

Predictors of whole-body vibration levels among urban taxi drivers

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To identify a set of important WBV predictors that could be used to develop a statistical instrument for exposure assessment in a large epidemiologic study, a total of 432 WBV measures were taken from a sample of 247 male drivers in Taipei City, Taiwan. In accordance with the ISO 2631-1 (1997) methods, we measured the frequency-weighted vertical acceleration (z -axis) over drivers' seat surface, under conditions representing different types of rides (vacant vs. short vs. long) assigned to random destinations. Mixed effect models were used to analyse the WBV data including repeated measures. For this group of urban taxi drivers regularly exposed to WBV of low intensity (mean = 0.31 ms^{-2} , ranging from 0.17 to 0.55 ms^{-2} r.m.s.), our analyses indicated that average driving speed was the primary predictor ($p < 0.0001$). As average driving speed increased, measured vertical acceleration increased in a quadratic-linear manner ($p < 0.0001$). Other WBV predictors, after adjusting for the effects of other covariates, included automobile manufacturer ($p = 0.02$), engine size ($p = 0.04$), body weight ($p = 0.002$), age ($p = 0.02$), use of seat cushion ($p = 0.03$), and traffic period ($p = 0.02$). Our study suggests that a similar statistical approach could be employed in future studies to improve the quality and efficiency of WBV exposure assessment in professional drivers.

1. Introduction

Whole-body vibration is one of the strongest risk factors for low back disorders (US National Institute of Occupational Safety and Health [NIOSH] 1997), and also the most common and costly occupational injury in most industrialized countries

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(Webster and Snook 1990, Frymoyer and Cats-Baril 1991, Kraut 1994, van Tulder *et al.* 1995, Maniadakis and Gray 2000). Since the 1950s, occupational epidemiologic studies have shown a consistent association between professional driving and various low back disorders (Hulshof and van Zanten 1987, Pope and Hansson 1992, Seidel 1993, NIOSH 1997, Bovenzi and Hulshof 1999). Long-term occupational exposure to WBV reportedly is associated with low back pain (Brendstrup and Biering-Sorensen 1987, Boshuizen *et al.* 1990a, Boshuizen *et al.* 1992), sciatica (Bovenzi and Zadini 1992), early spinal degeneration (Frymoyer *et al.* 1984), and herniated lumbar disc (Boshuizen *et al.* 1990b, Bovenzi and Zadini 1992).

Findings of these observational studies have been supported by biomechanical and biological research and have helped establish the causal link between WBV and low back disorders. For instance, it has been found that whole-body vibration results in elevated lumbar spinal load (Hinz *et al.* 1994, Fritz 1997, 2000), predicts endplate failure (Seidel *et al.* 1986), and causes muscle fatigue (Pope *et al.* 1987, Wilder *et al.* 1996). Animal studies also show that WBV may cause increase in intradiscal pressure (Hansson *et al.* 1988), decrease of nutrition supply to disc tissues (Holm and Nachemson 1985), interference of neuro-inflammatory mediators (McLain and Weinstein 1994), and microstructural changes in dorsal root ganglion (Weinstein *et al.* 1988).

However, the exposure-response relation between WBV and low back disorders (LBD) remains uncertain. Many investigators (Hulshof and van Zanten 1987, NIOSH 1997, Bovenzi and Hulshof 1999, Lings and Leboeuf-Yde 2000) attributed this uncertainty to insufficient work on WBV exposure assessment, and called for research on better exposure assessment with direct WBV measures. Indeed, exposure assessment plays an essential role in quantifying the health risks associated with prolonged exposure to WBV and in determining the exposure standard for occupational WBV. Moreover, it is noteworthy that most of above-mentioned occupational epidemiologic studies were conducted among drivers exposed to relatively high levels of WBV (with acceleration magnitudes mostly over 0.5 ms^{-2} in root mean square). There is even more uncertainty in extrapolating previous epidemiologic findings to projecting the health effects of WBV at lower exposure levels. It is therefore of scientific interest to study drivers with lower levels of WBV exposure in order to understand the health effects of WBV at lower intensity. From a public health perspective, results of these studies could provide very useful human data to determine the appropriate standards for occupational WBV exposure.

To address some of these concerns, we conducted an occupational epidemiologic study on urban taxi drivers. Although not fully documented in the literature, this study population was presumably exposed to relatively low levels of WBV exposure given the general characteristics of their operating vehicles and work environment. Direct exposure assessment is very important to quantify the cumulative WBV exposure at the individual level; however, we realized that we would be unable to take direct WBV measurements on each study subject, since thousands of urban taxi drivers would be included in our full study.

We therefore adapted statistical approaches to developing an instrument that could be used in large epidemiologic studies. Specifically, we first carried out an exposure assessment study among a sub-sample of drivers recruited from the study source population in order to identify important WBV predictors, such as personal factors, vehicle characteristics, and other occupational activities. Based on these identified WBV predictors, we will next develop a prediction rule, as a statistical

instrument for WBV exposure assessment, to estimate WBV exposure at the individual level. Finally, we will apply this instrument to quantifying the cumulative WBV exposures for those subjects without direct WBV data, and examine the exposure-response relation between WBV and LBD in the full study. Here we present our first study on direct exposure assessment. Results on analysing the vertical vibration measured at driver's seat surface are included in this report. The development and application of the statistical instrument, and the analyses of WBV measured in other coordinates, will be reported elsewhere.

2. Methods

Cab service is a very competitive business in Taipei City, Taiwan. According to the *Weekly Report of the Department of Budget, Accounting, and Statistic (DBAS)* of the Taipei City Government (Taipei DBAS 2000), at the end of 1999, there were 36 585 taxicabs registered in Taipei City, a number equivalent to 14 taxicabs for every 1000 residents. With the addition of all vehicles from neighbourhood cities and counties, within its geographic area of 272 square km, 77 246 automobiles were permitted to conduct regular taxi business in Taipei City, accounting for almost 70% of all taxicabs in Taiwan. Exposure assessment for our study was carried out during the summer of 2000. The study protocol was approved by the Human Subjects Committee of the Harvard School of Public Health and by the Institutional Review Committee of the Liberty Mutual Research Institute for Safety.

2.1. Study population

Potential participants were recruited from several large cab companies, taxi cooperatives, cab service radio stations and local unions. Inclusion criteria for eligible drivers were: (1) male; (2) registered professional taxi drivers; (3) active drivers; (4) operating vehicles made by Toyota, Nissan, Honda, or Ford (these being the manufacturers for approximately 85% of all automobiles used in Taiwan's cab business). At each recruitment site, an invitation letter indicating the study purpose, measurement procedures, confidentiality issues, registration procedures for participation, and remuneration (US \$10 for about 30 min of measurement) was given to drivers. Background information (registration status, vehicle information, and contact information etc.) for each registered driver was faxed to our central office by the staff of cooperating organizations. A list of potential participants was then compiled.

2.2. Sampling

In order to get a sample of drivers with various vehicle characteristics, the following stratified sampling scheme was adapted. Given their known vehicle information (manufacturers (four levels), years of make (nine levels), and engine sizes (two levels)), drivers and their operating vehicles were grouped into 72 categories, each used as the basic sampling block. In the order they entered the compiled contact list, drivers were then contacted by telephone by a research assistant to check their eligibilities. If more than five eligible drivers were grouped in the same block, a random sample of five drivers was selected from each of 72 blocks. Otherwise, all eligible drivers were invited to participate in the test runs. Appointment with drivers for measurement would not be made if: (1) they would not be available after the second contact; (2) there had been five or more taxis being measured within the vehicle category that they belonged to; or (3) they had broken their prior appointment without notification.

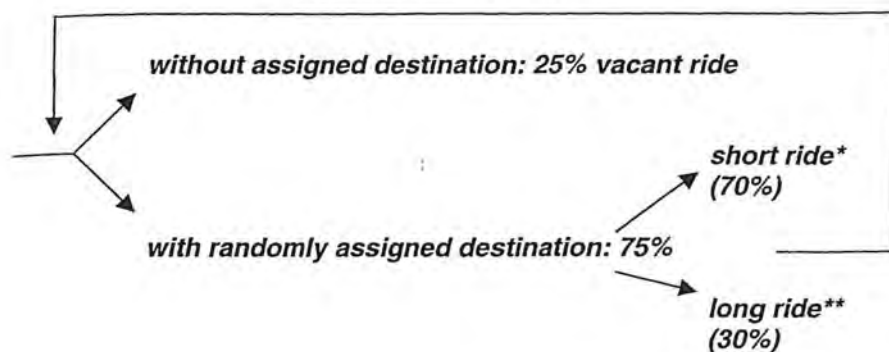
2.3. WBV measurement instrument

We developed a WBV record-replay system at the Liberty Mutual Research Institute for Safety (LMRI) in Hopkinton, MA, USA. The detailed technicalities had been documented elsewhere (LMRC 1998, TEAC 1991). In brief, this system includes a tri-axial accelerometer (PCB Piezotronics, NY, USA; Model Number 352M69), one RD-130T PCM data recorder (TEAC, Tokyo, Japan), and one LMWBV meter 2.0 (LMRI, MA, USA). The overall system, including the accelerometers and LMWBV meter, was calibrated with procedures in compliance with International Organization for Standardization (ISO) 8041 (ISO 1990). Each axis of the tri-axial accelerometer was also calibrated to comply with ISO 10012-1 (ISO 1992a). The main components of the LMWBV meter consisted of a laptop computer (IBM ThinkPad 380D), an analog-to-digital converter card (Computer Boards, Middleboro, MA, USA, Model Number: PCM-DAS16S/12), and proprietary amplifier box and software. The computer software performed digital filtering to the incoming vibration signal and calculated various output based on the frequency-weighting functions specified in the ISO 2631-1 method (ISO 1997). The software used the ISO method to achieve comparability with prior field studies. Following the technical specifications of the ISO 10326-1 (ISO 1992b), we mounted the accelerometer onto the seat surface. We recorded the WBV signals during the fieldwork and replayed them into the meter for signal analyses. The test-retest reliability of the replaying process, as evaluated by the intraclass correlation coefficient, is 0.997. The results of WBV signal analyses are output as frequency-weighted root-mean squares (r.m.s.) of acceleration magnitude measured in three coordinates. We chose the *z*-axis as the major source of WBV exposure but did not use the vector-sum for two reasons. Firstly, our pilot measurements in Greater Boston areas suggested that vertical acceleration is the predominant vibration in this occupational setting. Secondly, the weighting factors that convert tri-axial measures to a composite vector-sum are determined by subjective comfort evaluation, rather than by adverse health effects. Although the vibration dose value was also given as a reference, the root-mean square method was chosen to characterize the exposure intensity for our study because of the notion of energy equivalence principle (Lundstrom *et al.* 1998, Mansfield and Griffin 1998) assuming that the adverse health effect is proportional to the absorbed WBV energy.

2.4. Driving task assignment

To measure WBV under conditions representing the usual practices, the types of test ride (vacant, short, or long ride) and destinations were pre-determined by the algorithm shown in figure 1. A short ride was defined as a test ride of riding distance ≤ 4 km during rush hours or ≤ 6 km during non-rush hours, whereas a long ride was defined otherwise. For each driving task, the typical measurement duration was about 30 min. If the expected duration of the first selected test ride was less than 20 min, repeated measures within the same vehicle were taken, and the subsequent ride types were pre-selected again with probability independent of the prior ones. The indicated probability for each type of ride was based on an update survey on service pattern conducted by the Ministry of Transportation and Communications (MOTC) in Taiwan (Taiwan MOTC 2000), and was confirmed by interviewing a focus group of potential participants before we started this study.

if expected duration < 20 minutes



* Short ride is defined as ≤ 4 km of riding distance during rush hours or ≤ 6 km of riding distance during non-rush hours as measured on map.

** Long ride is defined otherwise.

Figure 1. An algorithm for assigning the driving task with different types of test rides.

On each test day, a total of 5–10 driving tasks were arranged, depending on time and availability of drivers and vehicles. For those belonging to the same sampling block, their driving tasks were arranged in either one of the following five traffic periods: morning rush hours (7.30–9.30), noon (11.30–13.30), daytime non-rush hours (9.30–11.30, 13.30–16.30), evening rush hours (16.30–18.30), and evening/night time (19.00–21.00). The starting point of the first run was selected from 10 sites discretely located within Taipei City, and alternated on a daily basis. The starting points of subsequent driving tasks were either taxi stops, subway stations, hospitals, banks, large office buildings, or other locations that reportedly were ‘hot spots’ for taxi service business. These sites were all located within 20–30 min of driving distance from the prior starting point. If the pre-selected ride type was a vacant ride, the drivers were instructed to roam the streets that were considered ‘hot routes’ for taxi services, as they usually did when looking for passengers. For the other two ride types, 692 street sections with assigned random digit numbers were available for appropriate selection. Regardless of the types of ride assigned, instructions given, or destinations selected, during the measurement sessions no driver was aware that there were subsequent driving tasks for other drivers. Furthermore, those assigned to more than one ride were not told the destinations of subsequent rides until the concurrent one was finished. After being informed of the pre-selected ride types and destination points for their designated rides, drivers were instructed to keep as much as possible to their usual speeds and driving patterns.

The repeatability of measured WBV for the same assigned driving task was difficult to assess, due to the change in driving conditions associated with different traffic flow which we were unable to control in the fieldwork. However, we did find a very good reliability of the obtained values (intraclass correlation coefficient 0.95) during the pilot measurements ($n = 16$) conducted in the Boston metropolitan and Hopkinton suburban areas of MA, USA.

2.5. *Covariates measurement*

All covariates measured are either personal or vehicle characteristics speculated to influence the vibration intensity, according to previous biomechanical studies or from automobile engineering perspectives. During the actual drive test, one researcher sat on the rear passenger seat, observing and recording the traffic routes being taken, driver's posture (upright, leaning forward/backward), odometer readings, fuel type (gasoline or natural gas), engine size (in c.c.), transmission type, use of seat surface or backrest cushion and use of seat belt. The reading of cumulative mileage at the end of each ride was taken from the uniformed taxi-fare meter standardized by the Central Bureau of Standardization in Taiwan, and the timing of measurement was tracked by the TEAC recorder. With these two together, we calculated the average driving speed (in kmh^{-1}) for each ride. At the end of driving task, each driver was interviewed by the same researcher to provide information on his age, body weight (kg) and height (cm), professional seniority (years), daily driving hours, daily driving distance (km), days off per month, and reported low back pain. In addition, the following variables were measured directly: wheelbase (cm), tyre width, treads depths of four tyres, and inclination of seat surface and backrest.

2.6. *Statistical analysis*

The major response variable is the vertical vibration magnitude (in ms^{-2} r.m.s.) measured at the z -axis of seat surface. Given the task assignment algorithm, the drivers would have various numbers of test rides, and as a result, we would have a highly imbalanced data structure contributed by some drivers with a single measure and by others with repeated measures. To account for this response imbalance in design, we used mixed effect models (Davidian and Giltinan 1998) to construct the effects of explanatory variables of interest on WBV magnitude. In this covariate-response matrix, driving speed, weather, ride type, driver's posture, and use of a seat belt could potentially be time-varying covariates, whereas personal factors, vehicle characteristics, and some other occupational factors were time-independent. For the comparison between nested models, the mean structures were determined by likelihood ratio test (LRT) based on standard maximal log likelihood (ML). Their corresponding variance-covariance structures (e.g. random intercept only vs. random intercept and slope) were determined by LRT based on restricted maximal log likelihood (REML). In building the mixed effect models, we first determined the best-fit 'base model', which included fixed effects of the three covariates (manufacturer, year of make, and engine size) we used to sample subjects, and fixed and random effects of average driving speed, the variable we found had essential influence on WBV intensity when we did pilot measures in Greater Boston area, MA, USA during the spring of 2000. A covariate was defined as a potential WBV predictor if the estimate of its fixed effect was significant at a 0.20 level when entering the base model. We defined potential confounder as any covariate whose entry into the base model would have changed the fixed effect estimate associated with average driving speed by more than 10%. We then fitted the 'full model' that included those variables already retained in 'base model' and all the other potential predictors and confounders. Lastly, the 'final model' was built, and only estimates of fixed and/or random effects statistically significant at 0.05 levels were included. All effect estimates were given by REML method. All of these statistical analyses were carried out by the PROC MIXED procedure of the SAS 8.0 software package (SAS institute, NC, USA).

3. Results

Two hundred and ninety-two male drivers and their vehicles were sampled from the compiled list of 751 subjects to participate in 470 pre-selected test rides. Two hundred and forty-seven (85%) drivers completed the scheduled driving tasks, contributing a total of 432 (92%) WBV measurements. Reasons for absence included bad weather ($n = 30$), vehicle breakdown ($n = 3$), acute illness ($n = 3$), and unknown ($n = 9$). Out of 432 WBV measures, 49 (11%) had missing vibration data and thus did not contribute to the final model. Of these, 18 WBV signals were missing due to transient instrument failure, and the other 31 WBV output were missing because measurement duration was not recorded. The mixed effect models were then built on the exposure data information provided by the remaining 383 WBV measures.

Of the 247 drivers who completed driving tasks, 152 were assigned to repeated measures, whereas the other 95 drivers were assigned to a single measurement. The characteristics of all 247 drivers and vehicles were demonstrated in table 1. Their mean age (\pm SD) was 45 (\pm 8) years; on average they drove 9.7 h and 185 km a day, had become professional taxi drivers for 9.2 years, and 48% complained of low back pain in the past year. Comparing these data to the results of a nationwide survey (Taiwan MOTC 2000), these 247 study subjects had characteristics in age, professional seniority and daily driving distance that were comparable to other taxi drivers in Taipei City. Of the 247 sampled vehicles, the average engine size was 1650 c.c. (median 1600 c.c.), 58% were manufactured after 1995, and 63% had automatic transmissions. Table 1 also indicated those with repeated WBV measures which were not systematically different from those with only a single measurement, with respect to personal factors, vehicle characteristics, driving activities, and prevalence of low back pain. The mean WBV magnitude was 0.31 ms^{-2} , ranging from 0.17 to 0.55 ms^{-2} , which did not differ between these two groups of drivers. The vibration-dose value of the measured WBV, on average, was $15.06 \text{ ms}^{-1.75}$, ranging from 7.4 to $31.25 \text{ ms}^{-1.75}$.

Figure 2 depicted the relation between the vertical vibration measured at seat surface and the average driving speed. This graph suggested a quadratic-linear relation for the effect of average driving speed (km h^{-1}) on the frequency-weighted z -axis acceleration (ms^{-2} of r.m.s.). This finding was further confirmed by the statistical analyses using the mixed effect models to be illustrated later.

In table 2 the adjusted estimate of fixed effect of each covariate on WBV magnitude for each of the three mixed effect models is given, which all included a statistically significant random effect pertaining to intercept of WBV-speed relation (all p -values < 0.0001). In the 'base model', average driving speed and its quadratic term ($p < 0.0001$), manufacturer ($p = 0.02$), engine size ($p < 0.01$), and year of make ($p = 0.03$) were significant predictors of WBV intensity. After adjusting for the influence of those four 'base model' factors, use of seat surface cushion ($p = 0.03$), driver's body weight ($p = 0.002$) and age ($p = 0.04$), traffic period ($p = 0.01$), tyre width ($p = 0.06$) and wheelbase ($p = 0.05$) were six additional potential WBV predictors. However, when all these factors were included in the 'full model', only average driving speed and its quadratic term ($p < 0.0001$), driver's body weight ($p = 0.002$), age ($p = 0.03$), and traffic period ($p = 0.04$) remained statistically significant. The final model only retained the three covariates used for sampling, of which the manufacturer ($p = 0.02$) and engine size ($p = 0.04$) remained statistically significant, average driving speed and its quadratic term ($p < 0.0001$), and all the other statistically significant predictors including use of seat surface cushion

Table 1. Characteristics of 247 drivers and their operating vehicles

Characteristics	95 drivers assigned to one single measure	152 drivers assigned to repeated measures	All 247 drivers
	Mean \pm SD		
Age (years)	44.2 \pm 8.4	44.7 \pm 8.2	44.6 \pm 8.3
Body weight (kg)	70.1 \pm 13.2	68.1 \pm 10.8	68.9 \pm 11.8
Seniority (years)	9.8 \pm 7.4	8.8 \pm 7.2	9.2 \pm 7.3
Daily driving hours (h)	9.8 \pm 2.1	9.6 \pm 2.4	9.7 \pm 2.3
Daily driving distance (km)	188 \pm 53	187 \pm 53	187 \pm 53
Average speed (kmh ⁻¹)	19.5 \pm 5.8	19.0 \pm 5.0	19.2 \pm 5.3
Vertical vibration (ms ⁻²)	0.31 \pm 0.06	0.31 \pm 0.06	0.31 \pm 0.06
	Proportion (%)		
Type of transmission			
Automatic	68	60	63
Manual	32	40	37
Manufacturers			
Toyota	21	18	20
Ford	32	26	28
Nissan	19	35	28
Honda	28	21	24
Engine size (c.c.)			
< 1600	38	36	37
\geq 1600	62	64	63
Year of make			
\leq 1993	34	33	30
1994–1996	38	31	34
1997–2000	38	36	36
Use of seatbelt			
Yes	15	14	15
No	85	86	85
Use of seat cushion			
Yes	43	39	41
No	57	61	59
One-year LBP prevalence	53	45	48

* None of the vehicle and personal characteristics including the 1-year LBP (low back pain) prevalence are significantly different between two groups.

** Reference data from a nationwide survey by Taiwan MOTC: mean age = 43.9; mean seniority = 9.2 years; average daily driving hours = 10.2 h; average daily driving distance = 182 km.

($p = 0.03$), driver's age ($p = 0.02$), body weight ($p = 0.002$), and traffic period ($p = 0.02$). Our results did not suggest that there was a significant effect of seat belt use, posture, seat inclination, odometer reading, transmission type, fuel source, type of ride, or weather change, on the measured WBV intensity. Nor was significant WBV variation by weekdays found in our data.

The quadratic-linear relation between vertical WBV and driving speed was consistently significant across three mixed effect models, and the corresponding estimates of their fixed effects did not vary. In the final model, the significant quadratic trend of WBV-speed relation indicated that the population mean of vertical acceleration increased monotonously with increasing average driving speed

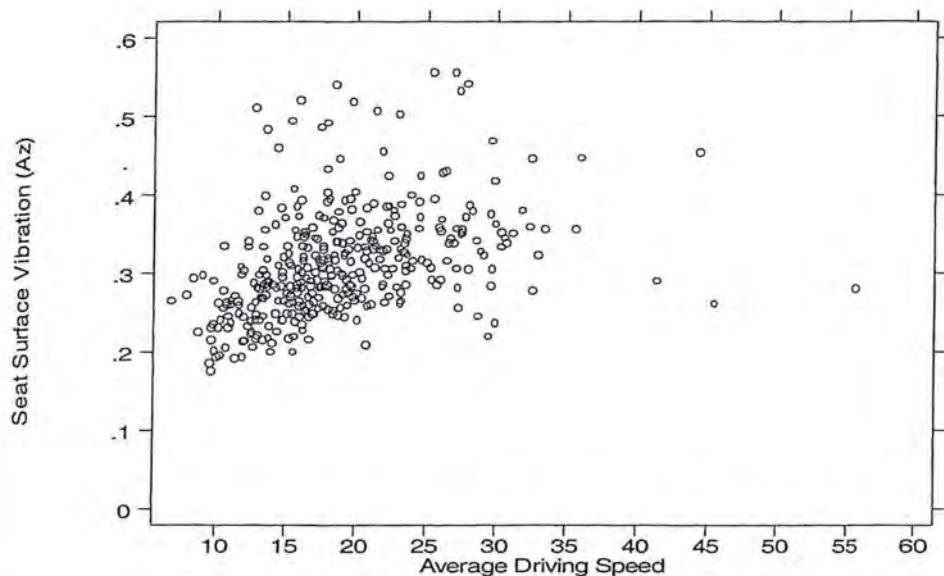


Figure 2. Relation of WBV acceleration (in ms^{-2} r.m.s.) measured at the Z-axis of seat surface (A_z) and the average driving speed (in kmh^{-1}). A quadratic-linear relation between A_z and average driving speed is depicted.

until it reached the maximum when average driving speed was approximating 32 kmh^{-1} . Given, as an example, a group of 34 year-old drivers with a body weight 70 kg, operating a 1500 c.c. 1998 Toyota during non-rush hours and using a seat surface cushion, the predicted means of vibration measured at seat surface (z -axis) were: 0.252 ms^{-2} at 10 kmh^{-1} , 0.324 ms^{-2} at 20 kmh^{-1} , 0.354 ms^{-2} at 30 kmh^{-1} , reaching climax 0.356 ms^{-2} around 32 kmh^{-1} , and 0.314 ms^{-2} at 40 kmh^{-1} .

Using a likelihood ratio test based on maximal log likelihood, we found that the 'final mixed effect model' fit the data as good as the 'full model' ($p = 0.39$). The estimate of error given by the final model was 0.001 ms^{-2} . Both supported the goodness-of-fit of the final mixed effect model we presented.

4. Discussion

To the best of our knowledge, no prior systematic work on the WBV exposure assessment for taxi drivers has ever been reported in English literature. Our study fully documented, for the first time, that urban taxi drivers are exposed to low-accelerating WBV. The majority (94%) of the WBV measures in our study, ranging from 0.17 to 0.55 ms^{-2} , were below 0.5 ms^{-2} , the lower margin of health guidance caution zone for an 8-h WBV exposure suggested in the most recent published ISO standard for occupational WBV (ISO 1997). However, 48% of these 247 taxi drivers had complained of low back pain over the last year. This prevalence was comparable to results of a recent Occupational Health Survey (Taiwan IOSH 2000) done in Taipei City, in which 51% of 1281 taxi drivers reported having low back pain in the last year, a figure significantly higher than the male general workforce nationwide (23%) (Taiwan IOSH 1999). As most prior epidemiologic studies on WBV were

Table 2. Adjusted coefficients (¶) and associated 95% confidence intervals (CIs) for the fixed effects of covariates on WBV levels obtained from three mixed effect models (§) for a total of 383 WBV measures

Covariates	Base model (<i>n</i> = 383)		Full model (<i>n</i> = 359)		Final model (<i>n</i> = 381)	
	β	95% CIs	β	95% CIs	β	95% CIs
Speed (per 10 kmh ⁻¹)	0.130	(0.099, 0.161)¥	0.130	(0.099, 0.161)¥	0.133	(0.010, 0.164)¥
Speed*Speed	-0.020	(-0.026, -0.011)¥	-0.021	(-0.027, -0.014)¥	-0.021	(-0.027, -0.014)¥
Manufacturer	† <i>p</i> = 0.02*; d.f. = 3		<i>p</i> = 0.07		<i>p</i> = 0.02*	
Honda	0.004	(-0.017, 0.025)	0.005	(-0.019, 0.028)	0.002	(-0.018, 0.022)
Ford	0.017	(-0.003, 0.036)	0.018	(-0.004, 0.040)	0.016	(-0.003, 0.035)
Nissan	0.027	(0.008, 0.046)	0.024	(0.004, 0.044)	0.024	(0.006, 0.043)
Toyota	0.000	-	0.000	-	0.000	-
Year of make	<i>p</i> = 0.03*; d.f. = 2		<i>p</i> = 0.24		<i>p</i> = 0.05	
1997-2000	-0.018	(-0.035, -0.001)	-0.010	(-0.028, 0.008)	-0.017	(-0.034, 0.000)
1994-1996	0.001	(-0.015, 0.019)	0.004	(-0.014, 0.022)	0.000	(-0.017, 0.017)
< = 1993	0.000	-	0.000	-	0.000	-
Engine size (c.c.)						
< 1600	0.019	(0.005, 0.033)**	0.006	(-0.014, 0.026)	0.015	(0.000, 0.029)*
> = 1600	0.000	-	0.000	-	0.000	-
Use of surface cushion			0.014	(-0.001, 0.030)	0.015	(0.001, 0.030)*
Body weight (per 10 kg)			-0.010	(-0.016, -0.004)**	-0.009	(-0.015, -0.003)**
Age (per 10 years)			-0.010	(-0.019, -0.001)*	-0.010	(-0.018, -0.001)*
Traffic period			<i>p</i> = 0.03*; d.f. = 2		<i>p</i> = 0.02*	
rush hours			-0.008	(-0.024, 0.008)	-0.005	(-0.020, 0.010)
noon			0.017	(-0.002, 0.036)	0.020	(0.002, 0.038)
non-rush hours			0.000	-	0.000	-
Tire width (per 10 mm)			-0.004	(-0.013, 0.005)		
Wheelbase length (per 10 cm)			-0.003	(-0.015, 0.008)		

¶ adjusted for effects of other covariates in indicated models.

* *p* < 0.05; ** *p* < 0.01; ¥ *p* < 0.0001.

† All *p*-values are given by likelihood ratio tests with indicated degrees of freedom (d.f.).

§ All models retain three sampling factors. The full model includes all potential WBV predictors.

The final model presents only statistically significant predictors.

conducted among professional drivers exposed to relatively higher levels of acceleration (e.g. fork-lift operators, wheel loaders, train operators, truck drivers, and helicopter pilots etc.), the health effects of low-accelerating WBV remain mostly unknown. Whether the observed higher prevalence of low back pain among taxi drivers in Taipei City is associated with prolonged exposure to low-accelerating WBV deserves further research. We believe that such studies should provide very useful human data for assessing the appropriateness of existing standards (e.g. ISO 2631-1:1997, British Standard 6841:1987) and for making occupational health policies to protect millions of workers who are regularly exposed to WBV in their workplace.

The major strength of our study is the repeated measures design (Ware 1985), which gives us the potential to do more precise estimates of covariate effects by within-subject comparison and better odds of identifying important WBV predictors. Constrained by time and resources, our repeated measures of WBV data were not balanced, a fact that led to our adaptation of mixed effect analyses. These mixed effect analyses model the covariates' influences on WBV intensities as a linear combination of the fixed effects, which refer to effects of factors that have neither between-subject nor within-subject variabilities, and the random effects, which are pertinent to effects of factors that could vary either between subjects or across repeated measures within the same subject. For instance, all three mixed effect models in our study contained a statistically significant random subject effect ($p < 0.0001$), suggesting that, given the same data information contributed by the fixed effects of driving speed, personal and vehicle characteristics, there was residual significant between-subject WBV variability. This random subject effect could result from unmeasured between-subject or between-vehicle variabilities, such as differences in driving behaviour, performance of suspension system, and road surface factors.

Fixed effect estimates from all three mixed effect models identified average driving speed as the primary predictor of WBV exposure in this occupational setting. The disclosed quadratic-linear relation between vertical WBV and driving speed was a consistent finding across three mixed effect models, and the corresponding estimates of their fixed effects did not vary. This robustness implied that the fixed effect of average driving speed was not greatly confounded by the other covariates that we considered in the modelling process. In Taipei City, the driving speed limit is 30 kmh^{-1} in metropolitan areas and 40 kmh^{-1} in suburban areas. Higher speed is only permitted for driving on highways and express connections. Presumably taxi drivers in Taipei City frequently encounter traffic jams, especially when driving around metropolitan areas. It is possible that WBV generated by taxicabs running at higher speed were likely to occur in the areas with relatively smoother road surfaces, such as highways or express connections. Therefore, it is arguable that the observed quadratic-linear relation between WBV and driving speed is likely to be confounded by the unmeasured effect of road surface factors. However, after we restricted the analyses to 363 observations taken at driving speeds of less than 30 kmh^{-1} , the quadratic trend (driving speed and speed square) remained statistically significant ($p < 0.001$).

Although we could not present real-time acceleration data for these measurements of WBV at low levels, we did observe WBV variation during each measurement session. The instantaneous vibration during a journey usually varied from near zero when the vehicles were stationary to high values when encountering obstacles. This

observation, to some extent, explains the effect of vehicle speed for WBV measurements taken at low average speed. For some rides with low average driving speed, the measurement sessions were more likely to contain more stationary periods resulting in low average WBV in r.m.s. Mechanically, the transmission of road conditions to the seat-vibrations is a highly complex and non-linear relationship (Griffin 1990). For a non-linear system, the resonant frequencies and overall spectra of the WBV may shift the relationship between the average speed and WBV in r.m.s. As the vehicle speed increases, the frequency of excitation may also increase. This may explain, in part, why we observed the quadratic-linear relationship between driving speed and frequency-weighted WBV, because the ISO method gives a lower weight on the vibration generated at higher frequency.

In addition to driving speed, we identified other statistically significant WBV predictors. Our data revealed that taxicabs with either larger engine size (≥ 1600 c.c.), larger wheelbase or larger tyre width generated less WBV, after controlling for the effects of those factors retained in 'base model'. Although the final mixed effect model showed that vehicles produced by different manufacturers had significant differences in generating WBV acceleration, further statistical analyses using Kruskal-Wallis test found that the four groups of sampled vehicles produced by different manufacturers also significantly differed from each other with respect to tyre width ($p = 0.0001$) and inter-axial length ($p = 0.0001$). As a result, the observed between-manufacturer WBV variability might have been caused by either the design difference in suspension systems or the combined effects of those potential predictors included in the full model but dropped in the final model, because the estimated fixed effect associated with manufacturer was not significant in the full model ($p = 0.07$). We also noticed that use of surface cushion was associated with higher levels of vertical WBV. Because the majority of seat cushions observed in this study were not firmly attached to the drivers' seats, using surface cushions in this way might have augmented the decoupling between drivers and their seat surface, thus increasing the measured WBV acceleration. The alternative explanation for this observation was that drivers might choose to use a surface cushion simply because of the high level of WBV generated by their vehicles. However, it is interesting to know that none of our study participants complained of any discomfort caused by the vibration during the measurement and none of the measured WBV intensity fell within the 'uncomfortable' category ($0.8 - 1.6 \text{ ms}^{-2}$) indicated in the current ISO standard (ISO 1997).

A few recent reports had pointed to the potential effect of repeated shock on human physiologic and comfort response (Dupuis *et al.* 1991, Hinz *et al.* 1994, Sandover 1998), although no related epidemiologic data are available. Investigators (Howarth and Griffin 1991, Griffin 1998, Sandover 1998) had indicated that using the root-mean-square average might underestimate the vibration during periods containing intense oscillatory accelerations (shocks, impact, or bumps) and advocated the use of other measures (e.g. vibration-dose values). In the ISO method (ISO 1997), a crest factor (CF, defined as the ratio of instantaneous peak acceleration to r.m.s.) greater than 9 was used to guide the selection of different averaging methods. However, in their daily business urban taxicab drivers very often encountered traffic jams resulting in long periods of pause with very low vibration. In such an exposure condition where the WBV exposure is not continuous, a high CF may not necessarily indicate high acceleration events. In our example, the CF (mean \pm SD) was 12.1 ± 3.39 whereas the average peak acceleration was $3.7 \pm 1.04 \text{ ms}^{-2}$ for the data collected in Taipei City. Similar results were found

when we did the pilot measurements. For the data collected in Boston metropolitan where the traffic jams and obtained WBV r.m.s. values were both comparable to Taipei City, all of the CF measures were greater than 9. In contrast, for the data collected in Hopkinton suburban areas where the traffic pauses were much shorter and the obtained WBV was either comparable or slightly higher, very few (less than 10%) vertical vibrations had CF greater than 9.

Task sampling is a very important process in occupational exposure assessment. It is crucial for the sampled tasks to have exposure matrix representing what workers are exposed to in their daily practices and regular operations. Unfortunately, the driving tasks for taxi businesses in urban areas are mostly unexpected, making implementation of the usual task sampling difficult and unfeasible. Instead, we chose to randomly assign drivers to different driving tasks with characteristics of their daily practices (e.g. service pattern, selected route, driving behaviours) that we hoped would be representative and reproduced by different types of test rides. If the ride type *per se* has a significant effect independent of other predictors on the WBV exposure, the residual WBV variability between driving tasks needs to be taken into account in constructing the exposure matrix at individual level. Among this group of 247 urban taxi drivers, we did not see significant WBV variability between different types of ride. When added into any of the three mixed effect models, the effect estimates of ride type ranged from 0.003 to 0.006 with all *p*-values greater than 0.78, suggesting that ride type is not an independent WBV predictor, after taking into account the explained variability by the other factors included in each model.

The statistical approach demonstrated in this study provides a possible alternative to directly measuring WBV exposure among professional drivers. There is no doubt that exposure assessment with direct WBV measurement plays a crucial role in studying the effect of WBV on low back pain. However, direct WBV measurement is both very expensive and time-consuming; thus it is not a feasible fieldwork practice to be carried out on each study subject enrolled in a large-scale study. Instead, our approach in the first stage is to identify a set of important WBV predictors through direct WBV measurements done in a sample of drivers. If this set of predictors could jointly work well in predicting WBV levels, then in the second stage we could use the results of direct WBV measures in the first stage to characterize the WBV exposures among those subjects on whom we were unable to directly measure WBV. Our exposure assessment work identified those important WBV predictors, of which the accurate information could be efficiently obtained either from self-administered questionnaires, structured interviews, or driving diary records. We believe that a similar approach could be applied to other professional drivers in assessing their occupational WBV exposure. Exposure assessment work of this kind is probably more important in other settings where drivers are exposed to higher WBV, as it could help identify appropriate targets for exposure control, either through engineering redesign, administrative control, personal protective equipment, or even medical intervention, if necessary.

There were several limitations in our exposure assessment study. First, the influence of road surface factors, which are potential sources of WBV variabilities, was not fully determined in our model. The trade-off for trying to make each test ride as unexpected as it would be in daily taxi business was that we made it more difficult to control for the effects of road surface factors on the WBV measured in each random driving task, unless we could simultaneously measure road surface. Unfortunately, a good and feasible measurement tool for road surface factors was

not available at the time we conducted this study. The second limitation, as shown in figure 2, was the uncertainty about the relation between WBV and higher driving speed. Indeed, only 18 WBV measures were taken at driving speed greater than 30 km^{-1} . This uncertainty limited the generalizability of our results to other settings of professional drivers where driving at high speed is not uncommon. The third limitation was that our software program did not allow us to separate the continuous WBV signals from those periods with traffic pauses, making it difficult to interpret the CF and assess the effect of transient shocks in this occupational setting.

5. Conclusion

Our study identified several important WBV predictors that could be used to quantify individual WBV exposure among urban taxi drivers. The demonstrated feasibility of our statistical approach provides a possible alternative to direct WBV measurement. A similar approach could be employed in future studies to develop more efficient strategies and to improve the quality of exposure assessment for WBV. Our study also documents that while urban taxi drivers are exposed to low-accelerating WBV, a large proportion still reported low back pain. Whether the reported low back pain among urban taxi drivers is associated with prolonged exposure to low levels of WBV deserves further research, as it should shed important light on establishing evidence-based standards for occupational exposure to WBV.

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