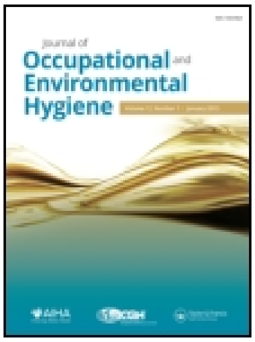

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# Whole-body Vibration Exposure Intervention among Professional Bus and Truck Drivers: A Laboratory Evaluation of Seat-suspension Designs

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*Long-term exposure to seated whole-body vibration (WBV) is one of the leading risk factors for the development of low back disorders. Professional bus and truck drivers are regularly exposed to continuous WBV, since they spend the majority of their working hours driving heavy vehicles. This study measured WBV exposures among professional bus and truck drivers and evaluated the effects of seat-suspension designs using simulated field-collected data on a vibration table. WBV exposures were measured and compared across three different seat designs:*

1. *an air-ride bus seat,*
2. *an air-ride truck seat, and*
3. *an electromagnetically active (EM-active) seat.*

*Air-ride seats use a compressed-air bladder to attenuate vibrations, and they have been in operation throughout the transportation industry for many years. The EM-active seat is a relatively new design that incorporates a microprocessor-controlled actuator to dampen vibration.*

*The vibration table simulated seven WBV exposure scenarios: four segments of vertical vibration and three scenarios that used field-collected driving data on different road surfaces—a city street, a freeway, and a section of rough roadway. The field scenarios used tri-axial WBV data that had been collected at the seat pan and at the driver's sternum, in accordance with ISO 2631-1 and 2631-5.*

*This study found that WBV was significantly greater in the vertical direction (z-axis) than in the lateral directions (x-and y-axes) for each of the three road types and each of the three types of seats. Quantitative comparisons of the results showed that the floor-to-seat-pan transmissibility was significantly lower for the EM-active seat than for either the air-ride bus seat or the air-ride truck seat, across all three road types. This study also demonstrated that seat-suspension designs have a significant effect on the vibrations transmitted to vehicle operators, and the study's results may prove useful in designing future seat suspensions.*

**Keywords** ergonomics, low back pain, road surface evaluation, vibration simulator

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## INTRODUCTION

Full-time professional drivers of buses and trucks regularly spend long hours (typically 8 hours per day) seated in heavy vehicles, where they are regularly exposed to whole-body vibration (WBV). Long-term exposure to WBV and manual material handling tasks are two of the leading risk factors for the development of low back disorders, especially low back pain (LBP).(1) A European study of professional drivers found a strong link between WBV exposure and LBP development, with evidence for a dose-dependent pattern.(2) Epidemiology studies have also shown an association between the development of occupational back pain and long-term exposure to WBV.(1,3,4) The risk for low back injury has been shown to increase with the duration and dose of WBV exposure.(5,6)

According to the U.S. Bureau of Labor Statistics, truck drivers in the transportation and warehousing sector average 5.5 recordable injuries/year/100 full-time workers. This figure is higher than the total private industry rate (3.5 injuries/year/100 full-time workers), as well as the rate for other job classifications that involve extended hours in the seated position, such as administrative assistants (2.7 injuries/year/100 full-time workers).(7) The long hours worked by professional truck drivers contribute to the increased rate of driver injury.(8,9) Physical exposures experienced by truck drivers—such as WBV and prolonged sitting in a static position—increase drivers' risk for developing LBP, sciatic pain, and degenerative disc disease.(10)

Transit bus drivers represent a large population of professional drivers who are at risk for back injuries, including LBP.

Up to 81% of professional bus drivers in the United States have reported developing LBP during the course of their work.(11) Several studies of professional bus drivers have established a strong association between LBP development and WBV exposure.(12–14) However, the effort to isolate the etiology of LBP development among professional drivers is complicated by several factors, including that up to 80% of the general U.S. population will eventually develop LBP.(15)

Exposure to WBV has been linked to several types of spinal injuries, including damage to the disc and bony endplates of the lumbar vertebral body.(16) Researchers have reported that micro-fractures in those endplates can lead to disc degeneration.(17–19) Biomechanical research has also linked WBV to elevated spinal loads,(20, 21) muscle fatigue in the supporting musculature,(14) and thinning of the intervertebral discs and subsequent disc herniation.(22, 23) Continuous vibration exposure in the occupational environment can lead to changes in cartilage, discs, muscle, and bone.(24) Development of LBP from WBV exposure may be gradual and insidious, unlike the often acute onset of back pain typically associated with manual material handling and lifting tasks.(14, 24)

Chronic exposure to WBV can also affect the body's musculoskeletal, cardio-vascular, cardiopulmonary, metabolic, endocrine, nervous system, and gastrointestinal systems.(21) Impulsive shocks associated with large bumps are particularly damaging(16) to the thoracic and lumbar regions of the spine.(25) In addition to the adverse health effects arising from chronic WBV exposure, significant discomfort has been reported by subjects exposed to multiple, short-duration vertical shocks, such as those that are produced by driving over a pothole.(26)

Air-ride seats currently dominate the seating market for transit buses and trucks. This technology utilizes a compressed-air bladder to passively attenuate WBV exposure. However, impulsive shocks can cause large oscillatory vibrations that air-ride seats may not be able to fully attenuate.

A seat that utilizes electromagnetically active (EM-active) seat-suspension technology has recently been introduced into the market. This technology relies on a built-in microprocessor and a linear actuator to continuously and instantaneously control vertical, vibration-induced seat motion. The technology is designed to actively attenuate both low frequency oscillations and high frequency impulsive vibrations.

This study evaluated and compared the abilities of an air-ride bus seat, an air-ride truck seat, and an EM-active seat to attenuate WBV exposures. This study also compared WBV exposure by road types and subject weight classes, including the measurement of the vertical vibration transmission from the floor, seat pan, and sternum of subjects.

## METHODS

### Study Population

The cohort recruited for this study consisted of 12 healthy males, 10 of whom were professional drivers. The subjects had a mean (± SD) age of 36.8 (± 9.4) years, a mean height of 182.0 (± 9.0) cm, a mean weight of 112.0 (± 35.0) kg, and a mean Body Mass Index (BMI) of 34.0 (± 9.0) (Table I). Potential subjects were presented with a recruitment flyer, and selected subjects were given a monetary incentive for their participation in the study. To model the influence of subject weight on vibration exposure, subjects were selected based on their mass and then divided into two classes: a lightweight class (<102 kg) and a heavyweight class (>128 kg). There were six subjects enrolled in each weight class. Study procedures were approved by the University of Washington's Institutional Review Board and all subjects gave their informed consent.

### Vibration Simulation Testing Procedure

#### *Vibration Simulation Platform*

The use of a vibration platform to simulate real-world WBV exposure is novel and facilitates the rapid evaluation of seating systems for multiple field exposures. The test procedure used a six-degree-of-freedom vibration simulation hexapod (Model MB-E-6DPF, Moog Inc., East Aurora, NY) to play back WBV exposures that had been previously field-collected from a city transit bus and a truck. The simulated WBV exposures were three snapshot 180-second signal clips taken from separate routes—one route for the bus and one for the truck. To reflect WBV exposures commonly experienced by professional bus and truck drivers, both routes include three types of roads:

- a segment of city streets (the "city-street segment")—(180-sec clip)
- a freeway segment (the "freeway segment")—(180-sec clip) and
- a section of rough streets (the "rough-road segment")—(180-sec clip).

The bus route data were obtained from a standard route on a 40-ft New Flyer bus in Seattle, WA,(27) and the truck route data were obtained from a typical route on a Freightliner truck pulling a loaded flatbed trailer in Framingham, MA. The data used for the hexapod simulation did not include any stops, and the average speed was commensurate with the type of road: 35 mph, 60 mph, and 10 mph for the city-street, freeway, and rough-road segments, respectively.

To evaluate differences in WBV exposures associated with seat-suspension designs and road conditions, each subject rode the hexapod on all three seats: an air-ride suspension bus seat, an air-ride suspension truck seat, and an EM-active suspension seat (Figure 1). All the seats were available on the commercial market and had similar foam seat pan designs and suspension travel characteristics.

#### *Vibration Simulation Protocol*

Identical tri-axial accelerometers were mounted:

1. on the floor of the platform,
2. on the seat pan of each seat, and
3. on each subject's sternum (to measure WBV transmission through the spine).

Seat height was fixed at the mid-point of travel. Each seat back was reclined 10 degrees, and the subjects were not

**TABLE I. Subject Demographics, All Subjects Grouped on Their Weight to Generate Two Categories Light (<102 kg) and Heavy (>128 kg) [n = 12].**

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

permitted to adjust a seat's fore-and-aft position. To enable efficient completion of the data collection effort, two subjects rode the hexapod simultaneously (Figure 2).

### Data Collection Hardware

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

## Data Analysis

Data analysis was performed on a Dell laptop (Series 1500, Dell Inc., Round Rock, TX), running Windows 7 (Microsoft Inc., Redmond, WA) using LabVIEW (Version 2010, National Instruments Corp., Austin, TX).

Since it is common for professional bus and truck drivers to work at least 8 hours a day, the ISO 2631-1 time-weighted

**(1) Air Ride Truck Seat** **(2) Air Ride Bus Seat** **(3) EM-Active Seat**

**FIGURE 1**. Three seats used in the WBV simulations. Seat (3) was used with both the bus and truck vibration signal exposures.

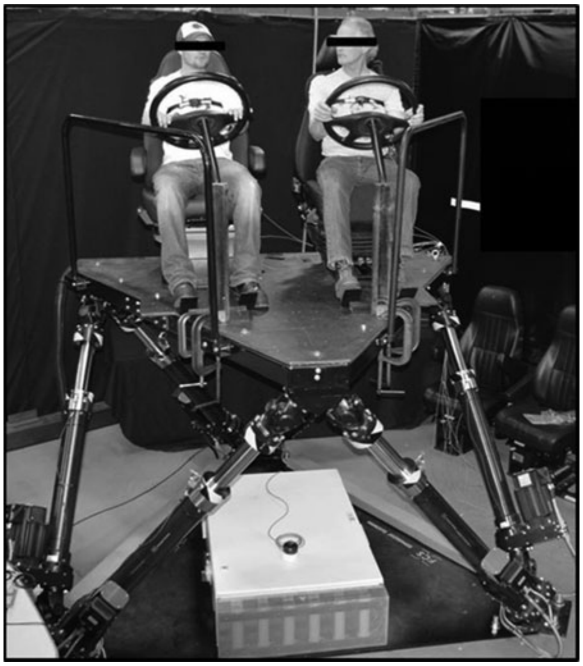

**FIGURE 2**. Lightweight subjects (<120 kg) on the vibration simulator hexapod.

average parameters were normalized to represent an 8-hour exposure, and the study assumed drivers drove 8 hours.$^{(28)}$ The WBV data from each simulation segment were normalized using the following equations:

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

$$\mathrm{VDV(8)} = \mathrm{VDV}\left[\frac{\text{exposure time(sec)}}{28,800\text{(sec)}}\right]^{\frac{1}{4}} \tag{2}$$

$$\mathrm{D_{kd}}\ (8)\ \&S_{ed}\ (8) = \mathrm{D_kd\ or\ S_{ed}}\left[\frac{\text{exposure time(sec)}}{28,800\text{(sec)}}\right]^{\frac{1}{6}} \tag{3}$$

For each road segment, Eq. 4 was used to calculate the RMS average weighted vibration, $A_w$, at three locations: (1) the floor of the platform, (2) the seat pan, and (3) each subject's sternum.

$$A_w = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{\frac{1}{2}} \text{ (units m/s}^2\text{)} \tag{4}$$

The resulting values were then normalized to an 8-hr daily exposure using Eq. 1. To reduce the likelihood of adverse health effects, the EU Vibration Directive recommends an A(8) daily action limit (AL) of 0.5 m/s$^2$ and a daily exposure limit (EL) of 1.15 m/s$^2$.$^{(29)}$

For each road segment, Eq. 5 was used to calculate the vibration dose value (VDV) at the same three locations as $A_w$.

$$VDV = \left\{\int_0^T [a_w(t)]^4\, dt\right\}^{\frac{1}{4}} \text{ (units m/s}^{1.75}\text{)} \tag{5}$$

The resulting values were then normalized to an 8-hour daily exposure using Eq. 2. VDV reflects the cumulative vibration and is more sensitive to impulsive vibration than is the average vibration. The EU's VDV(8) daily AL (9.1 m/s$^{1.75}$) and daily EL (21.0 m/s$^{1.75}$) are recommended to prevent adverse health effects.$^{(29)}$

ISO 2631-1 defines "crest factor" as the modulus of the ratio of the maximum instantaneous peak value of the frequency-weighted acceleration signal to its RMS value. The crest factor is relevant in determining whether the RMS parameter ($A_w$) is effective in characterizing WBV. ISO 2631-1 suggests that the $A_w$ be interpreted with caution when crest factors exceed nine.

Static compressive stress ($S_{ed}$) is defined in ISO 2631-5, and it has been developed through biomechanical modeling to capture the linear relationship between peak acceleration and input shocks to responses in the spine. In this study, $S_{ed}$ was evaluated at the subject's seat pan and then normalized to an 8-hour exposure using Eq. 3.

An intermediate step in calculating $S_{ed}$ was determining the acceleration dose ($D_{kd}$), which is designed to estimate the vibration dose.

$$D_{kd} = \left[\sum A_{ik}^6\right]^{\frac{1}{6}} \text{ (units m/s}^2\text{)} \tag{6}$$

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

$$S_{ed} = \left[\sum_{k=x,y,z} (m_k D_k)^6\right]^{\frac{1}{6}} \text{ (units MPa)} \tag{7}$$

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

According to ISO 2631-5, $S_{ed}(8)$ values less than 0.50 MPa represent a low probability of an adverse health effect (AHE); values in the range 0.5 MPa – 0.80 MPa represent a moderate probability of an AHE; and values above 0.8 MPa represent a high probability of an AHE.$^{(16)}$

The vibration total value (vector sum) is a standard method of comparing performance for exposure scenarios where there is more than one predominant axis of vibration exposure. Vector sum exposures for A(8), VDV(8), and $S_{ed}(8)$ were calculated using Eq. 8.

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

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

How well a seat attenuates vibration is commonly quantified by calculating a Seat Effective Amplitude Transmissibility (SEAT) factor, which is the ratio of the vertical WBV exposures measured at the seat to those measured at the floor.

The SEAT values for A(8) and VDV(8) are:

$$SEATA(8)(\%) = \frac{A(8)_{seat}}{A(8)_{floor}} \times 100 \quad \textbf{(9)}$$

$$SEATVDV(8)(\%) = \frac{VDV(8)_{seat}}{VDV(8)_{floor}} \times 100 \quad \textbf{(10)}$$

The Power Spectral Densities (PSDs) referenced in this manuscript show the distribution of vibration over the frequency range from 0 to 30 Hz. The frequency dependent transfer function is the ratio of the seat acceleration to the resulting acceleration in each of the three vibration directions (measured at the sternum).

### Data Processing and Statistical Analyses

A repeated measure analysis of variance was performed using JMP Statistical Discovery Software (Version 10.0, SAS Institute, Cary, SC) to determine if there were differences in WBV exposures among the road types, driver weight classes, and the seat suspension designs for both the bus and truck road signals. Differences in vibration exposure by road type and seat design were considered significant when p-values were less than 0.05.

The JMP software was also used to statistically compare the vibration-transmission PSDs for three types of seats. A one-way analysis of variance (ANOVA) was performed at the low peak (1–5 Hz) and high peak (14–18 Hz) to study the effect of the seat on the vertical (seat-pan-to-sternum) transmission. That peaks are important to professional drivers has been shown in prior research, which has illustrated that prolonged exposure to these frequencies can result in spinal injuries.

## RESULTS

### Truck Signal Seat Performance by Weight Class

There were significant differences in seat-pan vibrations between the air-ride truck seat and the EM-active seat in the city-street, freeway, and rough-road segments (Table II). Although seat artifacts were not controlled during the analysis, the air-ride truck seat universally transmitted the highest seat-pan vibration in the z-axis, with the largest vibration occurring in the rough-road segment. However, the highest seat-pan exposures for the EM-active seat were in the y-axis in all cases, except for the heavyweight drivers on the rough-road segment. The largest exposures consistently appeared in the rough-road segment, although the exposures between the EM-active seat and the air-ride truck seat were not statistically different. This finding remained consistent for these seats for both the A(8) and VDV(8) parameters. To compare seat performance between various road and subject conditions that resulted in different dominant axes, vector sum calculations were performed. The calculations showed that the EM-active seat performed significantly better than the air-ride seat for both the lightweight and heavyweight classes across the vector sum A(8), VDV(8), and Sed(8) parameters for all road types ($\alpha = 0.05$).

### Bus Signal Seat Performance by Weight Class

There were significant differences in seat-pan vibration exposures between the air-ride bus seat and the EM-active seat in the city-street, freeway, and rough-road segments (Table III). The air-ride bus seat universally transmitted the highest seat-pan vibration in the z-axis, with the largest vibration occurring in the rough-road segment. Unlike the truck signal, the highest seat-pan exposures for the EM-active seat on the bus signal were in the z-axis, with the largest vibration also being in the rough-road segment, although at levels significantly lower than those from the air-ride bus seat. These findings remained consistent for both the air-ride bus seat and the EM-active seat, for both the A(8) and VDV(8) parameters.

Vector-sum values were calculated to compare exposures between the truck signal (Table II) and the bus signal (Table III) with different dominant axes. The calculations showed that the EM-active seat performed significantly better on the bus signal than the air-ride bus seat, across the A(8), VDV(8), and $S_{ed}(8)$ parameters on all road types ($\alpha = 0.05$).

### Power Spectral Density Analysis

The power spectral densities (PSDs), which show the distribution of vibration over the frequency range from 0 to 30 Hz, were also examined. The relation between the PSDs at the seat and at the sternum-mounted accelerometers provides a measure of the vibration transmission from the seat to the subject's spine. Figure 3 shows a typical PSD diagram for the seat and sternum transfer function.

#### *WBV z-axis Transmission by Truck and Bus Signal: City-Street Segment*

The results of the z-axis analysis on the city-street bus and truck signals are shown in Figure 4. At the low peak (1–5 Hz) on the bus signal, the EM-active seat had significantly lower seat-pan-to-sternum transmission of z-axis vibration than the air-ride bus seat for all subjects grouped (n = 12) and the lightweight subjects (n = 6). There was no significant difference between the two types of bus seats for heavyweight subjects (n = 6). At the high peak (14–18 Hz) on the bus signal, there was no significant difference between the two types of bus seats for all subjects, for the lightweight subjects, or for the heavyweight subjects.

At the low peak (1–5 Hz) on the truck signal, the EM-active seat did not show a significantly lower seat-pan-to-sternum transmission of z-axis vibration than the air-ride truck seat for all subjects or the heavyweight subjects. The EM-active seat had a significantly lower seat-pan-to-sternum transmission of z-axis vibration than the air-ride truck seat for lightweight subjects. At the high peak (14–18 Hz) for the truck signal, the air-ride truck seat had a significantly lower seat-pan-to-sternum transmission of z-axis vibration than the EM-active seat for all subjects, the lightweight subjects, and the heavyweight subjects.

## TABLE II. Truck Signal WBV Mean (S.E.) Seat Pan Exposures by Segment, Weight Group, and Seat [n = 6 Light, n = 6 Heavy]

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

[A] Air-ride truck seat.

[B] ISO 2631-1 indicates that potential health risks exist at this level.

[C] This value exceeds the value of 0.5 $m/s^2$ that the EU Vibration Directive establishes as the A(8) daily action limit.

[D] This value exceeds the value of 9.1 $m/s^{1.75}$ that the EU Vibration Directive establishes as the VDV(8) daily action limit. Also, ISO 2631-1 indicates that potential health risks exist at this level.

[E] According to ISO 2631-5, $S_{ed}(8)$ values less than 0.50 MPa represent a low probability of an AHE. All $S_{ed}(8)$ values presented in this table lie below 0.50 MPa.

**TABLE III. Bus Signal WBV Mean (S.E.) Seat Pan Exposures by Segment, Weight Group, and Seat [n = 6 Light, 6 Heavy]**

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

Note: $^A$Crest factors greater than 9.

$^B$Air-ride bus seat.

$^C$According to ISO 2631-5, $S_{ed}(8)$ values less than 0.50 MPa represent a low probability of an AHE. All $S_{ed}(8)$ values presented in this table lie below 0.50 MPa.

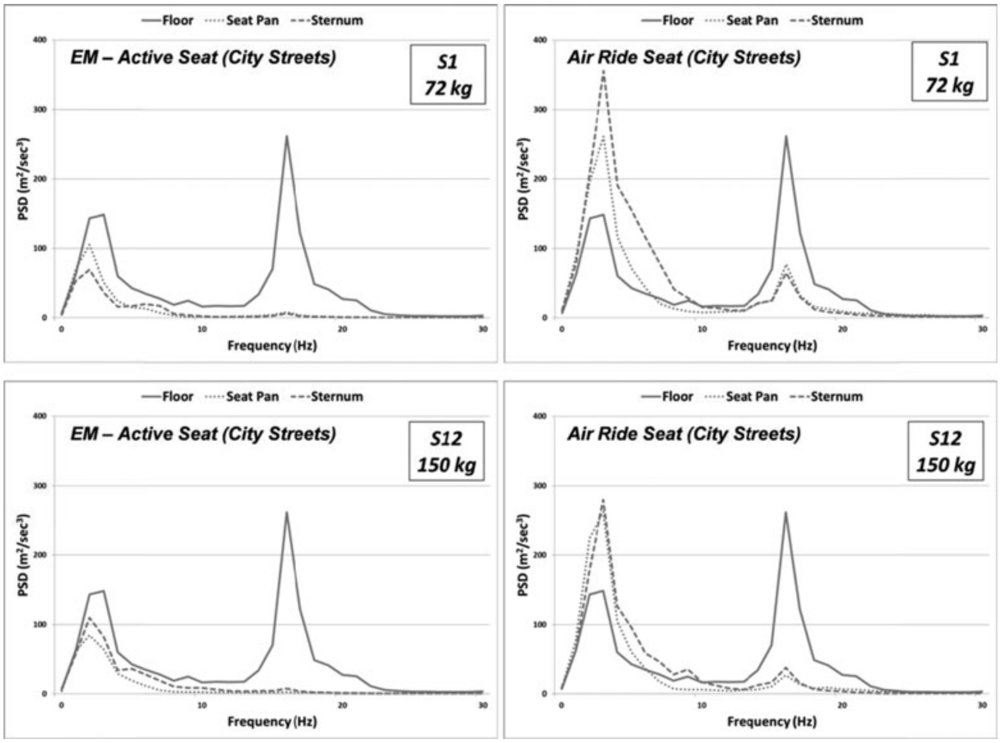

**FIGURE 3**. EM-active seat and air-ride seat PSD Plot in the vertical (z-axis) direction floor, seat, and sternum.

### *WBV z-axis Transmission by Truck and Bus Signal: Freeway Segment*

At the low peak (1–5 Hz) on the bus freeway signal, the EM-active seat had a significantly lower seat-pan-to-sternum transmission of z-axis vibration than the air-ride bus seat for all subjects and the lightweight subjects (Figure 5). There was no significant difference between the EM-active seat and the air-ride bus seat for the heavyweight subjects. For the high peak (14–18 Hz) on the bus signal, there was no significant difference in vibration transmission between seats for all subjects. However, the EM-active seat had a significantly lower seat-pan-to-sternum transmission of z-axis vibration than the

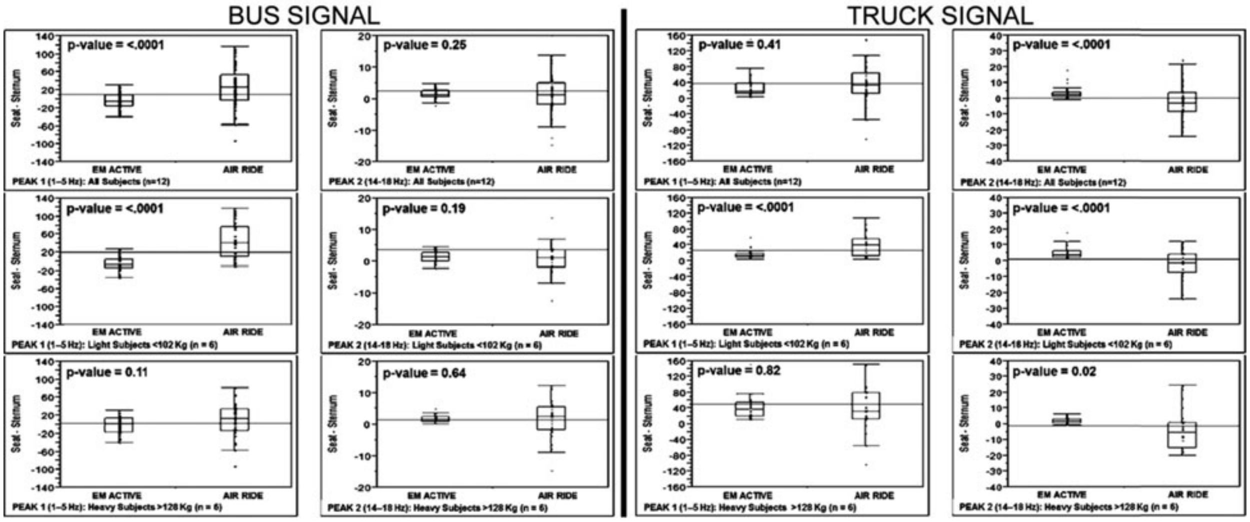

**FIGURE 4**. City-street PSD transmission seat pan to sternum over bus and truck signal. All subjects (n = 12), (lightweight (n = 6) and heavyweight (n = 6) comparison).

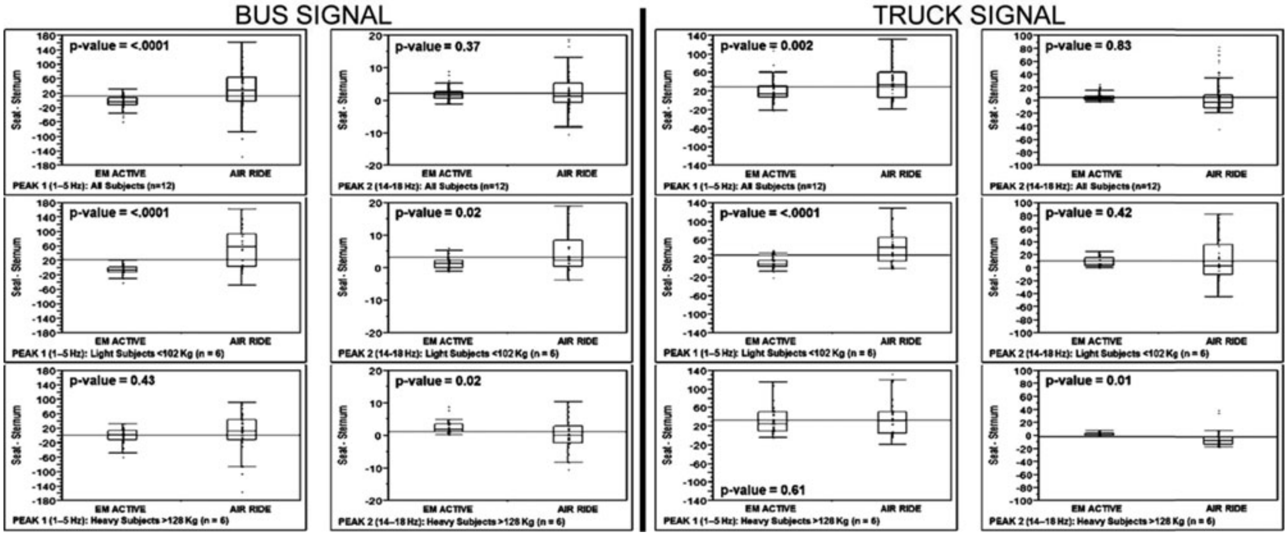

**FIGURE 5**. Freeway PSD transmission seat pan to sternum over bus and truck signal. All subjects (n = 12), (lightweight (n = 6) and heavyweight (n = 6) comparison).

air-ride bus seat for the lightweight subjects, while the air-ride bus seat performed significantly better than the EM-active seat for the heavyweight subjects.

For the low peak (1–5 Hz) on the truck signal, the EM-active seat showed a significantly lower seat-pan-to-sternum transmission of z-axis vibration than did the air-ride truck seat for all subjects and the lightweight subjects alone. The heavyweight subjects did not have significant vibration transmission differences on the truck freeway signal at the low peak. Finally, when comparing performance of the EM-active seat and air-ride truck seat at the high peak (14–18 Hz), there was no significant difference between the two types of seats for all subjects or the lightweight subjects. However, the air-ride truck seat had significantly lower seat-pan-to-sternum transmission of z-axis vibration than the EM-active seat for the heavyweight subjects.

### *WBV z-axis Transmission by Truck and Bus Signal: Rough-Road Segment*

At the low peak (1–5 Hz) for the bus signal, the EM-active seat had a significantly lower seat-pan-to-sternum transmission of the z-axis vibration than the air-ride bus seat for all subjects and the lightweight subjects (Figure 6). There was no significant difference between the two types of bus seats for the heavyweight subjects. At the high peak (14–18 Hz) on the bus signal, there was no significant difference between the two types of bus seats for all subjects, the lightweight subjects, or the heavyweight subjects.

At the low peak (1–5 Hz) for the truck signal, the EM-active seat showed a significantly lower seat-pan-to-sternum transmission of z-axis vibration than the air-ride truck seat for all subjects and the lightweight subjects alone. There was no significant difference between the two types of seats with the heavyweight subjects. At the high peak (14–18 Hz) for the truck signal, the air-ride truck seat had significantly seat-pan-to-sternum transmission of z-axis vibration than the EM-active seat for all subjects, lightweight subjects, and the heavyweight subjects.

### *Analysis of Variance by Segment and Seat Type*

At the low peak (1–5 Hz) for the bus signal, the EM-active seat reduced seat-pan-to-sternum transmission of z-axis vibration significantly more than the air-ride bus seat did for all three types of road segments (Table IV). There was no significant difference between the EM-active seat and air-ride bus seat at the high peak (14–18 Hz) signal on any of the three types of road segments.

At the low peak (1–5 Hz) for the truck input signal, the EM-active seat and the air-ride truck seat both amplified the seat-pan-to-sternum transmission of z-axis vibration on all three types of road segments. However, the EM-active seat resulted in significantly less amplification on the freeway and rough-road segments than the air-ride seat. At the high peak (14–18 Hz), the air-ride truck seat produced significantly less seat-pan-to-sternum transmission of z-axis vibration than the EM-active seat on the city-street and rough-road segments.

## DISCUSSION

### Truck Signal WBV Seat Performance

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

The EM-active seat transmitted approximately 30% less vibration than the air-ride seat (Table II). Since both seats were

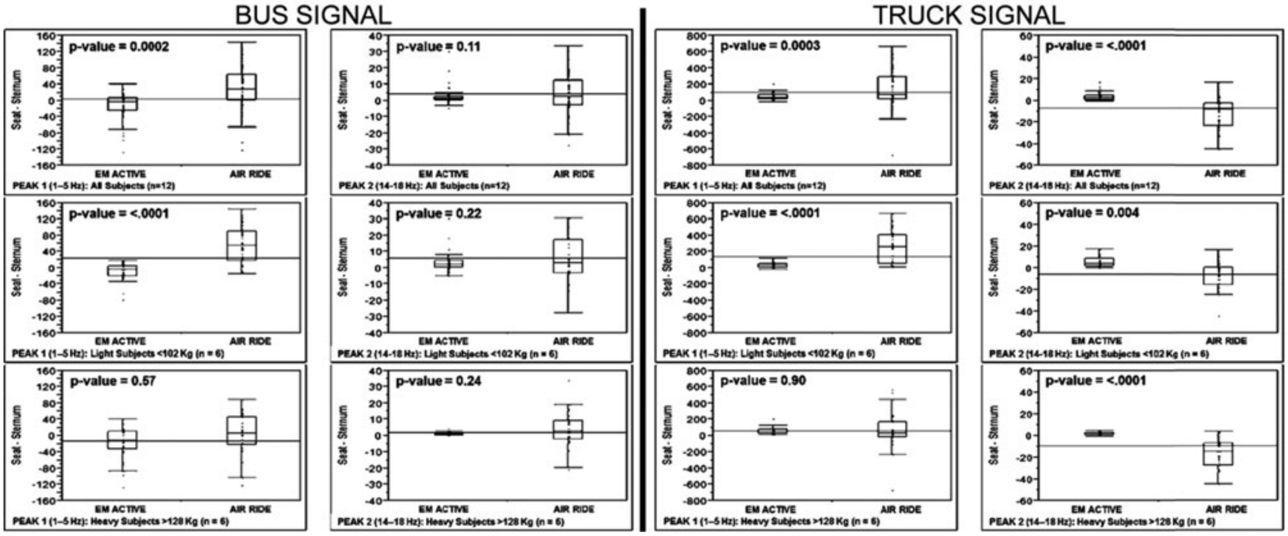

**FIGURE 6**. Rough-road PSD transmission seat pan to sternum over bus and truck signal. All subjects (n = 12), (lightweight (n = 6) and heavyweight (n = 6) comparison).

simultaneously mounted on the hexapod and were stimulated by the same input signal, this study illustrated the EM-active technology's exposure-reduction potential. The difference in vector sum values was similar across both the lightweight and heavyweight subjects. The vibration differences between seats was most pronounced during the rough-road segment of the simulation, with the EM-active seat transmitting approximately 46% less vibration than the air-ride truck seat.

Previous research on forklift operators has shown that seat-suspension design can significantly reduce vibration transmission from the cab floor to the operator's seat.(30) The EM-active seat has not been tested in forklifts; however, it is clear that seat-suspension design can significantly affect vibration exposure in a variety of vehicles, and this topic could be the subject of future research.

### Bus Signal WBV Seat Performance

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

The EM-active seat transmitted approximately 44% less vibration than the air-ride seat (Table III). The difference in vector-sum values was similar across both the lightweight and heavyweight subjects. The vibration attenuation differences between the EM-active and air-ride seats remained consistent across all types of road segments.

### WBV Power Spectral Density Analysis

An interesting and novel finding of this study concerned the difference in vibration transmission between the seat-pan and sternum-mounted accelerometers with the EM-active and air-ride seats. The plot of power spectral densities revealed bimodal frequency peaks at approximately 3 Hz and 16 Hz, showing two areas of concentrated signal power (low and high frequency) relevant to resonant frequencies for the human spine, as have been identified in prior research (at 5 Hz).(21) The EM-active seat resulted in lower transmission of vertical (z-axis) vibration from the seat-pan-to-sternum at the low peak (1–5 Hz) on both the bus and truck signals. This finding suggests that there is potential to reduce the vibration measured at the sternum of drivers by equipping their vehicles with the EM-active seat-suspension technology. However, this finding was not replicated at the high peak (14– 18 Hz), where:

(1) the air-ride truck seat performed better than the EM-active seat with the truck signal, and
(2) there was no statistically significant difference between the EM-active seat and the air-ride bus seat with the bus signal.

This analysis also found differences in the seat-pan-to-sternum transmissions between the lightweight and the heavyweight subjects. This finding illustrates that the body mass of the subject plays a role in the transmission of vertical vibration through the torso. A similar result has been shown in research measuring WBV transmission in cadavers.(31)

### Additional Factors Affecting WBV

Posture has been shown to have a significant effect on the WBV exposure outcomes for vehicle drivers, however, posture is difficult to control in real-world settings.(14) Additionally, the placement and adjustment of foot supports and the backrest can have a significant effect on the absorption of WBV for seated drivers.(32) Posture was controlled during this study. Subjects were not permitted to adjust the seat back, and they were required to keep one hand on the steering wheel and their feet on the simulation pedals at all times.

**TABLE IV. PSD Transmission Seat to Sternum. Means for One-way ANOVA Comparing Bus and Truck Signal by Seat and Segment, All Subjects Grouped [n = 12]**

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

Note: ↓ - Indicates z-axis attenuation from seat pan to sternum.
↑ - Indicates z-axis amplification from seat pan to sternum.

Employers of professional drivers and manufacturers of commercial trucks and buses should consider the type of seat suspension when designing and equipping the vehicle cab. In particular, the design of the driver cockpit and the selection of the seat suspension system can significantly affect the driver's exposure to vibration and can potentially reduce injury outcomes associated with chronic WBV exposure. Recent research has shown that the cab design and layout have the potential to significantly reduce vibration exposure.(33)

### Limitations of the Study

One limitation of this study was that the order of the seats ridden by each subject was not randomized. This limitation resulted from the limited access to the hexapod simulator and the extensive resources required to install seats. A second limitation was that the field-collected vibration signals used to generate the truck and bus exposures were collected on different roads in different cities, since it was not logistically feasible to collect vibration exposure data from the same roadway for both the bus and the truck. A third limitation is that the field-collected data had to be iterated for use with the hexapod to conform to the configuration and travel limits of the simulator. Consequently, the simulated exposures may have been an underestimation of actual exposures. Future studies that measure WBV exposure would benefit from having a larger cohort of subjects divided into more than two weight classes to better assess the relationship between WBV exposure and driver weight.

## CONCLUSION AND RECOMMENDATIONS

The selection of seating for professional drivers is often made with durability, cost, and comfort as the primary selection criteria. The driver's potential exposure to WBV is often only a distant consideration, and it may not be positively correlated with comfort. This study suggests that the type of seat suspension can have a significant effect on the overall WBV exposure. Given the high costs employers incur when drivers are injured or disabled with back pain, efforts should be made to reduce the occurrence of LBP and other conditions associated with chronic WBV exposure. Two specific steps would help achieve this goal. First, employers should consider including seat vibration attenuation as a primary criterion when selecting seats for bus and truck fleets. Second, seat designers should make a renewed effort to design and develop products that reduce the transmission of vibrations from the vehicle to the driver.

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## REFERENCES

1. **Bernard, B.P. (ed.):** Musculoskeletal Disorders and Workplace Factors. *DHHS (NIOSH) Publication No. 97-141*. Cincinnati, OH: National Institute for Occupational Safety and Health, 1997.
2. **Tiemessen, I.J.H.**, **C.T.J. Hulshof, and M.H.W. Frings-Dresen:** Low back pain in drivers exposed to whole body vibration: Analysis of a dose-response pattern. *Occup. Environ. Med. 65*(*10*):667–675 (2008).
3. **Pope, M.H.**, **G.B.J. Andersson**, **J.W. Frymoyer, and D.B. Chaffin (eds.):** Occupational Low Back Pain: *Assessment, Treatment and Prevention*. St. Louis, MO: Mosby Year Book, 1991.
4. **National Research Council (NRC) and Institute of Medicine (IOM):** Musculoskeletal Disorders and the Workplace: Low Back and Upper Extremities. *Panel of Musculoskeletal Disorders and the Workplace. Commission on Behavioral and Social Sciences and Education*. Washington, DC: National Academy Press, 2001.
5. **Teschke, K.**, **A. Nicol**, **H. Davies, and S. Ju:** Whole Body vibration and Back Disorders among Motor Vehicle Drivers and Heavy Equipment Operators: A Review of the Scientific Evidence. Report to Worker's Compensation Board of British Columbia, Vancouver, BC, Canada, 1999.
6. **Chen, J.C.**, **W.R. Chang**, **T.S. Shih, et al.:** Using exposure prediction rules for exposure assessment: An example on whole-body vibration in taxi drivers. *Epidemiology 15*(*3*):293–299 (2004).
7. **United States Bureau of Labor Statistics (BLS):** 2010 *Workplace Injuries and Illnesses*. United Stated Department of Labor. USDL-11-1502, 2011.
8. **Sabbagh-Ehrlich, S.**, **L. Friedman, and E.D. Richter:** Working conditions and fatigue in professional truck drivers at Israeli ports. *Injury Prev. 11*:110–114 (2005).
9. **Robb, M.J., and N.J. Mansfield:** Self-reported musculoskeletal problems amongst professional truck drivers. *Ergonomics 50*(*6*):814–827 (2007).
10. **Van der Beek, A.J.:** World at work: Truck drivers. *Occup. Environ. Med. 69*:291–295 (2012).
11. **U.S**. Department of Health and Human Services (DHHS): Summary Health Statistics for U.S. Adults: National Health Interview Survey, 2002. *Vital and Health Statistics Series 10, No. 222 (DHHS Publication No. (PHS) 2004-1550)*. Hyattsville, MD, 2004.
12. **Alperovitch-Najenson, D.**, **Y. Santo**, **Y. Masharawi, et al.:** Low back pain among professional bus drivers: Ergonomic and occupational psychosocial risk factors. *Israeli Med. Assoc. J. 12*:26–31 (2010).
13. **Okunribido, O.O.**, **M. Magnusson, and M. H. Pope:** The role of whole body vibration, posture and manual materials handling as risk factors for low back pain in occupational drivers. *Ergonomics 51*(*3*):308–329 (2008).
14. **Wilder, D.**, **M.L. Magnusson**, **J. Fenwick, and M. Pope:** The effect of posture and seat suspension design on discomfort and back muscle fatigue during simulated truck driving. *Appl. Ergon. 25*(*2*):66–76 (1994).
15. **Deyo, R.A.:** Low-back pain. *Sci. Am. 279*(*2*):49–54 (1998).
16. **International Organization for Standardization (ISO)**: *Mechanical Vibration and Shock - Evaluation of Human Exposure to Whole-Body Vibration - Part 5: Method for Evaluation of Vibration Containing Multiple Shocks* (ISO 2631-5). [Standard] Geneva: ISO, 2004.
17. **Brinckmann, P.**, **N. Johannleweling**, **D. Hilweg, and M. Biggeman:** Fatigue fracture of human lumbar vertebrae. *Clin. Biomech. 2*:94–96 (1987).
18. **Hansson, T. H.**, **T.S. Keller, and D.M. Spengler:** Mechanical behavior of the human lumbar spine, fatigue-strength during dynamic compressive loading. *Orth. Research 5*:479–487 (1987).
19. **Sandover, J.:** Dynamic loading as a possible source of low-back disorders. *Spine 8*:652–658 (1983).
20. **Fritz, M.:** Estimation of spine forces under whole-body vibration by means of a biomechanical model and transfer functions. *Aviat. Space. Envir. Md. 68*:512–519 (1997).
21. **Fritz, M.:** Description of the relation between the forces acting in the lumber spine and whole-body vibrations by means of transfer functions. *Clin. Biomech. 15*:234–240 (2000).
22. **Griffin, M. J.:** *Handbook of Human Vibration*. London: Elsevier Academic Press, 1990 pp. 171–219.
23. **Thalheimer, E.:** Practical approach to measurement and evaluation of exposure to whole-body vibration in the workplace. *Semin. Perinatol. 20*:77–89 (1996).
24. **Wilder, D. G., and M.H. Pope:** Epidemiological and aetiological aspects of low back pain in vibration environments—An update. *Clin. Biomech. 11*:61–73 (1996).
25. **Bass, C. R.**, **K.A. Rafaels**, **R.S. Salzar, et al.:** Thoracic and lumbar spinal impact tolerance. *Accident. Anal. Prev. 40*:487–495 (2008).
26. **Ahn, S. J., and M. J. Griffin:** Effects of frequency, magnitude, damping, and direction on the discomfort of vertical whole-body mechanical shocks. *Sound Vib. 311*:485–497 (2008).
27. **Blood, R.P.**, **J.D. Ploger**, **M.G. Yost**, **R.P. Ching, and P.W. Johnson:** Whole body vibration exposures in metropolitan bus drivers: A comparison of three seats. *Sound Vib. 329*:109–120 (2010).
28. **International Organization for Standardization (ISO)**: *Mechanical Vibration and Shock—Evaluation of Human Exposure to Whole-Body Vibration—Part 1: General Requirements* (ISO 2631-1). [Standard] Geneva: ISO, 1997.
29. **European Union:** Directive 2002/44/EC of the European Parliament and of the Council of 25 June 2002 on the Minimum Health and Safety Requirements Regarding the Exposure of Workers to the Risks Arising from Physical agents (Vibration) (Sixteenth Individual Directive Within the Meaning of Article 16(1) of Directive 89/391/EEC). *Official J. Eur. Commun.*, L177/13 (July 6, 2002).
30. **Blood, R.P., J. D. Ploger, and P.W. Johnson:** Whole body vibration exposures in forklift operators: Comparison of a mechanical and air suspension seat. *Ergonomics 53*(*11*):1385–1394 (2010).
31. **El-Khatib, A., F. Guillon, and A. Domont:** Vertical vibration transmission through the lumbar spine of the seated subject—First results. *Sound Vib. 215*(*4*):763–773 (1998).
32. **Nawayseh, N., and M.J. Griffin:** Power absorbed during whole-body vertical vibration: Effects of sitting posture, backrest, and footrest. *Sound Vib. 329*:2928–2938 (2010).
33. **Jorgensen, M.J., N.K. Kittasamy, and P.B. Aedla:** Repeatability of a checklist for evaluating cab design characteristics of heavy mobile equipment. *J. Occup. Environ. Hyg. 4*:913–922 (2007).