Whole Body Vibration Exposure and Seat Effective Amplitude Transmissibility of Air Suspension Seat in Different Bus Designs

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A number of studies have shown that whole body vibration (WBV) exposures contribute to low back pain in vehicle operators. Bus design may be an important factor in determining the WBV exposures that a driver receives. The purpose of this study was to determine whether differences exist in WBV exposures among three buses commonly used in long urban commuter routes: a high-floor coach bus, a low-floor coach bus, and a low-floor articulating bus. Each bus had the same new air-suspension installed and was driven over a standardized test route which included four road types: a smooth freeway, a rough freeway, a city street segment, and a road segment containing several speed humps. WBV exposures were evaluated per ISO 2631-1 action limits for acceptable WBV exposure levels. In this study, there were statistically significant differences among buses in WBV exposures. The high-floor coach bus had the highest fore-aft (x-axis) exposures, the low-floor articulating bus had the highest lateral (y-axis) exposures and the low-floor coach bus had the highest vertical (z-axis) exposures. With respect to ISO action limits, the z-axis WBV exposures did not exceed the 8-hour action limit (0.5 m/s^2). The study also found that the air suspension seat did not perform well in the coach buses. The air suspension seat transmitted 92% of the floor measured vibration to the seat of the operator on the high-floor coach bus, 88% on the low-floor bus, and 76% on the low-floor articulating bus. Due to the low vibration attenuation performance of the air suspension seat, an evaluation of the different types of seats and seat suspensions may be merited in future research.

 DOI 10.1177/1071181312561265

INTRODUCTION

Low back pain (LBP) among professional drivers is prevalent worldwide (Wikström et al., 1994, Magnusson et al., 1996) and can result in substantial direct and indirect costs (Baldwin, 2004). Exposure to whole-body vibration (WBV) is one of the known risk factors contributing to the onset and development of LBP (Krause et al., 2004, Okuniribido et al., 2008, Tiemessen et al., 2008).

As an oscillatory motion, WBV exposure is characterized by evaluating the direction, magnitude, frequency, and the duration of the exposure. The ISO 2631-1 (1997) WBV standard uses a seated posture and a three dimensional basicentric coordinate system to characterize the root mean square (r.m.s.) magnitudes of frequency-weighted acceleration (a_w) over the duration of the WBV exposures. In addition, transmissibility indicates how well the seat attenuates the vehicle vibrations.

Seat design plays an important role in reducing WBV exposures. A previous study (Paddan and Griffin, 2002) showed that a suspension seat resulted in lower transmissibility than a conventional static seat.

Air suspension seats, which are now standard seats on most buses in the United States, are thought to reduce the bus driver's exposure to WBV. However, it is uncertain whether air suspension seats perform similarly on all bus designs, since there may be some interaction between the seat and bus suspension systems.

The purpose of this study, using the same air-suspension seat, is to determine whether there are differences in WBV exposures and transmissibility values across three common buses used in urban transit settings.

METHODS

Study Design

Subjects. WBV exposures in a high-floor coach bus were collected from 11 professional bus drivers and WBV exposures in low-floor coach and articulating buses were collected from a different group of 13 drivers (Table 1).

Table 1 – Mean (SD) Statures of Subjects

		High-floor coach bus N = 11		**Low-floor buses* N = 13**		
		Number (%)	**Mean (SD)**	**Number (%)**	**Mean (SD)**	**p-value**
Age (year)			43.5 (7.9)		44.2 (13.2)	0.86
Gender	Male	8 (73%)		12 (92%)		
	Female	3 (27%)		1 (8%)		
Height (cm)			168.4 (9.7)		178.2 (9.3)	0.02
	≤ 165	5 (45%)		1 (8%)		
	165-180	4 (36%)		5 (38%)		
	≥ 180	2 (18%)		7 (54%)		
Weight (kg)			92.6 (34.1)		95.3 (13.8)	0.80
	≤ 75	4 (36%)		1 (8%)		
	75-95	4 (36%)		5 (38%)		
	≥ 95	3 (27%)		7 (54%)		
BMI (kg/m^2)			32.2 (9.7)		30.0 (3.5)	0.46
	18.5-24.9	1 (9%)		2 (15%)		
	25.0-29.9	5 (45%)		3 (23%)		
	≥ 30	5 (45%)		8 (62%)		

***Same subjects used in low-floor coach and articulating buses.**

Vehicles. The experiment was conducted on a 13.9-meter-long, 5-year-old, high-floor coach bus (Model D4500; Motor Coach Industries Inc; Winnipeg, Manitoba, Canada), a 12.2-meter-long, 11-year-old, low-floor coach bus (Model D40LF; New Flyer; Winnipeg, Manitoba, Canada) and an 18.3-meter-long, 11-year-old, low-floor articulating bus (Model D60LF; New Flyer; Winnipeg, Manitoba, Canada). These buses had different suspension systems. That is, the suspension system in low-floor coach and articulating buses has limited travel and was designed for rapid passenger entry and exit, whereas the suspension system in high-floor coach bus had a greater range of travel and was designed for longer haul travel.

Figure 1 - high-floor coach bus (left), low-floor coach bus (middle), and low-floor articulating bus (right)

Seat. The same seat with an air suspension, a foam seat pan, and an adjustable lumbar support (model Q91; USSC Group; Exton, Pennsylvania, USA) was used in all the buses for testing purposes. Since the seat had been the standard seat currently used in the buses, the drivers were familiar with the seat and adjusted the seat to their preferences prior to each bus run.

Test route. All subjects drove on a standardized test route developed by Blood et al. (2010). The route included four different road segments: 12 km of city streets, 14 km of a newer smooth freeway, 10 km of an older rough freeway, and a 1 km circular route containing ten 4-meter-wide speed humps. The experiment was conducted during non-peak hours in moderate traffic and the route took approximately 75 (SD ± 2.5) minutes to complete. The buses, when driven over the route, were empty and not carrying any other passengers apart from the driver and the data collection personnel.

Whole Body Vibration Exposures

According to ISO 2631-1 (1997), WBV exposures were represented by the average, frequency weighted r.m.s. acceleration (a_w). WBV exposures were calculated in all three axes: fore-aft (x), lateral (y), and vertical (z).

Furthermore, the a_w exposures were extrapolated to an 8-hour daily equivalent values (A(8)) and evaluated per the ISO 2631-1 action limit for acceptable exposure level of 0.5 m/s^2.

Seat Effective Amplitude Transmissibility

Seat Effective Amplitude Transmissibility (SEAT) is defined as the ratio between vertical WBV exposures measured at the operator's seat divided by vertical WBV exposures measured at the floor. A SEAT value of 100% indicates that WBV exposures at seat are as same as WBV exposures at floor of the vehicle, meaning that the seat does not provide isolation from the vehicle's floor vibration. Accordingly, lower SEAT values indicate better seat vibration attenuation. SEAT values were calculated by dividing the r.m.s. vibration at the seat by the r.m.s. vibration at the floor.

Data Collection and Processing

The data acquisition system consisted of an eight-channel data recorder (Model DA-40; Rion Co., LTD.; Tokyo, Japan). Raw, un-weighted, tri-axial WBV exposure measurements were collected at 1,280 Hz per channel using tri-axial accelerometers (Model 356B40; PCB Piezotronics; Depew, New York, USA) mounted at the seat and at the floor of the buses. Prior to data collection, accelerometer calibrations were tested and verified using a calibration exciter (Model 4294; Bruel & Kjaer Sound & Vibration Measurement A/S; Nærum, Denmark) with an acceleration level of 10 m/s^2 (r.m.s.) and 159.2 Hz oscillation frequency.

Simultaneously, in order to identify the location of the buses associated with the measured WBV exposures, Global Positioning System (GPS) data was collected using a GPS logger (Model DG-100; GlobalSat; Chino, California, USA). Speed, latitude, and longitude of the buses were collected once every second. The collected WBV exposure data were downloaded after each run, synchronized with the buses' position and velocity data from the GPS and saved in a single file. Using the LabVIEW program, r.m.s. WBV exposures were calculated and the descriptive summary measures for each subject and bus were saved into a text file for statistical analysis.

Statistical Analysis

JMP Statistical Discovery Software (version 9.0; SAS Institute; Cary; South Carolina, USA) was used to perform the statistical analysis. Summary measures (mean and standard error) for each bus were calculated. Since different subjects drove different buses, the A(8) exposures and SEAT values were treated as independent samples and analyzed using ANOVA methods to determine whether there were any differences in WBV exposures across the three buses. Differences were considered significant when p-values were greater than 0.05.

RESULTS

Whole Body Vibration Exposures

Table 2 presents A(8) exposures in three directions. To determine health effects, as outlined in ISO 2631-1, the fore-aft (x) and lateral (y) axes were multiplied by a factor *of 1.4* and the vertical (z) axis was multiplied by a factor *of 1*.

A(8) exposures on the high-floor coach bus did not have a predominant exposure axis. The predominant direction of A(8) exposures in the low-floor coach buses was z-axis whereas the predominant direction of A(8) exposures in the low-floor articulating bus spanned to two axes, the y- and z-axis.

A(8) exposures were significantly different across the buses (Table 2). When the A(8) exposures were compared by axis, the high-floor coach bus had the highest $A(8)_x$ exposures, the low-floor articulating bus had the highest $A(8)_y$ exposures and the low-floor coach bus had the highest $A(8)_z$ exposures.

Comparing the measured A(8) to the action limit in the ISO 2631-1, the A(8) exposures on all buses were less than the action limit (0.5 m/s^2).

Seat Effective Amplitude Transmissibility

Based on the SEAT-A(8) values (Table 2), the performance of the air suspension seat depends on the bus type. The air suspension seat reduced the floor transmitted vibration on the low-floor articulating bus more than on the other two coach buses.

Table 2 – Mean (SE) WBV exposures over the whole route by bus and axis including SEAT ratios

		High-floor coach bus [n = 11]	**Low-floor coach bus [n = 13]**	**Low-floor articulating bus [n = 13]**	**p-value**
A(8)	1.4 x-seat	0.28 (0.02)	0.18 (0.01)	0.21 (0.01)	0.0003
	1.4 y-seat	0.25 (0.02)	0.20 (0.01)	0.35 (0.02)	< 0.0001
	z-seat	0.38 (0.01)	0.41 (0.01)	0.38 (0.02)	0.01
	z-floor	0.42 (0.01)	0.47 (0.01)	0.50 (0.02)	< 0.0001
SEAT-A(8)		92 (3) %	88 (2) %	76 (2) %	< 0.0001

DICUSSION

Whole Body Vibration Exposures

The predominant axes of WBV exposures on three buses were different. The greater $A(8)_x$ on the high-floor coach bus seemed to be related to the movement of the bus as the bus driver sat much higher over the bus suspension and road relative to the low-floor buses. When the high-floor bus went over the speed humps, due to the greater height, the driver could have undergone higher angular and linear x and y translations. The $A(8)_y$ on the low-floor articulating bus were greater than on the other two non-articulating buses. This might be because the pivoting joint in the middle of the bus could have caused the back deck to swing to the sides transmitting WBV exposures to the driver. The $A(8)_z$ on the low-floor non-articulating bus were greatest and this could have been due to either its lower suspension travel, the single coach acting as a rigid mass, or a mismatch between the seat and bus suspension systems.

The different directions of WBV exposures may result in different types of injuries to the spine. That is, WBV exposures in vertical axis may cause compression in driver's spine whereas WBV fore-aft and side-to-side exposures may create shear forces in driver's spine. A combination of vertical and horizontal WBV exposures should be analyzed as it changes the mechanism of lumbar disc herniation leading to spine instability (Wilder et al., 1988).

Seat Effective Amplitude Transmissibility

The calculated SEAT values indicate that the air suspension seat did not provide an absolute isolation from the bus but still marginally attenuated the WBV exposures. The air suspension seat transmitted 76% of the floor measured vibration to the seat of the operator in the low-floor articulating bus, 88% of the floor measured vibration in the low-floor coach bus, and 92% in the high-floor coach bus. This performance may be due to a mismatch between the seat and bus suspension.

Future Studies

Future studies may evaluate WBV exposures and the performance of different seat designs in order to optimize the performance and interactions between the seat and bus suspension systems. Some alternatives to the air suspension seat include a height-adjustable static seat and an active suspension seat. The other alternatives may be air-inflated seat cushions. One study has found the air-inflated seat cushion outperformed a traditional foam seat cushion (Seigler, 2002). These seats and seat cushions could possibly be implemented to reduce WBV exposure as well as seat vibration transmissibility. Eventually, a seat selection guideline for buses may be developed in the same way as the guidelines Gunaselvam and van Niekerk (2005) developed for mining vehicles, which was based on the WBV parameters in ISO 2631-1 and transmissibility functions of the seats.

ACKNOWLEDGEMENTS

The authors would like to thank the drivers and management of Pierce County Transit and King County Metro Transit, Washington, USA, for participating in this research. The study was funded by NIOSH RO1 Grant number 1R01OH008777-01A2 with supplemental funds from the Washington State Medical Aid and Accident Fund.

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