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Whole-body vibration exposure in metropolitan bus drivers

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Background Back injuries are common in transit drivers, and can result in substantial direct and indirect cost to the employer and employee. Whole-body vibration (WBV) is one risk factor for drivers. Standards have been adopted (ISO 2631-1) to guide researchers in measuring and analysing WBV levels. Lately, a new standard has been added (ISO 2631-5) that takes impulsive exposures into account.

Aims The aims of this study were to determine the levels of vibration for bus drivers using both ISO 2631-1 and 2631-5 standards, and whether there are differences in vibration levels and seat transmissibility between different road types.

Methods Thirteen bus drivers drove a 7-year-old bus, instrumented to measure WBV in the seat and floor. The 52 km long test route included freeway, city streets and speed humps. Additionally, for comparison, a subset of five drivers also drove a car over the same route.

Results Road type had a significant effect on all the vibration parameters. Based on exposure limit values in the standards, the continuous z-$A_w(8)$ exposures exceeded the limit value on freeways, and the impulsive z-VDV(8) and S_{ed} exposures were above limit values in city streets and speed humps. Bus WBV exposures were about twice as high relative to the car and the bus seat amplified rather than attenuated WBV exposures.

Conclusions Bus drivers are potentially being exposed to daily vibration levels higher than recommended especially on certain road types. The current seat in this study does not attenuate the vibration.

Key words Bus drivers; ergonomics; whole-body vibration.

Introduction

Back injuries represent both a substantial occupational injury burden and a financial burden in the US workforce [1,2]. Work-related musculoskeletal disorders (MSDs) affecting the back account for 47% of all US workers' reported MSDs [3]. Rapid work pace, repetitive motion patterns, insufficient recovery, heavy lifting and non-neutral body postures and whole-body vibration (WBV) are risk factors that can contribute to the onset and development of low back disorders [4–8]. WBV can increase muscle forces and muscle fatigue [9], decrease the disc height in the lumbar spine, elevate spinal load [10] and fatigue-induced micro-fractures have been reported in *in vitro* lumbar vertebral endplates from transient impulsive WBV exposures, which may be lead to subsequent disc degeneration [11–13].

The International Organization for Standardization (ISO) standard 2631-1, 'Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration – Part 1: General Requirements' [14], specify how to measure and analyse WBV. Action limits and exposure limits regarding the weighted root mean square (r.m.s.) acceleration (A_w) as well as the Vibration Dose Value (VDV) have been established in the European Physical Agents (Vibration) Directive (2002/44/EC). The exposure action value (EAV) is a daily amount of vibration exposure above which employers are required to take action to control exposure, and the exposure limit value (ELV) is the maximum amount of vibration an employee may be exposed to on any single day. For an 8 h exposure, the A_w action and exposure limits are 0.5 m/s^2 and 1.15 m/s^2, respectively, and for the VDV they are 9.1 $m/s^{1.75}$ and 21.0 $m/s^{1.75}$, respectively [15].

To address the limited guidance available regarding impulsive WBV exposures under ISO 2631-1, ISO recently adopted a new standard, ISO 2631-5: 'Evaluation of Human Exposure to Whole-body Vibration – Part 5: Method for Evaluation of Vibration Containing Multiple Shocks', [16]. It provides guidance on the calculation of cumulative acceleration dose (D_k), which takes into account multiple shock/peak exposures and recommendations for computing a daily equivalent static compression dose (S_{ed}) to the spine. S_{ed} less than 0.5 MPa are expected to have a low probability of adverse health effects after a lifetime of exposure, while those over 0.8 MPa are expected to have a high probability of adverse health effects. So far, only a few studies have reported results with the recent ISO 2631-5 standard on impulsive WBV exposure [17,18], and even fewer studies have compared the relationship between measurements made with ISO 2631-1 and the impulsive measurements made with ISO 2631-5 [19].

Mass transit operators represent one of the largest working populations in the transportation sectors in the USA and have substantial occupational exposures to WBV [3]. An exponential dose–response relationship between hours of weekly driving and injury risk has been found [20]. Additionally, Johanning [21] identified back disorders as one of the largest sources for medical impairment and early permanent disability among mass transit operators. Currently, there is limited data available on WBV levels experienced by workers on transit systems, but much of the data that have been published suggests that these workers' exposures exceed recommended standards [22]. Also, due to impulsive exposures being underestimated, measurements made according to ISO 2631-1 often underestimate the true WBV exposure level, and therefore allow workers to be exposed to WBV for a longer period of time than some other standards, such as the British Standard on WBV, BS 6841 [22]. In addition, studies have identified road conditions as a major contributor to levels of WBV exposure [5,23]. However, most of these studies have focused on short-term exposures for vehicle operators traveling along a fixed route or a test track, or equivalent average exposure for vehicle operators traveling a variable route.

The aim of this study was to determine the levels of vibration exposure for bus drivers using a standardized test route in an urban area, using both the ISO 2631-1 and 2631-5 standards, and to assess whether there are differences in vibration levels and seat transmissibility between different road types.

Methods

Thirteen Seattle Metro bus drivers were recruited to participate in this study (Table 1). This study was approved by the University of Washington Human Subjects division.

The floor and seat of a bus was instrumented to simultaneously collect: (1) time-weighted average (TWA) WBV data, (2) raw, continuous WBV data and (3) GPS data. The bus was a 7-year-old 12 m, high floor bus (Gillig, Hayward, CA, USA), which had the original air suspension driver's seat (Model ALX-3; USSC Group, Exton, PA, USA). The same bus was used for the entire duration of the study. The runs were completed with no passengers other than the driver and data collection staff (one or two researchers). Additionally, a subset of five drivers also drove the same route in a 1-year-old car (2005 Ford Taurus Sedan), which was instrumented the same manner as the bus.

Data were collected from each driver as they drove over the 52 km long standardized test route. The route included three common road types encountered by bus drivers: 12 km of stop and go driving on city streets; 1 km street segment with ten, 4 m wide speed humps; and 29 km of continuous new freeway.

A PDA-based, portable WBV data acquisition system was developed as well as the associated software to analyse WBV exposures per ISO 2631-1 and 2631-5 standards. Raw, unweighted tri-axial WBV measurements were collected at 640 Hz from the bus driver's seat using a seat pad ICP accelerometer (model 356B40; PCB Piezotronics, Depew, NY, USA) and simultaneous z-axis measurements were collected with an identical accelerometer mounted to the bus floor immediately adjacent to the driver's seat. As shown in Figure 1, two portable (15.5 × 8.0 × 2.8 cm) Larson Davis HVM 100 loggers were used as accelerometer amplifiers and an HP H5555 Pocket-PC Personal Digital Assistant (PDA) with a PCMCIA expansion pack and a 16 bit National Instruments data acquisition card (Model 6036E; National Instruments, Austin, TX, USA) was used to collect the WBV signals. A thin rubber seat pad accelerometer was placed between the seat pad of the bus driver's seat and the ischeal tuberocities (buttocks) of the bus driver. Through a cable connected to the serial

Table 1. Demographics of the study population (mean (SD))

	Bus	Car
N	13	5
Age (years)	53.4 (7.9)	50.4 (4.8)
Weight (kg)	87.5 (23.7)	84.9 (16.7)
Height (cm)	174.4 (11.4)	174.0 (7.1)
BMI	28.6 (6.4)	28.4 (7.1)
Bus driving experience (years)	17.1 (14.9)	13.8 (17.2)

Table 2. Mean (SE) bus seat vibration exposures by axis and road type (n = 13)

	Axis	Bus (n = 13)			P
		Freeway (F)	City street (S)	Speed humps (H)	
$A_w(8)$ (m/s^2)	x	0.16 (0.06)	0.20 (0.05)	0.25 (0.06)	<0.001
	y	0.17 (0.02)	0.21 (0.02)	0.28 (0.02)	<0.001
	z	**0.51 (0.04)**	0.47 (0.04)	0.46 (0.08)	NS
Crest factor	x	8.6 (2.7)	**13.9 (5.4)**	8.0 (2.2)	<0.001
	y	6.2 (0.75)	11.8 (2.3)	7.0 (0.9)	<0.001
	z	8.5 (1.4)	**15.3 (3.8)**	**11.8 (2.5)**	<0.001
VDV(8) (m/s$^{1.75}$)	x	3.4 (1.2)	5.3 (1.8)	5.7 (1.4)	<0.001
	y	3.2 (0.4)	4.6 (0.9)	6.3 (0.5)	<0.001
	z	**10.8 (0.7)**	**12.7 (1.7)**	**12.5 (3.3)**	<0.001
$D_k(8)$ (m/s^2)	x	3.8 (1.2)	6.8 (2.85)	6.0 (1.5)	<0.001
	y	2.9 (0.5)	5.8 (0.5)	5.6 (1.2)	<0.001
	z	14.3 (1.8)	24.4 (6.9)	20.1 (7.2)	<0.001
$S_{ed}(8)$ (MPa)	All	0.42 (0.05)	**0.71 (0.21)**	**0.58 (0.2)**	<0.01
SEAT$_{Aw}$ (%)	z	101.7 (1.30)	106.9 (1.68)	122.8 (3.04)	<0.001
SEAT$_{VDV}$ (%)	z	109.3 (1.14)	112.3 (5.39)	139.2 (5.22)	<0.001
Speed (km/h)		83.4 (7.4)	32.7 (2.9)	21.4 (2.7)	<0.001

Bold values indicate exposure above exposure action value.

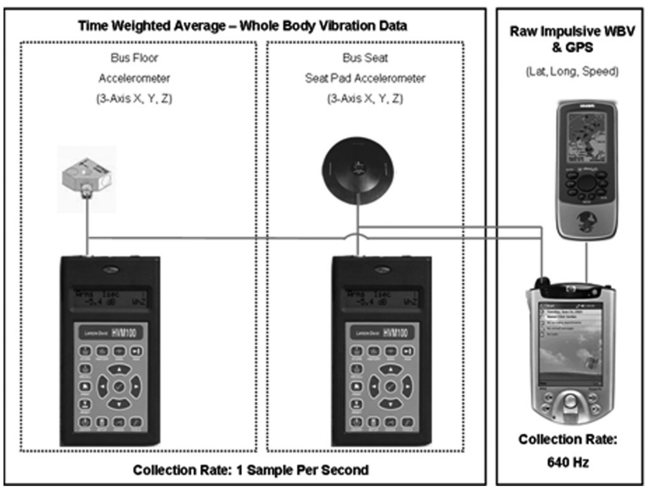

Figure 1. Data acquisition set-up.

port of the PDA, every second the PDA also acquired the location of the bus using a Global Positioning System (GPS) unit (Model16A; Garmin, Olathe, KS, USA). The GPS obtained the bus positions to within a 10 m radius of the actual location of the bus and was integrated with the WBV exposure data to determine the bus location, velocity and the type of road associated with the WBV exposures.

The continuous data were downloaded onto a PC and a Matlab-based routine was implemented to appropriately weight the continuous signals [24]. The ISO 2631-1 [14] and 2631-5 [16] algorithms were implemented into a LabVIEW program with a graphical interface (Version 7.1; National Instruments, Austin, TX, USA).

The parameters analysed were: frequency-weighted r.m.s. acceleration (A_w), vibration dose value (VDV), crest factor, acceleration dose value (D_k), Static Spinal Compression Dose (S_{ed}) and Seat Effective Amplitude Transmissibility (SEAT). Equations used to attain the desired vibration parameters can be found in Appendix 1. The parameters were normalized to reflect 8 h of driving exposure (e.g. $A_w(8)$, VDV(8), $D_k(8)$ and $S_{ed}(8)$).

JMP Statistical Discovery Software (Version 8; SAS Institute, Cary, NC, USA) was used with a mixed model analysis of variance to determine whether there were differences in WBV exposures between the different road types. Difference was considered to be significant when $P < 0.05$.

Results

The bus driver WBV exposures by axis and road type are presented in Table 1. The predominant exposure was in the z-axis. The Crest Factor exceeded nine in the z-axis for the city street and speed hump road types indicating that impulsive exposures were present in the data. This indicates that the $A_w(8)$ values must be interpreted with caution and may underestimate the actual exposures. The $A_w(8)$ exceeded the EAL in z direction for the freeway, while the VDV(8) in the z-axis exceeded the EAL for all three road types. The S_{ed} exposures were greater than 0.5 for the city street and speed hump section, indicating a moderate lifetime probability for adverse health effects in the lower back. Road type had a significant effect on all the vibration parameters listed in Table 1, except for the $A_w(8)$ in z direction.

The z-axis $A_w(8)$ and VDV(8) from the seat and floor of the bus as well as the S_{ed} from the seat are presented in Figure 2. For reference, data from five of the subjects driving the same route in a car are also included in Figure 2. The average speed of the bus and car were similar and not significantly different when

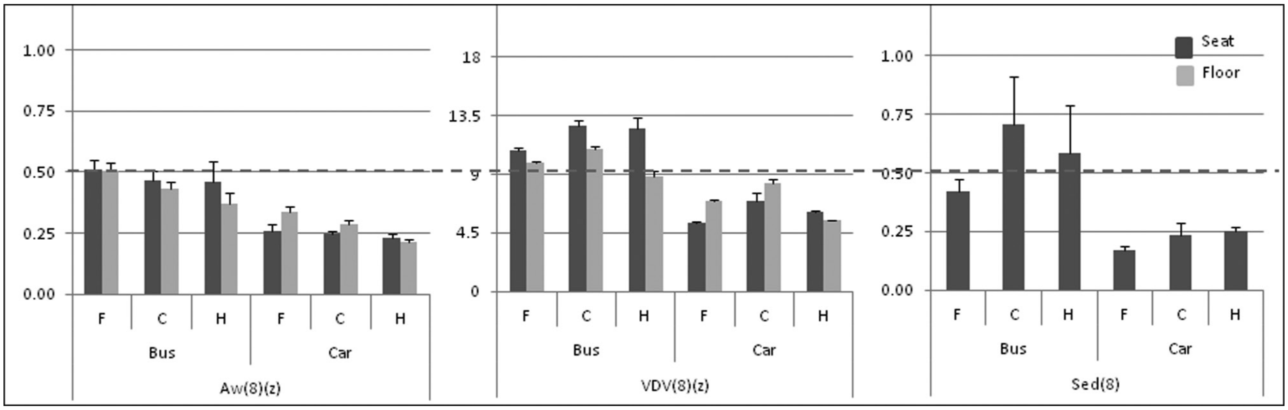

Figure 2. Mean (SEM) seat and floor (for Sed(8), no floor values) z-axis vibration exposures (Aw(8), VDV(8), Sed(8)) measured from the bus and car grouped by road type (F = Freeway, C = City street and H = Speed Humps). The dotted line represents the action limit value.

driving the freeway route (83 ± 7.4 versus 86 ± 9.0 km/h), city street route (32.7 ± 2.9 versus 32.2 ± 2.3 km/h) and speed humps route (21.4 ± 2.7 versus 21.2 ± 3.2 km/h). The $A_w(8)$ was slightly higher in the freeway section of the route for both the bus and car. For the impulsive exposure, the VDV(8) were highest on the city street. The main difference between car and bus was that the vibration exposures were all roughly 2-fold lower in the car, in all road types. A notable performance difference between the car and bus seat was the bus seat amplified rather than attenuated all exposures. This amplification was more prominent with the impulsive exposures.

Discussion

It was clear that the vibration levels of the bus in most cases exceeded the recommended action values, especially the parameters sensitive to impulsive exposures. Road type had a significant effect, and both in the bus and car, the freeway had a slightly higher z-axis $A_w(8)$ vibration exposure as compared with the other road types. The city street and speed hump sections had the highest z-axis impulsive exposures (VDV(8) and $D_{kd}(8)$). The bus seats amplified the vibration.

This study evaluated WBV for bus drivers using both ISO standards, which gives a better description than using only the ISO 2631-1 standard. Also, it provides measurements on three common road types separately. The speed hump road type exposure is likely to be overestimated, as it is not common to drive over speed humps for an entire 8 h day, but it was normalized for comparison purposes. Due to the limited number of drivers that drove the car, we chose not to statistically compare the bus and car exposures. Also, we did not control for bottoming out of the seat, or driving posture.

The vehicles were always moving when on the freeway and the vibration was always on, as compared with the city street stop and go driving where the vibration had an on/off pattern dependant on whether the vehicle was moving or stopped at a stoplight. City street and speed humps were more likely to cause large impulses, or shock-type vibrations, whereas the freeways were smoother and the vehicles tended to slowly oscillate over undulations in the freeway terrain. Both these factors explain the lower average vibration ($A_w(8)$), and the higher impulsive exposures such as VDV(8) and $S_{ed}(8)$ in the city street and speed hump road types, whereas the freeway had the opposite exposure pattern.

Our VDV(8) levels for the speed hump section (13 m/s$^{1.75}$) were similar to those found by Khorshid *et al.* [25] who had vehicle operators driving at a similar speed (20 km/h) in bus driving over speed humps. They, however, added the VDV in x and z direction, but the z direction peaks were 500% larger than the x-direction and therefore constituted the major part of the combined VDV parameter. Our freeway $A_w(8)$ was slightly higher than previously reported in buses. Blood *et al.* [26] reported z direction $A_w(8)$ of 0.4 m/s^2, and Bovenzi *et al.* [27] as low as 0.3 m/s^2. Unlike Blood *et al.*'s study where the bus seats (slightly different model made by the same manufacturer as the present study) were brand new, the bus seat in the present study was 7 years old and wear and tear to the seat suspension may have contributed to the higher exposures. Okunribido *et al.* [28] reported bus z-axis vibrations between 0.1 and 1.01 m/s^2. They, however, included bus standing idle for longer periods in some of the buses, which explain the low 0.1 m/s^2 A_w. The seat age, vehicle age and road types were not defined in Bovenzi's and Okunribido *et al.*'s study, which makes comparisons uncertain.

The seat in the car had lower vibration exposures than in the bus, and as shown by the lower vibration values measured from the car floor, the car suspension reduced the vibration. In addition, as indicated by the differences in SEAT values, the bus seat amplified whereas the car seat attenuated the vehicle vibration. When travelling over the speed humps, the bus seat amplified the average vibration (z-A_w(8)) by 23%, and the daily vibration dose value (z-VDV(8)) by a 39%. Finally, none of the vibration exposures in the car were above action limits, whereas for the bus the action limits were exceeded for each parameter on most road types.

Our transmissibility values revealed a higher vibration exposure in the seat as compared with the floor for the bus. The bus seat amplified rather than attenuated the vibration as would have been expected. We did not control for 'bottoming out', which can occur when an air-ride seat is not properly adjusted to the weight of the driver, or if the seat is leaking air. These have been reported by some of the Metro Bus drivers and could account for some of the high seat vibration levels. However, the raw peak (+) and peak (−) data (not reported) seemed to indicate the seats were not bottoming out since the positive and negative peaks were similar in magnitude.

When only looking at the A_w(8) in the present study, one might come to the conclusion that the freeway driving was the most hazardous, as the ISO 2631-1 standard and EU directive [15] action values were exceeded. However, when evaluating the VDV(8) the action values were exceeded on all road types. If the newer ISO 2631-5 [16] S_{ed} exposures are considered, the city street and speed hump road types exceeded action values, but not the freeway. This shows the importance of choosing the right parameters for the exposure, and understanding that some parameters have limitations in the information that they provide. Unfortunately, the vast majority of epidemiological studies conducted on transit workers to date are limited due to their WBV exposures being based on time-weighted acceleration data as proscribed by ISO 2631-1 and other standards. These measures most likely underestimate WBV exposures due to the inability of these methods to measure the impulsive mechanical exposures [29,30]. As outlined in ISO 2631-5, continuously collected raw WBV data are needed to more adequately characterize impulsive mechanical exposures. Also, the VDV(8) has been shown to be a better predictor for low back pain as compared with A_w [27]. Regarding the S_{ed} no dose–response relationship has been established yet.

An area worthy of further study would be assessing how seat and vehicle characteristics affect and influence WBV exposures. In addition, we would like to better understand the biological and biomechanical mechanisms leading to low back disorders. Inputting our vibration exposure data into mechanical systems (seats, human cadaver spines and/or human spine analogues) may help to develop a better understanding of these mechanisms.

Key points

- Bus drivers are potentially being exposed to daily vibration levels that are higher than recommended values.
- The seat design used in this study does not seem to effectively attenuate the vibration after being in service for a while.
- Both ISO 2631-1 and 2631-5 standards should be used for better understanding of the exposure.

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Conflicts of interest

None declared.

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