accelerations (3.43 m/s^2, but not 2.75 m/s^2 or 2.06 m/s^2)
Schust, Blüthner, and Seidel, 2006	Participants were asked to press foot pedals as fast as possible in response to a stimulus displayed on-screen.	No significant change in reaction time
Ljungberg, Neely, and Lundström, 2004	The participant was asked to read a string of two, four, or six letters presented on a computer screen for one, two, or three seconds, respectively. After a pause, a “probe letter” appeared, and the participant’s task was to indicate as quickly and accurately as possible whether the probe had been or had not been present among the letters, through a hand-held, thumb-operated device with yes/no buttons.	No significant change in reaction time

Study	Reaction-Time Task	Findings About the Effects of WBV
Ljungberg, 2007	Reaction time was measured as part of a search-and-memory task, in which participants were asked to memorize five letters at the beginning and then search for the letters among the following lines of 59 letters.	No significant change in reaction time No significant change in accuracy (post exposure)
Ljungberg and Neely, 2007	Same as Ljungberg, 2007.	Faster reaction time Poorer accuracy (post exposure)
Newell and Mansfield, 2008	The participant was asked to pay attention to two displays—one located at front, and one located behind and to the right of the participant. At any time, an arrow was shown on one of the displays. Depending on the direction of the arrow presented, the participant's task was to press the corresponding key (up, down, left, or right) on a keypad.	Slower reaction for three out of four posture/armrest combinations Poorer accuracy for posture with no armrest No significant change in accuracy for posture with armrest
Paddan et al., 2012	The participant was asked to respond to the numbers 2, 3, 4, or 5, that appeared randomly on the screen. If a high number (4 or 5) appeared on the left of the screen, the participant was expected to press the top-left button of the button box, and if a low number (2 or 3) appeared on the left of the screen, the participant was expected to press the lower-left button. The logic was reversed for numbers appearing on the right.	Slower reaction No significant change in accuracy
Costa, Arezes, and Melo, 2014	Two tests were applied. In the "action judgment test," the participant was asked to control two needles. The goal was to avoid contact between the needles and a peripheral red line as well as red arrows marked on the rotational disk behind the wheel. In the "omega test," the participant was asked to use two knobs to control a pointer. The goal was to guide the pointer along a sinuous line, which was shaped like the Greek letter *omega*.	Poorer performance (increased number of errors, increased total error duration, and increased total time to undertake the test)

Study	Reaction-Time Task	Findings About the Effects of WBV
Stamenković, Popović, and Tirović, 2014	The participant was asked to press a button in respond to a stimulus (audio or visual). The audio stimulus was a sound transmitted through the headphones, and the visual stimulus was a change in the color display of a monitor from black to green.	Longer reaction time, with the most detrimental influence observed at 5 Hz Reaction time increases with exposure duration
Zamanian et al., 2014	Two reaction-time tasks were tested: The first was the “selective attention test,” in which different letters of the alphabet were displayed continuously on the computer screen, and the participant was asked to carefully look at them and then push the space bar on a keyboard only if they saw the letters *S* or *M*. The second test was a “divided attention test,” in which a series of letters of the alphabet was shown to the participant, and the respondent was expected to push buttons according to predetermined rules (e.g., if the letter *M* was displayed on the right of the screen, press the ? button; if the letter *S* was displayed on left of the screen, push *Z* button).	In the “selective attention test”: No significant change in reaction time Poorer accuracy In the “divided attention test”: faster reaction time better accuracy

Table A.3. Tracking Tasks Summary

Study	Tracking task	Findings About the Effects of WBV on Tracking Ability
Mozell and White, 1958	The participants were asked to maintain a half-inch line that moved in a slowly varying pattern in the center of the screen using an aircraft control stick.	No significant change
Hornick, 1962	The participant guided a dot on screen by means of a steering wheel for compensatory tracking.	Poorer
Lewis and Griffin, 1978	The participants were asked to control a cursor such that the cursor stayed within a moving circle on the screen.	Tracking errors were associated with increasing WBV accelerations (level tested: 0, 0.4, 0.8 1.2, 1.6, and 2.0 m/s^2). No difference between 3.15 Hz and 5.00 Hz
Webb et al., 1981	The participants were tasked to maintain a constant speed on a simulated speedometer by operating a foot pedal similar to that of an accelerator on a vehicle. The simulated speedometer was subject to a pseudorandom perturbation, for which the participants had to compensate.	Poorer (compared to no vibration); also greater decrements were observed for higher WBV intensity
McLeod and Griffin, 1993	The participants were asked to control a cursor such that the cursor stayed within a moving circle on the screen. In addition, the participants were asked to press a button when the cursor was inside the circle.	No significant impact
Costa, Arezesa, and Melo, 2012	The participants were asked to move a pointer along a sinuous line without touching the edge.	Poorer
Paddan et al., 2012	Participants were asked to use a joystick to keep a horizontally moving cross within a fixed target area on a screen.	Poorer