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Comparison of whole-body vibration exposures in buses: effects and interactions of bus and seat design

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Bus and seat design may be important for the drivers' whole-body vibration (WBV). WBV exposures in buses during actual operation were assessed. WBV attenuation performance between an air-suspension seat and a static pedestal seat in low-floor buses was compared; there were no differences in WBV attenuation between the seats. Air-suspension seat performance in a high-floor and low-floor bus was compared. Relative to the pedestal seat with its relatively static, limited travel seat suspension, the air-suspension seat with its dynamic, longer travel suspension provided little additional benefit. Relative to the measurement collected at the bus floor, the air-suspension seat amplified the WBV exposures in the high-floor bus. All WBV exposures were below European Union (EU) daily exposure action values. The EU Vibration Directive only allows the predominant axis of vibration exposure to be evaluated but a tri-axial vector sum exposure may be more representative of the actual health risks.

Practitioner Summary: Low back pain is common in bus drivers and studies have shown a relationship with whole body vibration. Relative to a pedestal seat with its limited travel seat suspension, the air-suspension seat with its longer travel suspension provided little additional benefit. Exposures were below European Union daily exposure action values.

Keywords: SEAT; Seat Effective Amplitude Transmissibility; European Vibration Directive; ISO 2631-1; low back pain; WBV

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1. Introduction

In a Swedish review covering 25 scientific international articles, a strong association has been shown to exist between low back pain as well as sciatica and long-term exposure to whole-body vibration (WBV) (Torén, Albin, and Järvholm 2012). A dose-response pattern between low back pain and WBV has been reported in Europe (Bovenzi 2009) and the USA (Magnusson et al. 1996) and exposure to WBV when combined with non-neutral, rotated trunk postures is believed to increase the likelihood of a vehicle operator developing low back discomfort (Mansfield et al. 2014). Besides contributing to low back pain, it is not uncommon for WBV to contribute to injuries in other parts of the body and contribute to disruption of certain physiological processes (Gruber and Ziperman 1992). Urban bus drivers are exposed to both continuous vibration and impulsive shocks when driving a bus (Blood et al. 2010; Lewis and Johnson 2012; Thamsuwan et al. 2013), and the bus suspension and the bus driver's seat can affect the magnitude of the WBV exposures. Other important factors not addressed in this study that could contribute to and cause the low back pain include prolonged sitting, poor postures such as trunk rotation and other non-driving factors such as age, heavy lifting, poor diet or psychosocial factors (Kyung and Nussbaum 2013; Morgan and Mansfield 2014; Robb and Mansfield 2007).

The European Union (EU) directive (European-Council 2002) was developed to limit professional drivers' exposures to WBV. The EU directive specifies two levels of exposure: the daily exposure action values (DEAVs) and the daily exposure limit values (DELVs). When the DEAVs are exceeded, the directive recommends that employers establish and implement technical and/or organisational measures to reduce the operator's exposures to WBV. When the DELVs are exceeded, the directive recommends that employers take immediate action to reduce the WBV exposures below the exposure limit value. For continuous WBV vibration exposures which do not contain shocks or impulses, the average, frequency-weighted acceleration, normalised to reflect an eight-hour period, A(8), should be used for the risk assessment. However, if there are shocks and impulsive exposures present in the WBV exposure data, the Vibration Dose Value (VDV), normalised to reflect an eight-hour period, VDV(8), is thought to be a better measure for assessing risks (Bovenzi 2010). In 2005, The EU directive was implemented as a Swedish directive (Arbetsmiljöverket 2005) and only A(8) measures were recommended to be used to perform risk assessments (but not VDV(8)); however, if the vibration data were thought to contain shocks or

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Table 1. Daily action levels and exposure limits for whole-body vibration.

	European Union Directive, 2002 A(8) (m/s^2)	VDV(8) (m/s$^{1.75}$)
Daily exposure action value (DEAV)	0.5	9.1
Daily exposure limit value (DELV)	1.15	21

impulsive exposures, this directive refers to the international WBV standard 2631-5 (ISO 2004) and the calculation of the daily equivalent static compressive dose (S_{ed}) from the raw, continuously collected vibration data.

The association of low back pain and exposure to multiple shocks has been reviewed (Waters et al. 2007) and the authors found that the use of the ISO 2631-5 standard has not been validated and appears to dramatically underestimate health risks relative to the WBV exposure parameters in ISO 2631-1 (ISO 1997). There is still a lack of knowledge on the valid exposure assessment methods and associated injury mechanisms. There are numerous vibration exposure parameters described in the literature but we have chosen to evaluate parameters outlined in the EU Vibration Directive, and, as a result, the parameters outlined in the ISO standard 2631-5 are not addressed in this study. The EU Vibration Directive DEAVs and DELVs for A(8) and VDV(8) WBV exposures are shown in Table 1.

Using low-floor city buses, the purpose of the present study was to determine whether there are differences in WBV attenuation characteristics between two types of bus driver seats: (1) the industry standard air-suspension seat which has a fair amount of suspension travel and (2) a height adjustable pedestal seat with virtually no seat suspension travel. The second purpose of this study was to compare the performance of the industry standard air-suspension seat in two different bus designs: (1) a low-floor city bus and (2) a high-floor coach bus. The overall aim was to improve bus drivers' health by reducing WBV exposures and provide relevant seat recommendation based on bus design. This study of WBV exposures may lead to engineering improvements or administrative controls to reduce the risk of injury and improve the work ability of the bus-driving environment. WBV exposures will be assessed using the Swedish directive (Arbetsmiljöverket 2005), the EU directive (European-Council 2002) and the international standards ISO 2631-1 (ISO 1997).

2. Material and methods

2.1. Study design

In order to study typical WBV exposures, 54 measurements, averaging 26 minutes in duration, were collected from 12 bus drivers travelling in regular traffic with passengers on roads to and from airports in Gothenburg, Sweden. The standard routes included freeways, city streets and speed humps, and a typical daily driving distance was 500 km over an eight-hour shift of work. As can be seen in Table 2, WBV exposures were compared between two seat types (pedestal and air suspension) and two bus types (low floor and high floor). All study procedures were approved by the Regional Ethical Review Board in Gothenburg and subjects gave their informed consent prior to participating in the study.

2.1.1. Seat types

As shown in Figure 1, two seat types were evaluated in this study. One class of seats was air-suspension seats. These seats were height adjustable and used an air-filled bellows in the seat suspension to reduce the vibrations transmitted to the seat of the driver. In this class of seat, the seat suspension had a relatively large range of travel (approximately ±6 cm) and the suspension travel was designed for absorbing road-related perturbations. The other class of seats evaluated was pedestal seats, which contained a gas spring in the seat base for height adjustment. This class of seat was characterised by relatively limited travel of the seat suspension, relative to the air-suspension seats, and the majority of the shock absorption comes from the foam in the seat pans. With respect to ergonomic features, the seats were similar in that both seats had backrests which were adjustable in angle, both had adjustable height armrests and both had adjustable seat pan depths. The pedestal

Table 2. Distribution of seat and bus types evaluated.

Drivers	Seat type	Bus type	Number of buses	Average bus age (years)	Number of road segments
7	Pedestal	Low floor	4	8.75	28
3	Air suspension	Low floor	2	1.5	15
2	Air suspension	High floor	1	3	11

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Figure 1. Examples of mechanical pedestal seat (left) and air-suspension seat (right). The seat pad accelerometer was rigidly taped to the seats.

seat differed in that its seat pan was adjustable in angle, the height of the seat back and lumbar support was adjustable and the driver could unlock and rotate the seat to face passengers entering the bus. The exact age of the seats could not be determined, but based on bus age (Table 2) the pedestal seats likely had been in service longer than the air-suspension seats.

2.1.2. Bus types

As shown in Figure 2, in addition to the two seat types, two bus types were evaluated: a low-floor city bus and a high-floor coach bus. The high-floor coach buses were primarily designed for longer commuter routes and between city trips, whereas the low-floor city buses were often used as intercity busses and designed for easy passenger entry and exit. The main difference between the two buses was the travel in the bus suspensions. The high-floor bus had greater suspension travel and a greater ability to absorb terrain-related perturbations, whereas the low-floor bus has less suspension travel and a lesser ability to absorb road perturbations.

2.2. *Data collection and exposure calculation*

The data acquisition system consisted of a four-channel data recorder with appropriate anti-aliasing filters (model DA-20, Rion Co. Ltd., Tokyo, Japan). Raw, un-weighted tri-axial, WBV data were collected at 1280 Hz per channel using a seat pad ICP accelerometer (model 356B41, PCB Piezotronics, Depew, NY) taped on the driver's seat (Figure 1) in order to prevent undesirable movements of the transducer. Collected acceleration directions were 'fore and aft', 'side-to-side' and 'up and down' and denoted the *x*-, *y*- and *z*-axes, respectively. Simultaneously, *z*-axis measurements (single axis) were collected with a magnetically mounted accelerometer (model 352C33, PCB Piezotronics, Depew, NY) secured to the bus

Figure 2. Examples of low-floor city bus (left) and high-floor coach bus (right).

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floor under the driver's seat. In addition, a Global Positioning System (model DG-100, GlobalSat, Chino, CA) logged GPS data every second in order to record the location and velocity of the bus, and the road segments associated with the WBV exposures.

GPS data and vibrations measured from the data recorder were synchronised into a single file, and the beginning and ending GPS coordinates were used to identify the start and end points for each of the road segments evaluated. An interactive graphical software program (Labview 2010, National Instruments, Austin, Texas, USA) was then used to calculate and save the various summary measures to a text file for subsequent statistical analysis.

2.3. WBV parameters

2.3.1. ISO 2631-1 parameters

According to the *ISO 2631-1* standard and the EU Vibration Directive, two WBV exposures were calculated.

The root mean square average-weighted vibration (a_w) during the measurement period:

$$a_w = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{1/2} \quad \text{Unit is m/s}^2. \tag{1}$$

The VDV:

$$\text{VDV} = \left[\int_0^T a_w^4(t)dt\right]^{1/4} \quad \text{Unit is m/s}^{1.75}, \tag{2}$$

where $a_w(t)$ is the instantaneous frequency-weighted acceleration and T is the duration of measurement.

In addition, health effects were also evaluated based on the vector sum $a_{w\Sigma xyz}$ and $\text{VDV}_{\Sigma xyz}$ exposures as shown in the formulas below:

$$a_{w\Sigma xyz} = [(1.4a_{wx})^2 + (1.4a_{wy})^2 + (a_{wz})^2]^{1/2}, \tag{3}$$

$$\text{VDV}_{\Sigma xyz} = [(1.4\text{VDV}_x)^4 + (1.4\text{VDV}_y)^4 + (\text{VDV}_z)^4]^{1/4}. \tag{4}$$

2.3.2. Daily eight-hour exposure

Finally, in order to determine the daily doses of the WBV exposures, the exposures from each sample collected were normalised to represent an eight-hour exposures as shown in the formulas below:

$$A(8) = a_w \times \left[\frac{\text{exposure time}}{8 \text{ hours}}\right]^{1/2}, \tag{5}$$

$$\text{VDV}(8) = \text{VDV} \times \left[\frac{\text{exposure time}}{T}\right]^{1/4}, \tag{6}$$

where T is the measurement time in hours and the *exposure time* is eight hours.

2.3.3. Daily permitted driving time

The EU Vibration Directive recommends the calculation of the driving times to reach the DEAVs for a_w and VDV. Times to reach those values were calculated using the following equations:

$$\text{time to DEAV for } a_w = 8\,\text{hours} \times \left[\frac{0.5\,\text{m/s}^2}{A(8)}\right]^2, \tag{7}$$

$$\text{time to DEAV for VDV} = 8\,\text{hours} \times \left[\frac{9.1\,\text{m/s}^{1.75}}{\text{VDV}(8)}\right]^4. \tag{8}$$

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2.3.4. *Seat transmissibility*

As can be seen in the formulas below, the Seat Effective Amplitude Transmissibility (SEAT) value was defined as the ratio between WBV exposures measured in the vertical direction (z-axis) measured at the seat and floor of the vehicle (Paddan and Griffin 2002). When below 1.0, the SEAT ratio indicates how well the seat attenuates vibration, and when above 1.0, the SEAT values indicate how much the seat amplifies the vibrations.

$$\mathrm{SEAT}_{aw} = a_{wz}\,\mathrm{seat}/a_{wz}\,\mathrm{floor}, \tag{9}$$

$$\mathrm{SEAT}_{\mathrm{VDV}} = \mathrm{VDV}_z\,\mathrm{seat}/\mathrm{VDV}_z\,\mathrm{floor}. \tag{10}$$

2.4. *Statistical analysis*

Statistical software (JMP, SAS Institute, Cary, SC) was used to perform the statistical analyses. A one-way analysis of variance was used to determine whether there were any differences between the three test conditions. Significance level (α) was assessed at $p < 0.05$. Tukey–Kramer pair-wise comparisons were used to identify where there were differences in WBV exposures across the different test conditions comparing seats and buses. Unless otherwise noted, all values are presented as mean $\pm$ one standard error. For the analysis of the driving time to reach the DEAVs, box and whisker plots were used to show the interquartile range and minimum and maximum of driving times. A corresponding Wilcoxon Rank-Sum test was used to determine where there were differences in the driving times to reach daily exposure limit between the A(8) and VDV(8) exposures.

3. Results

Table 3 shows the demographics of the drivers from the various bus and seat conditions evaluated. As shown in the table, there were moderate differences in driver height, weight and BMI across the three conditions evaluated.

Table 4 summarises the mean and range of the z-axis WBV exposures from the three conditions evaluated. When comparing the low- and high-floor buses, the high-floor bus had significantly lower A(8) and VDV(8) values measured at the bus floor, but there were no differences in the WBV exposures measured at the seat. The air-suspension seat performance was bus dependent with the air-suspension seat attenuating the WBV exposures in the low-floor bus (8% on average) but amplifying the WBV exposures (8% on average) in the high-floor bus. When comparing the performance between the pedestal and air-suspension seats in the low-floor buses, there were no differences in the seat-measured WBV exposures or the amount of vibration attenuated by the seats (as indicated by SEAT values). On average, the pedestal and air-suspension seats only attenuated 5% and 8% of the floor-measured vibration, respectively. All seat-measured z-axis WBV exposures were below EU WBV DEAVs of 0.5 m/s^2 and 9.1 m/s$^{1.75}$ for A(8) and VDV(8), respectively. Finally, as can be seen in the bottom row of Table 4, there were no differences in average travel speeds across the three conditions evaluated ($p = 0.51$).

The seat-measured WBV exposures are presented by axis and grouped by the three conditions in Table 5. As can be seen in the table, the z-axis was the predominant axis of exposure and there were mostly no differences in WBV exposures with the exception of the x-axis A(8) exposures and the z-axis VDV(8) exposures. For the x-axis A(8) exposures, the pedestal seat had significantly lower exposures ($p = 0.01$); and for the more impulsive z-axis VDV(8) exposures, the air-suspension seat in the high-floor bus demonstrated a trend indicating potentially lower exposures ($p = 0.07$). All the vector sum exposures were significantly higher than the predominant, z-axis exposures (ps < 0.05) and the differences in WBV exposures across conditions were smaller when the vector sum exposures were compared.

Table 3. The mean and range of the subject demographics grouped by the bus and seat conditions evaluated.

	Low floor Pedestal ($n = 7$)	Low floor Air-suspension ($n = 3$)	High floor Air-suspension ($n = 2$)
Height [cm]	181.7 (176–195)	172.3 (164–178)	167.5 (165–170)
Weight [kg]	87.6 (69–110)	80.0 (74–85)	67.5 (60–75)
BMI	26.4 (22.3–32.8)	27.1 (23.4–30.1)	24.0 (22.0–26.0)

Table 4. The mean and range of the z-axis WBV exposures measured at the seat and floor of the buses, associated SEAT% values and the distance, time and average speed of the measurements.

z-axis		Low Floor pedestal ($n = 28$)	Low floor Air-suspension (n = 15)	High floor Air-suspension ($n = 11$)	p
A(8) [m/s^2]	Seat	0.34 (0.21–0.41)	0.32 (0.20–0.37)	0.32 (0.29–0.34)	0.13
	Floor	0.36^a (0.22–0.46)	0.34^a (0.26–0.44)	0.29^b (0.27–0.32)	0.002
	SEAT%	$96\%^a$ (78–113%)	$92\%^a$ (76–102%)	$110\%^b$ (103–122%)	<0.0001
VDV(8) [$m/s^{1.75}$]	Seat	7.5 (4.9–9.4)	7.1 (4.1–8.2)	6.6 (5.7–7.9)	0.07
	Floor	8.0^a (5.3–11.1)	7.8^a (5.9–10.5)	6.3^b (5.6–7.0)	0.0008
	SEAT%	$94\%^a$ (77–124%)	$92\%^a$ (70–110%)	$106\%^b$ (89–125%)	0.005
Distance [km]	–	25.1 (14.9–41.1)	28.6 (23.6–40.8)	28.3 (15.5–41.0)	0.36
Time [min]	–	26.7 (17.0–32.6)	29.1 (23.7–37.4)	26.6 (19.8–31.5)	0.26
Speed [km/h]	–	56.7 (29.3–88)	59.2 (40.2–79.7)	63.0 (44.3–92.4)	0.51

Note: p-values are provided and values across rows with different superscript letters indicate significant differences ($p < 0.05$); n = number of road segments measured.

When the WBV exposures in two or more axes are comparable, the vector sum (Σxyz) as calculated as in Equations (3) and (4) may be preferable to estimate health risk.

The driving times to reach the DEAVs for A(8) and VDV(8) WBV exposures are shown in Figure 3. As the box and whisker plots indicate, based on the z-axis WBV exposures, the median driving times to reach the DEAVs were at or above 16 hours. For the z-axis A(8) and VDV(8) WBV exposures, the only differences in the driving times to reach the DEAVs occurred with high-floor bus with the air-suspension seat, where the time to reach the DEAVs was substantially longer for the VDV(8) exposures. When vector sum WBV exposures were evaluated, the driving times to reach the DEAVs were roughly four hours shorter on average, with median driving times to reach the daily exposure action limits at or above

Table 5. The mean and range of the WBV exposures by axis measured at the seat, grouped by the three conditions evaluated.

	Axis*	Low floor Pedestal ($n = 28$)	Low floor Air ride ($n = 15$)	High floor Air ride ($n = 11$)	p
A(8) [m/s^2]	1.4x	0.13^b (0.07–0.21)	0.17^c (0.10–0.20)	0.17^c (0.12–0.25)	0.01
	1.4y	0.19 (0.13–0.25)	0.19 (0.13–0.46)	0.20 (0.14–0.26)	0.89
	z	0.34 (0.21–0.41)	0.32 (0.20–0.37)	0.32 (0.29–0.34)	0.13
	Σxyz	0.42 (0.30–0.49)	0.41 (0.34–0.51)	0.42 (0.35–0.49)	0.96
VDV(8) [$m/s^{1.75}$]	1.4x	4.6 (2.4–11.2)	4.4 (2.9–6.7)	5.1 (2.9–8.1)	0.70
	1.4y	5.0 (2.9–10.8)	4.4 (2.6–9.4)	5.4 (3.2–8.4)	0.40
	z	7.5 (4.9 to 9.4)	7.1 (4.1 to 8.2)	6.6 (5.7 to 7.9)	0.07
	Σxyz	8.4 (5.8–13.8)	7.9 (6.0–9.7)	7.9 (6.1–10.6)	0.53

Note: p-values are provided and values across rows with different superscript letters indicate significant differences ($p < 0.05$); n = number of route segments measured.
* According to the standard ISO 2631-1, risk assessment should be based on the predominant axis of WBV exposure (x, y or z) after multiplying the x- and y-axis by the factor 1.4.

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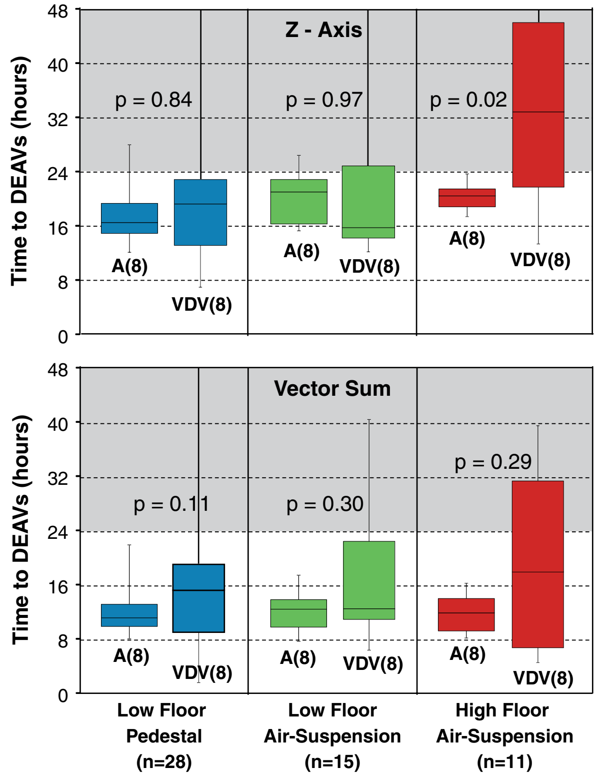

Figure 3. Box and whisker plots grouped by the three conditions showing the driving times to reach the daily exposure action values (DEAVs) for the *z*-axis (top) and vector sum (bottom) WBV exposures. Lower values indicate greater risk and shorter driving durations to reach DEAVs. *P*-values indicate whether the times to reach A(8) and VDV(8) DEAVs are significantly different. The grey areas represent daily driving times greater than 24 hours which are not feasible.

12 hours. For the vector sum WBV exposures, there were no differences in the A(8) and VDV(8) driving times to reach the DEAVs.

4. Discussion

4.1. Comparison between bus and seat combination

4.1.1. Floor vibration and SEAT values

The SEAT value is a measure of how well the seat attenuates the WBV exposures. The air-suspension seat surprisingly amplified the vibration in the high-floor bus 10% on average for A(8) and 6% on average for VDV(8). In the low-floor buses, there was no difference in SEAT values between the pedestal and air-suspension seats with the seats only attenuating the A(8) and VDV(8) WBV exposures 6% and 7%, respectively. The fact that the air-suspension seat attenuated the vibration on the low-floor bus but amplified the vibration on the high-floor bus may indicate that there is a seat and bus suspension mismatch on the high-floor bus. The amplification of the WBV exposures by the air-suspension seat in the high-floor bus may indicate that a different type of seat may be better suited for this type of bus.

4.1.2. Seat WBV exposures

The lower *x*-axis A(8) exposures with the pedestal seat may indicate that there was more fore-and-aft translation with the air-suspension seat direction and this difference was not seen in *y*, *z* and vector sum exposures. These differences were absent in the VDV(8) exposures since the measure is more sensitive to transients rather than continuous low-level vibrations.

In the low-floor buses, the *z*-axis A(8) and VDV (8) exposures were marginally higher with pedestal seat, but the differences were not significant indicating that there was no advantage or substantial reduction in WBV exposures when using the air-suspension seat. This lack of difference may be even more surprising given that the pedestal seats were substantially older than the air-suspension seats.

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4.1.3. Daily permitted time – driving times to reach WBV action values

The WBV exposures were below EU DEAVs for all the bus and seat combinations evaluated. The conventional A(8) WBV exposures may underestimate the health risks if impulsive shocks are present. However, given the lack of differences between the times to DEAVs between the A(8) and VDV (8) exposures in Figure 3, it appears that the bus drivers' exposures to transient shocks were likely limited. However, with some of the VDV(8) times to DEAVs in Figure 3 below eight hours, some of the measurements likely had impulsive exposures.

Calculating the driving times to reach DEAVs is a more intuitive way to characterise the risks associated with the WBV exposures, especially for users with a limited background in WBV assessment and control. Figure 3 shows that, under the routes, buses and seats we evaluated, driving a bus for more than eight hours per day was acceptable, in concern of DEAVs, in the majority of road segments we evaluated.

4.2. Methodological considerations

4.2.1. Differences between buses and seats evaluated

In a previous experiment measuring exposures to WBV at different driving speeds, the A(8) and VDV(8) increased when the speed increased (Ismail et al. 2010). In our study, as shown in the bottom of row of Table 3, there were no significant differences in bus speeds for the three conditions indicating that any contribution to any differences were not due to differences in bus speeds. Unlike other studies using standardised routes and empty buses (Blood et al. 2010; Lewis and Johnson 2012; Thamsuwan et al. 2013), the exposure measurements we collected were representative, i.e. normal routes with passenger load giving normal suspension function. However, the different ages of the buses and seats could have influenced on the results. It was interesting that there was little difference between the relatively new high-floor coach bus (3.0 years of service) with the air-suspension seat (3.0 years of service) and, the oldest buses (average 8.75 years of service), the low-floor city buses with the pedestal seats. These results appear to indicate that, at least on the city routes we evaluated, there is little to no detriment to using low-floor buses with pedestal seats. Given the lack of difference between the buses, seat types and given that all SEAT values were above 100% with the superior suspension in the newer, high-floor bus, this also appears to indicate that an air-suspension seat may not be the appropriate type of seat for this type of bus. In future studies, it would be interesting to evaluate a pedestal seat in a high-floor bus.

Based on the comparison to the newest buses with the newest seats, the low-floor bus with the air-suspension seats (average 1.5 years of service) and the low-floor buses with the pedestal seats (average 8.75 years of service), no differences in WBV exposures were observed between the two seats. Again, this raises the question of the appropriateness of air-suspension seats in buses predominantly driving on city routes. One weak point was the limited number of drivers and buses evaluated in the high-floor coach bus condition; however, based on SEAT values comparing low-floor city and high-floor coach buses reported by Thamsuwan et al. 2013, our results between bus SEAT values were similar with the high-floor coach bus always having higher SEAT values.

4.2.2. Seat function, adjustability and comfort

Besides the attenuation of WBV exposures, the bus driver seats also have the primary function of supporting the occupant in a comfortable seated posture. Both seats had adjustable armrests, were adjustable in height and the backrests had multiple inclination settings. However, the pedestal seat had additional adjustment features. The backrest and lumbar height were also height adjustable, the seat pan was adjustable in depth and angle and the whole seat could be unlocked to allow the driver to rotate and face the passengers as they entered the bus. In future studies, in addition to WBV exposure measurement, measuring short- and long-term comfort and differences in comfort between the various seat types would also be worthwhile. In our study, the drivers drove one type of bus and seat combination and the driving shifts were of different lengths. These WBV and comfort measurements would be most suitable in a repeated measures study where the drivers have shifts of roughly equal length. Since bus drivers typically 'slip seat' and drive several different buses, measuring long-term seating comfort would be more challenging; this would only work where bus drivers only drove one type of bus with a particular model of seat.

4.3. Future perspectives

Seat or vehicle suspension engineering could reduce the vibration exposure. An air-inflated cushion was shown to have more favourable WBV attenuation than foam cushion in a commercial truck population (Seigler 2002), and an air-suspension seat was found to reduce WBV exposures relative to a mechanical seat suspension in forklift trucks (Blood, Ploger, and Johnson 2010). Active suspension seats, using a computerised electromagnetic system, have been shown to

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dramatically reduce vibration exposure (Blood et al. 2011). Our study now indicates that pedestal seats may be suitable engineering control for low-floor city buses.

5. Conclusions

1. Relative to the pedestal seat with a limited travel mechanical suspension, the air-suspension seat provided little to no additional benefit.
2. The amplification of the vibration exposures by the air-suspension seat in the high-floor coach bus may indicate that a pedestal seat with mechanical suspension may be better suited for this type of bus.
3. The European Vibration Directive only allows the predominant axis of vibration exposure to be evaluated. In this bus study, all exposures were below the European DEAVs; however, details on all three axes should be provided to allow comparisons between other studies on WBV.
4. If there is more than one predominant axis of exposure, which not uncommon in buses, the predominant axis approach used by the EU Vibration Directive may underestimate WBV exposures and the actual health risks. We feel that the vector sum WBV exposure is more relevant for assessing health effects than the predominant axis. Our results showed that the vector sum exposures also were below the European action daily exposure values.

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