Quantifying whole body vibration exposures in metropolitan bus drivers: an evaluation of three seats

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The objective of this study was to evaluate three seats amongst a population of metropolitan bus drivers as they drove a standardized test route including city streets, old and new freeways, and a street segment containing ten large speed humps. Three comparisons were made: 1) comparing seats made by different manufactures (Seat 1 and Seat 2), 2) comparing seats with a standard foam (Seat 2) and silicone foam (Seat 3) seat pans, and 3) comparing WBV exposures based on road types. Whole body vibration (WBV) exposures were measured using a tri-axial seat pan accelerometer and the attenuation capabilities of each seat were evaluated by comparing the vibrations measured at the floor and seat of the bus. There were significant WBV exposure differences between the various street types, which were shown across all seat types. The city street and older freeway segments had the highest WBV exposures with both segments producing WBV exposures slightly above the action limit for Vibration Dose Value (VDV(8)). Relative to Seat 2, Seat 1 performed better at attenuating impulsive and shock related WBV exposures, however, neither seat performed significantly better when Average Vibration (Aw(8)) and VDV(8) WBV exposures were compared. In addition, no performance differences were seen between the standard foam (Seat 2) and silicone foam (Seat 3) seat pans. This study provided a unique opportunity to explore WBV exposures among bus drivers and potential ergonomic interventions in the way of seat options to reduce WBV exposures and potentially reduce workplace injuries.

Keywords: low back pain, driving injuries, ergonomics, transportation industry, street surfaces

1. INTRODUCTION

Injuries to the back are considered the most significant non-lethal medical condition affecting the US workforce [1]. Throughout their lives approximately 80 percent of adults will experience back pain and 4-5 percent of the population has an acute low back pain episode every year [2]. Low back injuries require extensive treatment and often result in long periods of absence from work for the injured worker. Back injuries occurring at work account for 20 percent of all US workers' compensation claims, this translates to 33-41 percent of all workers' compensation costs, creating a drain on the economy totaling in the billions of dollars [3, 4].

One of the leading risk factors for the development of low back disorders is continuous exposure to whole-body vibration (WBV) [5, 6]. WBV elevates spinal load as indicated by biomechanical and biological research [7]. Spinal loading causes muscle fatigue in the supporting musculature and has been shown to cause damage to the spinal column [8-11]. WBV can also degrade other systems in the body hampering the function of the musculoskeletal, cardiovascular, cardiopulmonary, metabolic, endocrine, nervous and gastrointestinal systems [12]. There are also safety concerns associated with WBV, vibration frequencies which match the resonant frequency of the body have been shown to hamper a worker's ability to perform job tasks [13]. Extended periods of vibration exposure lead to worker irritability, fatigue, stress, and problems with concentration. Previous research indicates a causal relationship between WBV exposure and the large number of low back disorders among public transit drivers [14, 15].

Numerous studies have shown an association between exposure to WBV in professional driving occupations and back pain [6, 16, 17]. A dose-response relationship has been established showing that increases in the duration of WBV exposure [18], the magnitude of the WBV exposure [19] or both are associated with an increased risk for injury. The assessment methods for measuring Time Weighted Average (TWA) WBV exposures and multiple shock exposure are described in the ISO standard documents ISO 2631-1:1997 [20] and ISO 2631-5:2004 [21], respectively, and provide guidance on the assessment of health effects. However, to date the assessment methods used to measure multiple shock exposures in ISO 2631-5 [21] is relatively new and has not been extensively used.

Back disorders have been identified as the largest source of early permanent disability among mass transit operators [15]. In the greater Seattle Metropolitan area, transit drivers experienced a high number of low back claims when compared to other metropolitan employees. The main description for the cause of low back injuries were 'driving' and 'jarring/bouncing' accounting for 43% of all low back injuries. Safety officials indicate that the bus seat "bottoming out" may be one possible source for injury. Seattle Metropolitan bus drivers are off work longer than all other occupations within the same agency combined, missing 13 days compared to a median of 8 days for all other occupations. The rate of low back injury among bus operators was 3.4%, a rate which is consistent with the incidence of accepted back injury claims in Washington State for specialized (3.4%) and general (3.1%) freight trucking [22]. The 'jarring/bouncing' and 'bottoming out' of bus driver seats suggests that further investigation of impulsive vibration exposures is needed.

Seats can perform differently in their ability to attenuate vibration exposure for the driver. In some cases the seat can amplify the exposure and the understanding of seat performance is not well quantified [23, 24]. In addition, impulsive exposures have recently been identified as a possible risk factor for low back disorders and the International Organization for Standardization (ISO) has published new guidelines for measurement and assessment of impulsive exposures [21]. The magnitude of the impulsive-related risk amongst bus drivers has not been well characterized. Currently there is a wide array of seats that can be selected for installation in Metropolitan buses.

Using a standardized test route, and calculating time-weight average (TWA) and impulsive WBV exposure parameters from ISO 2631-1 and ISO 2631-5 respectively, the purpose of this study was to determine whether there are performance differences in WBV attenuation between two bus seats made by two different major bus seat manufacturers. In addition, second goal of this study was to determine whether there were differences in WBV attenuation between a standard foam and silicone foam seat pan. Currently, based on King Country Metro repair records, the average life of a standard foam seat pan is six months, and after the foam fatigues, replacement of the seat pan is required. Silicone foam is being offered as an alternative seat pan material and is purported to have a fatigue life of five years. If the silicone foam seat pad has the same or better performance than the foam seat pad, then this may be a cost effective alternative due to its purported longer life. Beyond simply comparing seats, an additional goal of this study was to determine whether there were differences in WBV exposures based on road type.

2. METHODS

2.1 SEATS TESTED

The first goal of this study was to determine whether there were WBV exposure differences, over a standardized test route, using two different seats from two different seat manufactures. To enable a controlled comparison between seats, both seats used in the study were brand new. The two seats used in the study were the Recaro Ergo M (Seat 1) and USSC Q91 (Seat 2). Both seats have foam seat pans, air suspensions, and adjustable lumbar support.

A second goal of this study was to determine whether there were WBV exposure differences based on the type of foam used to construct the seat pan. As a result a third seat was introduced to the study which was identical to Seat 2, except the foam seat pan in Seat 2 was replaced with a silicone seat pad (Seat 3).

2.2 BUS AND TEST ROUTE

The standardized test route was designed to include three common road types encountered by bus drivers and included 12 km of city streets, 29 km of new freeway, 10 km of old freeway and a 1 km circular route containing 10 speed humps (4 m wide). The same 12.2 m New Flyer (Manufactured in Winnipeg, Manitoba) low floor bus was used throughout the entire study. This is important as it has been shown in prior research that there are large variations in vibration magnitude within and between vehicle categories and types [25]. The runs were completed with no passengers other than the driver and two data collection staff (one or two researchers).

2.3 WHOLE BODY VIBRATION INSTRUMENTATION

Figure 1 shows the schematic and set up of the WBV data collection system. A Personal Digital Assistant (PDA)-based portable WBV data acquisition system was used to collect WBV exposures per ISO 2631-1 and 2631-5. Raw, unweighted tri-axial WBV measurements were collected at 640 Hz using a seat pad ICP accelerometer (model 356B40; PCB Piezotronics; Depew, NY) mounted on the driver's seat and simultaneous z-axis measurements were to be collected with an identical accelerometer mounted immediately adjacent to the driver's seat. Accelerometer calibrations were conducted prior to all data collection sessions using a Type 4294 Bruel & Kjaer Calibration Exciter. The system

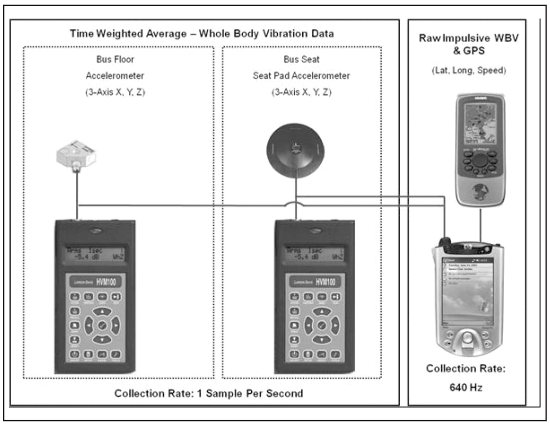

Figure 1. Schematic of WBV Data Collection System

calibrations were evaluated using a LabVIEW program written to analyze and verify calibration exciter measurements.

As shown in Figure 1, two Larson Davis HVM 100's loggers were used as accelerometer amplifiers and a Pocket-PC PDA with 2 Gigabytes of compact flash memory, an external battery pack, and a PCMCIA expansion pack instrumented with a data acquisition card was used to collect the WBV signals. Using the serial port on the PDA, once every second, Global Positioning System (GPS) data was also collected and integrated with the WBV exposure data to identify the location, velocity, and type of road associated with the WBV exposures.

2.4 SUBJECTS

The mean age of the participants was 50.8 (range 38-60) the mean weight of subjects was 80.9 kilograms (range 49.4-116.1 kg) and an equal number of male and female drivers participated in the study. Half of the study participants were part-time bus drivers and half-were full time bus drivers. The majority of drivers worked year round with a mean of 241.7 driving days per year (range 150-300). The majority of drivers had less than 10 years of experience driving buses with a mean of 9.9 years (range 1-22).

2.5 DATA ANALYSIS

The data was analyzed using a WBV data analysis program written in LabVIEW. The LabVIEW routine used a Matlab-based program to appropriately weight the continuous signals [26] and WBV calculations were performed as outlined in ISO 2631-1-1997 and 2631-5-2004. WBV measures were calculated over the whole route (all road segments) as well as by individual road segment.

The ISO 2631-1 parameters were normalized to reflect 8 hours of driving and evaluated and compared between seats, road types, seat settings and driver weights included:

The eight hour root mean square average vibration ($A_w(8)$) calculated at the floor and at the seat pan of the bus (m/s^2).

$$A_w(8) = \left[\frac{1}{T} \int_0^T a_w^2(t)\, dt \right]^{\frac{1}{2}} \qquad (1)$$

The eight hour vibration dose value (VDV(8)) which is more sensitive to impulsive vibration and reflects the total, as opposed to average vibration, over the measurement period at the seat pan and floor of the bus (m/s$^{1.75}$).

$$VDV(8) = \left\{ \int_0^T \left[a_w(t) \right]^4 dt \right\}^{\frac{1}{4}} \qquad (2)$$

TWA Peak – the highest magnitude of A_w measured during the measurement period (m/s^2).

The ISO 2631-5 parameters were normalized to reflect 8 hours of driving and evaluated and compared between seats, road types, seat settings and driver weights included:

The eight hour daily dose ($D_k(8)$) is designed to be an estimate of daily vibration dose (m/s^2).

$$D_k(8) = \left[\sum A_{ik}^6 \right]^{\frac{1}{6}} \qquad (3)$$

The eight hour static compressive dose ($S_{ed}(8)$) measured in megapascals, which has been developed through biomechanical modeling, is designed to capture the linear relationship between peak acceleration and input shocks to responses in the spine (MPa).

$$S_{ed}(8) = \left[\sum_{k=x,y,z} (m_k\, D_{kd})^6 \right]^{\frac{1}{6}} \qquad (4)$$

In addition to the WBV measures covered by Part 1 and Part 5 of the ISO

2631 standard, the Raw (+) Peak – the highest vibration measured in the positive direction (Z-axis topping out), the Raw (-) Peak – the highest average vibration measured in the negative direction (Z-axis bottoming out).

2.5 STATISTICAL ANALYSES

The data segments analyzed with the LabVIEW routine created output files with all the desired summary measures. In order to determine whether there were differences in WBV exposures between the seats made by different manufactures (Seat 1 and Seat 2), repeated-measures analysis of variance (RANOVA) methods were used. The same methods were used to test whether there were differences between the standard foam (Seat 2) and silicone foam seat (Seat 3).

3. RESULTS

3.1 WBV RESULTS COMPARING SEATS AND SEAT ATTENUATION

3.1.1 Comparison of different seat manufacturers (Seat 1 versus Seat 2)

The left portion of Table 1 compares the seats of the different manufacturers (Seat 1 and Seat 2). As shown in Table 1, there were no differences between seats in average vibration exposures (A_w). However, according to ISO 2631-1, when Crest Factors are above 9, this indicates impulsive exposures were likely encountered; A_w may be underestimated and should be interpreted with caution. As an alternative, the Vibration Dose Value (VDV) is recommended for evaluation when impulsive exposures are present. As revealed in Table 1, there were no differences between seats in VDV exposures. Finally, the daily acceleration dose (D_k), measured at the seat pan, was significantly lower for Seat 1 when compared to Seat 2. This measure, part of ISO 2631 part 5, is designed to give a prediction of long term health effects related to spinal compression. The differences in performance between seats in daily acceleration dose and crest factors suggest that there is some difference in the performance of seat suspensions when attenuating impulsive exposures.

3.1.2 Foam (Seat 2) versus silicone (Seat 3) seat pan

As shown in Table 1, there was virtually no difference in exposures between the seat with the standard foam seat pan (Seat 2) and the silicone foam seat pan (Seat 3).

3.1.3 Floor versus Seat

Not shown in Table 1 are the p-values comparing the floor versus the seat WBV exposures. In all instances, with the exception of crest factor, the seats significantly attenuated all WBV exposures.

Table 1. Mean (SEM) WBV exposures over the whole route, normalized to an 8 hour day, comparing Z-axis floor and seat measured exposures by seat type (n=12).

Parameter	**Accelerometer Location**	**p-value Seat 1 v 2**	**Seat 1**	**Seat 2**	**Seat 3**	**p-value Seat 2 v 3**
Aw(8) (m/s^{2})	Floor	0.12	0.45 (± 0.01)	0.43 (± 0.01)	0.48 (± 0.02)	0.02
	Seat	0.72	0.41 (± 0.01)	0.40 (± 0.02)	0.40 (± 0.01)	0.89
Crest Factor	Floor	0.40	19.8 (± 1.63)	21.7 (± 1.48)	14.9 (± 0.98)	0.001
	Seat	0.001	9.25 (± 0.44)	11.6 (± 0.34)	11.9 (± 0.52)	0.45
VDV(8) (m/s$^{1.75}$)	Floor	0.79	12.0 (± 0.38)	12.2 (± 0.43)	11.9 (± 0.77)	0.13
	Seat	0.98	9.26 (± 0.27)	9.24 (± 0.42)	9.33 (± 0.36)	0.69
Dk (8) (m/s^{2})	Floor	0.54	14.0 (± 1.06)	13.3 (± 0.67)	12.4 (± 1.10)	0.51
	Seat	0.01	9.01(± 0.39)	11.5 (± 0.84)	12.1 (± 0.74)	0.23
Speed (km/h)	—	0.13	55.7 (± 1.56)	53.1 (± 1.58)	57.5 (± 1.03)	0.04

Table 2: Mean (SEM) WBV tri-axial exposures, normalized to an 8 hour day, comparing seat measured exposures by road type (n=12).

Parameter	**Axis**	**City Streets**	**Speed Humps**	**New Freeway**	**Old Freeway**	**p-value**
Aw(8) (m/s^2)	X	0.14 (± 0.01)	0.17 (± 0.01)	0.11 (± 0.01)	0.13 (± 0.01)	<0.0001
	Y	0.11 (± 0.01)	0.15 (± 0.01)	0.11 (± 0.01)	0.12 (± 0.01)	<0.0001
	Z	0.36 (± 0.01)	0.36 (± 0.01)	0.43 (± 0.01)	0.51 (± 0.01)	<0.0001
Crest Factor	X	14.1 (± 1.54)	8.4 (± 0.50)	8.8 (± 0.25)	7.4 (± 0.27)	<0.0001
	Y	13.9 (± 0.72)	7.3 (± 0.33)	8.4 (± 0.22)	8.3 (± 0.27)	<0.0001
	Z	14.5 (± 0.63)	11.8 (± 0.49)	8.2 (± 0.22)	6.9 (± 0.23)	<0.0001
VDV(8) (m/s$^{1.75}$)	X	3.4 (± 0.16)	4.1 (± 0.22)	2.5 (± 0.14)	2.7 (± 0.17)	<0.0001
	Y	2.9 (± 0.09)	3.3 (± 0.08)	2.1 (± 0.06)	2.4 (± 0.07)	<0.0001
	Z	9.4 (± 0.24)	9.6 (± 0.37)	8.9 (± 0.18)	10.3 (± 0.22)	<0.0001
Dk(8) (m/s^2)	X	7.3 (± 1.47)	6.4 (± 0.39)	3.9 (± 0.27)	4.2 (± 0.31)	0.004
	Y	4.0 (± 0.21)	4.6 (± 0.18)	2.5 (± 0.10)	2.7 (± 0.12)	<0.0001
	Z	12.8 (± 0.77)	13.2 (± 0.85)	8.9 (± 0.26)	9.4 (± 0.28)	0.03
SED(8) (MPa)	Z	0.45 (± 0.03)	0.42 (± 0.03)	0.29 (± 0.03)	0.30 (± 0.03)	<0.0001
Speed (km/h)	—	28.3 (± 0.89)	29.9 (± 0.69)	82.6 (± 1.26)	82.9 (± 1.64)	<0.0001

3.2 WBV RESULTS COMPARING ROAD TYPES

WBV exposures measured across the different road segments was compared across four ISO 2631-1 time weighted vibration exposure parameters (A_w, Crest Factor, VDV and TWA Peak) and four ISO 2631-5 impulsive exposure parameters (Raw (+) Peak, Raw (-) Peak, D_k and S_{ed}). Since there were very few differences between seats, Tables 2 shows the vibration exposures, averaged across all seats, grouped by road type.

As can be seen in Table 2, with the exception of Crest Factor (which is a normalized measure), z-axis exposures were the highest and the y- and x-axis exposures were lower. The y-axis exposures (side-to-side) tended to be slightly higher than the x-axis (fore-aft) exposures. In general, most WBV exposures were low and below recommended exposure limits; however, there were a few exceptions. The z-axis measures for A_w(8) was highest and above the 0.5 m/s^2 action limit for the older freeway segment. However, given that the z-axis crest factors were above 9 in the street and speed hump segments, this indicates that impulsive exposures were encountered, the A_w (8) exposures should be interpreted with caution, and the VDV(8) evaluated. Table 2 shows that there were significant differences across road types in z-axis VDV(8) measurements, with the VDV(8) exposures above the action limit in the street, older freeway and speed hump segments.

Differences in peak exposures between seats grouped by road type are shown in Figure 2. The results show that there were some differences between Seat 1 and Seat 2, but no significant differences between Seat 2 and Seat 3. Across all seats, the highest peaks (TWA Peak, Raw (+) Peak, and Raw (-) Peak) were measured on the street segment while the lowest peak measurements were on the freeways.

There were significant differences in S_{ed}(8) exposures between seats, these exposures are shown by road type in Figure 3. The highest exposures for static compression were exhibited in the street segment with the silicone seat (seat 3), Seat 2 was intermediate, and Seat 1 had the lowest static compressive doses. With the exception of the streets, the seat with the foam seat pan (seat 2)

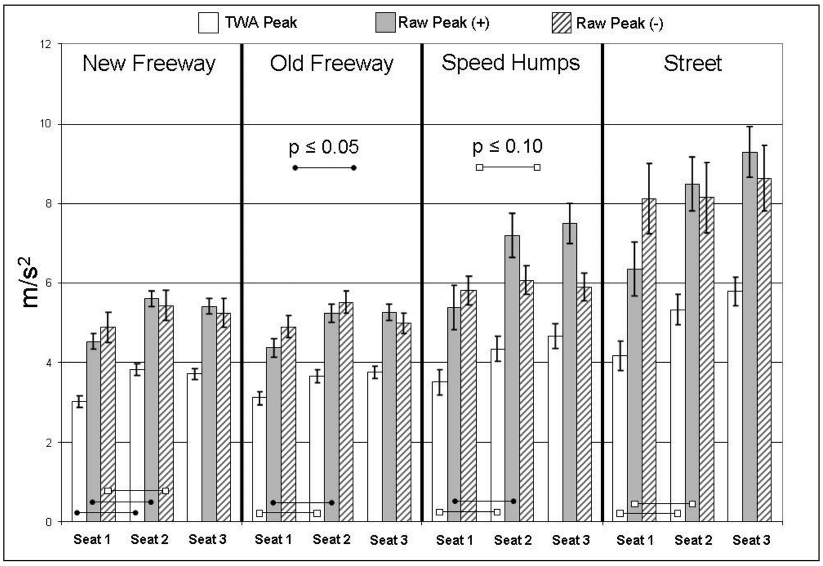

Figure 2. Mean (SEM) time weighted average TWA Peak, Raw (+) Peak, and Raw (-) Peak by seat grouped by road type (n=12)

performed similarly to the seat with the silicone seat pan (seat 3) and Seat 1 always had significantly lower $S_{ed}(8)$ values than Seat 2.

4. DISCUSSION

In a standardized controlled setting, this study evaluated and compared two different seats and two types of seat foam for attenuating WBV exposures. Seat 1 performed significantly better than Seat 2 in the attenuation of impulsive WBV exposures, however, no seat performed better on all road types. There were significant differences in WBV exposures across the various road types. As a result, a possible administrative control to reduce a bus driver's exposure to WBV could involve assigning routes based on road type, with the goal of limiting or distributing WBV exposures based on road type. The study was conducted in North America, however, the results of this study may translate to European busses which fall under the current European Directive 2002/44/EC [27].

4.1 WBV RESULTS COMPARING SEATS

The WBV exposure differences between

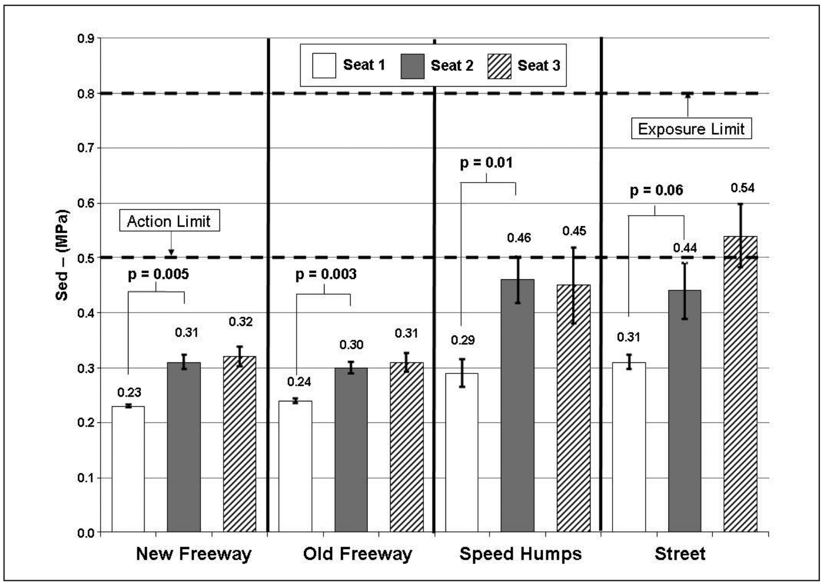

Figure 3. Mean (SEM) daily static compressive stress (Sed(8)) across seats grouped by road type (n=12)

Seat 1 and Seat 2 showed that the seats performed similarly in attenuating TWA WBV exposures, however, Seat 1 performed better in attenuating impulsive exposures. The results also indicated that no seat performed universally well on all road segment types. In the future, it would be interesting to evaluate the performance of commercially available semi-active seat suspensions.

The WBV exposures between Seat 2 and Seat 3 were not significantly different from one another. One interesting result was that there were significant differences between Seat 2 and Seat 3 in the transmission of peak vibrations from the floor to the seat. The denser silicone foam appears to transmit more of the peak vibration signal to the operator.

4.2 WBV RESULTS COMPARING ROAD TYPES

This study found significant differences in vibration exposure across the road types with z-axis street segment exposures near or slightly above the established action limit (9.1 $m/s^{1.75}$) for VDV(8). $A_w(8)$ z-axis exposures were below the action limit (0.5 m/s^2) as established by ISO 2631-1. However, as indicated in ISO 2631-1, A_w measurements with crest factors above 9 should be interpreted with caution. This was the case with the WBV data collected from the street segments.

High VDV(8) z-axis exposures were also present in the older freeway segment and above the action limit. The continuous nature of WBV exposures combined with the large number of impulsive exposures from expansion joints indicates that both TWA and impulsive WBV exposures were present on the freeway segments. The exposure differences between the different road types indicate that one potential work organization intervention could be route rotation so that drivers do not spend excessive time on noxious routes and/or drive on different segments to vary the exposure between continuous and impulsive vibration exposures. It is noteworthy that the freeways had the highest $A_w(8)$ exposures due to the continuous nature of the WBV exposures. This was due to the on/off nature of the street WBV exposures associated with alternating WBV exposures between moving/driving and being idle at stoplights. The freeway routes represent a fairly constant exposure which leads to less idle time than the street segments, however, the street segments have more starts and stops from stop lights and bus stops.

4.3 LIMITATIONS OF THE STUDY

One potential limitation in the study was due to practical limitations associated with switching seats, as a result, seat order was not randomized. All subjects tested the seat in the same order (Seat 1, Seat 2, Seat 3). The sample size (n=12) was somewhat small, testing more subjects would increase the ability to determine if there were any systematic WBV exposure effects associated with the conditions evaluated in this study.

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FOOLISH LANDLORD LOSES LICENCE FOR LACK OF A LIMITER

Angus (Scotland) councillors have suspended the licence of Montrose pub Albert Bar’s indefinitely until a noise-limiting device is installed. The licencing board had received a number of complaints from neighbouring residents and asked Angus Council officers to work with the pub and people living nearby in a bid to resolve the issue. A noise management plan was agreed and the licensee was to install a noise limiting device which was to be operated to the satisfaction of officers to prevent continuing complaints. These are attached to the power supply of a venue’s amplification system to monitor noise level. If it exceeds a pre-set level, the device cuts the system’s electricity supply. Licensing board chairman Councillor John Whyte said that the step had been taken because a limiter had not been installed despite reminders and “extensive support and guidance from council officers” leading to further complaints.