Industrial Health 2010, **48**, 606–614 **Original Article**

Long Term WBV Measurements on Vehicles Travelling on Urban Paths

Giovanni MOSCHIONI[1], Bortolino SAGGIN[1] and Marco TARABINI[1]*

[1]Politecnico di Milano, Dipartimento di Meccanica, Polo Regionale di Lecco, Via Marco d'Oggiono 18/a, 23900 Lecco, Italy

Received July 2, 2009 and accepted June 1, 2010

Abstract: This paper describes the results of a long-term whole-body-vibration monitoring campaign performed on different cars with different drivers. The weighted and the un-weighted root-mean-square acceleration, the *MTVV* and the *VDV* have been monitored on five different cars in regular usage for over one hundred hours of measurements on urban roads and highways. The variability of the above parameters has been statistically analyzed in order to assess the time requested for the convergence of standard indexes to their average values. The aim is to supply a general reliability evaluation so as to minimize the on-field tests and to provide a scientific support to the design of such experiments. A comparison between different vehicles is presented and discussed; the correlation with speed measured by a GPS system is analyzed with probabilistic assessments. Results showed that the minimum time for reliable measurement was approximately 30 min for each driving condition (urban, carriage road, highway). The MTVV/a_w ratio was usually larger than 1.5 (even on short measurement periods), thus indicating the unsuitability of the basic ISO 2631 criterion. The 8-h based VDV provided indications compatible with the a_v criterion.

Key words: Whole-body vibration, Long term monitoring, Measurement variability, Professional drivers

Introduction

The correlation between the exposure to whole-body vibration (WBV) and the low back pain (LBP) has been the focal point of many research works[1–8]. Some reviews of epidemiological studies concluded that long-term WBV exposure may increase the risk of LBP[2–5]. In other studies a correspondence was found to exist between LBP and physical factors such as heavy manual work and uncomfortable driving posture[6–8]. In their review, Gallais and Griffin stated that there is no clear evidence of correlation between WBV exposure, postural factors and low back problems in urban vehicle drivers[1]. A similar conclusion was also found by Bovenzi and Hulshof[2]: due to the cross-sectional design of the majority of the reviewed studies, there is no evidence of a correlation between WBV exposure and LBP disorders.

Because of the presence of the confounding factors (age, body mass index, heavy materials handling, awkward postures), the role of vibration exposure in the aetiopathogenesis of low back disorders is not yet defined. LBP may be seen as the consequence of several variables whose weight is still to be determined. A multivariate data analysis for the identification of the contribution of each factor to the LBP occurrence showed that exposure to WBV and physical loading factors are the most important components among the different origins of LBP[9].

A viable approach for the identification of the effects of WBVs to the occurrence of LBP is the study of groups of people that are not exposed to confounding factors. Under this perspective, car drivers are an interesting category for several reasons. First of all, there are millions of drivers that are exposed every day to WBV and such a large population leads to very small uncertainty levels in any statistical analysis. This large group is set-up of people that might be exposed to the previously listed confounding factors; consequently, the identification of the effect of WBV on LBP can take benefits from this analysis.

The starting point for the identification of the WBV-related pathologies, though, is the reliability of the parameters used to describe the vibration. In particular, literature shows a lack of knowledge about the long term behavior of the risk estimators suggested by the current standards[10]. ISO 2631 states that the duration of measurement shall be sufficient to ensure reasonable statistical precision and to ensure that the vibration is typical of the exposures which are being assessed. The standard here is quite ambiguous, as clearly evidenced by the presence of literature studies[11, 12] based on observation periods of 5 to 20 min.

The aim of this paper is to describe the results of a long term WBV measurement campaign on cars travelling over urban paths. The work is focused on the variability of the WBV indexes over long periods, both on the same or different tracks, with different vehicles and drivers. One of the main outcomes of this analysis is the identification of the minimum requested measurement time, of the uncertainty related to the repeatability of measurement, according to the ISO GUM[13] when a specific car-driver-road-speed combination is given.

*To whom correspondence should be addressed.
E-mail: marco.tarabini@polimi.it

Moreover, an indication of the expected WBV exposure for a class of workers is provided; this may help in the identification of the seat-transmitted whole body vibration effects on the low back pain.

Subjects and Methods

Tests were performed on five different cars in different maintenance status, driven by five persons. Each driver drove a given car, thus limiting the possibility of comparative analyses to identify any possible car-driver interaction. The car tires pressure was periodically monitored and was kept within the interval suggested by the car manufacturer. Details for each car are listed in Table 1. WBVs were measured according to the ISO 2631[10] procedure using a specifically-designed monitoring system based on virtual instrumentation. Non-weighted time domain signals measured by a triaxial accelerometer (PCB 356A21, nominal sensitivity 10 mV·s^2/m) were A/D converted by a 24 bits National Instruments data acquisition board (NI 9233) with a sampling frequency of 2 kHz and eventually recorded by an ultra-mobile PC. The accelerometer was attached to a seat-pad accomplishing ISO 10326-1 indications. The seat-pad was taped to the surface of the seat pan so that the transducer was located midway between the ischial tuberosities of the driver. The seat-pad was re-positioned after each measurement session, in order to include in the experimental results the uncertainty deriving from the transducer position. Each data buffer had a time length of 10 seconds; raw un-weighted waveform data were stored so as to perform any kind of off-line analysis. Digital IIR (infinite impulse response) weighting filters were implemented following the approach described by Rimell and Mansfield[14]. The instantaneous car speed and position were detected by a GPS receiver. Quantities that have been analyzed are:

- Weighted acceleration levels along three mutually perpendicular axes (a_{wx}, a_{wy}, a_{wz});
- The combination of the three mutually perpendicular accelerations a_v, hereafter referred to as vector sum;
- The maximum transient vibration value along the three measurement axes ($MTVV_x$, $MTVV_y$ and $MTVV_z$)
- The ratio between $MTVV$ and the weighted acceleration level along the three axes ($MTVV_x/a_{wx}$, $MTVV_y/a_{wy}$, $MTVV_z/a_{wz}$);
- The vibration dose value along three axes (VDV_x, VDV_y, VDV_z); and
- The worst VDV.

Data were analyzed on different levels: the first analysis aimed to evaluate the expected vibration levels for each car depending on the speed. Repeatability of measurements was then investigated with the repetition of the same path in nominally identical conditions (i.e. with the same car, the same diver, in similar traffic conditions). A statistical analysis (based on the probability density functions) of a_v and of the worst VDV was performed on each car, to identify the variables confidence intervals and their dependence on the car speed. Finally, the minimum time required for a reliable exposure assessment was studied.
The dependence of the vibration from the car speed was analyzed splitting the WBV-data in four groups:

- v_0: 5 to 30 km/h (slow urban traffic)
- v_1: 30 to 50 km/h (ordinary urban traffic)
- v_2: 50 to 80 km/h (carriage roads traffic)
- v_3: 80 to 130 km/h (highways and motorways)

In the following, v_λ will be used to point out a generic speed range, being λ an integer between 0 and 3. Each speed group was composed by a variable number of records depending on the route of each car. The estimation of the expected vibration exposure of a driver was not straightforward: data measured on different journeys and at different speeds have to be averaged with criteria that follows the indication of the ISO 2631 but accounts for the fact that the measurements are not representative of the daily exposure (but of the exposure in the condition of our test). Hence, daily exposure has to be evaluated on the basis of an assumption about the driver activity in terms of paths, speed, type of car, etc. In order to provide a generic exposure all the values presented in the following give the same weight to different cars and to the different speed classes, independently from the actual mileage of our tests. The blind adoption of the energy summation procedures indicated by the ISO 2631 would have lead to results dependent on how our tests were performed (biased by the different duration of the monitoring performed on a given car or kind of path) and, consequently, not representative of a more generic situation.

Data averaging

Let us initially consider data acquired on a single car: an average can be computed grouping all the data within a certain speed class: said $\left(a_{wi,j}^{10\,s}\right)_{v_\lambda}$ the weighted RMS acceleration along the i axis during the j-th 10-seconds-lasting test, measured on one car travelling at a speed belonging to the v_λ interval, and said n_{v_λ} n the number of 10-s events within the speed interval, one can define $\hat{a}_{v_\lambda}$ as follows:

$$\left(\hat{a}_{v_\lambda}\right)_i = k_i \cdot \sqrt{\frac{\sum_j \left(a_{wi,j}^{10\,s}\right)_{v_\lambda}^2}{n_{v_\lambda}}} \quad i = x, y \text{ or } z \tag{1}$$

k_i are the multiplying factors indicated by the ISO 2631, (1.4

Table 1. Description of the cars used for the long term monitoring campaign

ID	Manufacturer	Car Type	Engine size and fuel	Year	Mileage (km)
1	Citroen	C3	1,400 cc petrol	2004	70,000
2	Opel	Astra	1,700 cc diesel	2007	25,000
3	Saab	9-3	1,900 cc diesel	2007	50,000
4	Volkswagen	Polo	1,000 cc petrol	1997	140,000
5	Volkswagen	Touran	1,900 cc diesel	2005	130,000

for x and y and 1 for the z axis). W_d weighting curve was used for x and y axes, W_k was used for the z axis. The hat reminds that quantities are estimated through averages and, consequently, must be treated as random variables. If the vehicle speed history is known, the actual driver vibration exposure could theoretically be obtained as a weighted average of $\left(\hat{a}_{v_\lambda}\right)_i$; weights have to be proportional to the time that the driver spends in the speed interval v_λ.

The "average" exposure $\left(\hat{a}_{v_\lambda}\right)_i$ does not contain any information concerning the data variability; hence, speed-grouped data can be described on the basis of the $a_{i,j}^{10\,s}$ standard deviation (SD_{v_λ}), which is representative of the data dispersion in "similar" travel conditions. Said $\left(\bar{a}_{v_\lambda}\right)_i$ the arithmetic average of $a_{i,j}^{10\,s}$ along the i axis[1], $(SD_{v_\lambda})_i$ is:

$$\left(SD_{v_\lambda}\right)_i = k_i \cdot \sqrt{\frac{\sum_j \left(\left(a_{wi,j}^{10\,s}\right)_{v_\lambda} - \left(\bar{a}_{v_\lambda}\right)_i\right)^2}{n_{v_\lambda} - 1}} \quad i = x, y \text{ or } z \qquad (2)$$

A comparison between different vehicles travelling on a combination of different paths can be made on the basis of the "vehicle expected vibration" $\hat{a}_i$. Said m the number of speed classes (in our case 4), the expected vehicle RMS vibration:

$$\hat{a}_i = k_i \cdot \sqrt{\frac{\sum_{\lambda=1}^{m}\left(\hat{a}_{v_\lambda}\right)_i^2}{m}} \quad i = x, y \text{ or } z \qquad (3)$$

If the average is computed on the number of cars nc instead than on the speed classes, one can derive $\left(\hat{a}_{v_\lambda}^*\right)_i$, that is the expected vibration level with an "average car" within the v_λ speed interval. The parameter would be representative of the exposure of a driver using all the cars considered in the study, assuming that the car-driver interaction can be neglected. In the following, asterisks indicate quantities that are averaged for all the nc cars that underwent our tests.

$$\left(\hat{a}_{v_\lambda}^*\right)_i = k_i \cdot \sqrt{\frac{\sum_{car=1}^{nc}\left(\hat{a}_{v_\lambda,car}\right)_i^2}{nc}} \quad i = x, y \text{ or } z \qquad (4)$$

The most generic parameter that describes the exposure of a nonspecific vehicle along a certain direction i can be derived averaging the different vehicles' expected vibration $\hat{a}_i$

$$\hat{a}_i^* = k_i \cdot \sqrt{\frac{\sum_{car=1}^{nc}\left(\hat{a}_{i,car}\right)^2}{nc}} \quad i = x, y \text{ or } z \qquad (5)$$

Data along different axes can be combined using the vector sum a_v^*, that can be derived for each speed class v_λ as[10]:

$$a_v^*\Big|_{v_\lambda} = \sqrt{\left(\hat{a}_{v_\lambda}^*\right)_x^2 + \left(\hat{a}_{v_\lambda}^*\right)_y^2 + \left(\hat{a}_{v_\lambda}^*\right)_z^2} \qquad (6)$$

Similarly to what was previously done, the vector sum can be computed on $\hat{a}_i^*$ (independently from the speed), obtaining:

[1] $\left(\bar{a}_{v_\lambda}\right)_i$ is the arithmetic average of the random variable $\left(a_{wi,j}^{10\,s}\right)_{v_\lambda}$, while $\left(\hat{a}_{v_\lambda}\right)_i$ is the quadratic average of $\left(a_{wi,j}^{10\,s}\right)_{v_\lambda}$ as per ISO 2631.

$$a_v^* = \sqrt{\left(\hat{a}_x^*\right)^2 + \left(\hat{a}_y^*\right)^2 + \left(\hat{a}_z^*\right)^2} \qquad (7)$$

Both $a_v^*\Big|_{v_\lambda}$ and a_v^* were also calculated with data acquired on a specific car; these vector sum accelerations will be referred to as $a_v\Big|_{v_\lambda}$ and a_v.

The second quantity that was analyzed was the *MTVV*, defined by ISO 2631 as:

$$MAX\left\{\frac{1}{\tau}\int_{t_0-\tau}^{t_0}\left[a_{wi}(t)\right]^2 dt\right\}^{1/2} \qquad (8)$$

Where $a_{wi}(t)$ is the instantaneous frequency weighted acceleration along the i axis, τ is integration time constant (1 s) and t_0 is the time at which acceleration is evaluated. Two analyses were performed on this quantity. The first was the analysis in speed groups, similarly to what was previously done for the weighted acceleration. The second was performed checking the percentage of events in which the ratio $MTVV_i/a_{wi}$ was larger than 1.5, so as to check the applicability of the basic exposure assessment method of the ISO 2631.

The last parameter that was analyzed was the fourth power vibration dose, defined by ISO 2631 as:

$$VDV_i = \left\{\int_0^T\left[a_{wi}(t)\right]^4 dt\right\}^{1/4} \quad i = x, y \text{ or } z \qquad (9)$$

The exposure was assessed on the basis of the most severe axis (worst *VDV*), i.e. by the maximum value between $1.4{\cdot}VDV_x$, $1.4{\cdot}VDV_y$ and VDV_z. Owing to the cumulative nature of this quantity, the comparison between different cars or different sessions has to be performed on the basis of a unique time length. Our choice, similarly to what was previously done for a_v^*, was:

i. to evaluate the measurements repeatability on the basis of VDV_x, VDV_y, VDV_z and worst *VDV* measured during the repetition of the same 2 km path with the same car;
ii. to analyze the probability density of the worst *VDV* measured during each single 10-s acquisition test. Said d_t the inverse of the sampling frequency, one can compute $\left(VDV_{v_\lambda}^{10\,s}\right)_i$ along three axes as:

$$\left(VDV_{v_\lambda}^{10\,s}\right)_i = \sqrt[4]{\sum_j\left(\left(a(t)_{wi,j}\right)_{v_\lambda}^4 \cdot dt\right)} \quad i = x, y \text{ or } z \qquad (10)$$

$VDV_{v_\lambda}^{10\,s}$ (without the "i" subscript) expresses the worst axis condition; and
iii. to evaluate the daily vibration dose value along each axis $\left(VDV_{v_\lambda}^{8\,h}\right)_i$. This value is computed according to the ISO 2631 combining 2880 $\left(VDV_{v_\lambda}^{10\,s}\right)_i$ measurements. If more than 8 h of measurements were performed within a certain speed range v_λ, the 2880 10-s buffers were chosen randomly (i.e. not consecutively) in order to limit the effect of the path on the analysis. If, within the speed range v_λ, the measurement time was less than 8 h, $\left(VDV_{v_\lambda}^{8\,h}\right)_i$ was computed as follows

Table 2. Summary of the car-averaged $\left(\hat{a}^*_{v_\lambda}\right)_i$ of the whole measurement campaign. Coherently with the equations presented in the text, data along *x* and *y* axes include the multiplying factor of 1.4. All the values are expressed in [m/s^2]

Speed Class	Quantity	$i = x$	$i = y$	$i = z$	Vector Sum
v_0	$\left(\hat{a}^*_{v_0}\right)_i$	0.24	0.23	0.26	0.42
	$\left(SD^*_{v_0}\right)_i$	0.11	0.10	0.12	0.17
v_1	$\left(\hat{a}^*_{v_1}\right)_i$	0.21	0.19	0.33	0.43
	$\left(SD^*_{v_1}\right)_i$	0.10	0.09	0.19	0.21
v_2	$\left(\hat{a}^*_{v_2}\right)_i$	0.19	0.17	0.26	0.36
	$\left(SD^*_{v_2}\right)_i$	0.10	0.08	0.10	0.14
v_3	$\left(\hat{a}^*_{v_3}\right)_i$	0.24	0.21	0.35	0.48
	$\left(SD^*_{v_3}\right)_i$	0.10	0.08	0.12	0.15
Average	$\left(\hat{a}^*\right)_i$	0.22	0.20	0.30	0.43
	$\left(SD^*\right)_i$	0.10	0.09	0.14	0.18

$$\left(VDV^{8\,h}_{v_\lambda}\right)_i = \left(VDV^{T\,Meas}_{v_\lambda}\right)_i \cdot \left(\frac{8h}{T\ Meas}\right)^{1/4} \tag{11}$$

$VDV^{8\,h}_{v_\lambda}$ with no subscript refers to the most critical axis.

Results

General overview

The total number of 10 s buffers acquired was 37,720, for a total acquisition time of 104 h. A summary of the vibration data averaged on all the five cars that underwent our tests is presented in Table 2, which abridges $\left(\hat{a}^*_{v_\lambda}\right)_i$ for the four speed classes. Data show that the most severe axis is generally the vertical one, although, within the v_0 speed class, accelerations are comparable. The vector sum of accelerations increases its magnitude with the speed, except for the v_2 group. The standard deviation of the vector sum indicates the large data variability, ranging between 0.14 m/s^2 within the v_2 speed interval and 0.21 m/s^2 in v_1. The analysis of $(\hat{a}^*)_i$ (i.e. data averaged on all the speed classes, last row of Table 2), shows that a_v^* is 0.43 m/s^2; the most severe car-averaged axis (largest $\hat{a}_i^*$) is the vertical one, with a weighted acceleration level of 0.30 m/s^2. The value is smaller than the Exposure Action Value (EAV=0.5 m/s^2[15]) and, consequently, also eight hours of exposure would theoretically not require actions to be taken by the employer. Owing to the large $\hat{a}^*$ standard deviation (0.18 m/s^2), $\hat{a}^*$ uncertainty is also significant for the vector sum.

The reason of the data dispersion was investigated with repetition of the same 2 km path (carriageway in good conditions) in nominally identical conditions with the same car at similar velocities. Results are presented in Fig. 1 (a) and (b) and in Fig. 2. Plots of Fig.1 show that even on the same path and with reasonably similar speeds, data variability is large. This can be endorsed to the presence of localized faults on the road surface (manhole covers, small holes, asphalt joints) that

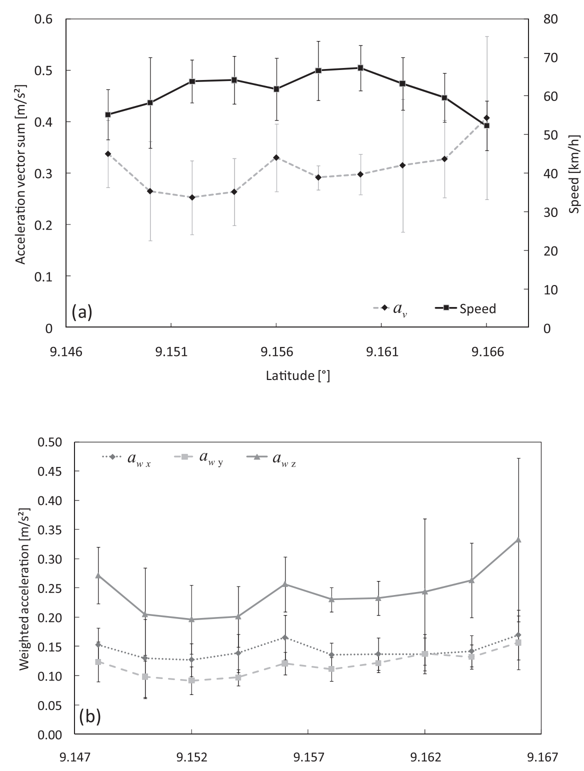

Fig. 1. Data variability of acceleration and speed data measured in ten repetitions of the same path with the same car (car 2). Points represent the RMS of ten passages, bars indicate the standard deviation.

(a) acceleration vector sum a_v and car speed.

(b) a_{wx}, a_{wy}, a_{wz} (including the multiplying factors of 1.4 along *x* and *y* axes).

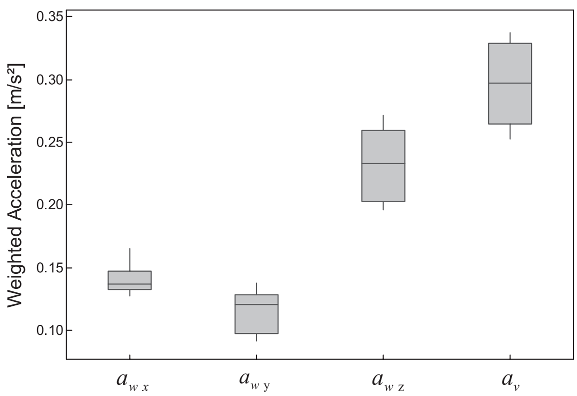

Fig. 2. Boxplots of the weighted accelerations a_{wx}, a_{wy}, a_{wz} (including the multiplying factors of 1.4 along x and y axes) and of the vector sum a_v measured in ten repetitions of the same 2 km path with the same car (car 2).

are encountered only with a specific trajectory. The importance of localized faults was also evidenced by the a_v measured during two passages at very similar speeds (differences smaller than 2 km/h): the final RMS levels differed for nearly 10%, with "local" differences larger than 20%. Boxplots[16)] of Fig. 2 show the variability of the weighted acceleration RMS measured on the 2 km path. The top and the bottom of the boxes symbolize the third and the first quartiles (Q_3 and Q_1). The horizontal line symbolizes the median and each whisker has a length that is equal to 1.5(Q_3-Q_1). Values beyond the whiskers are considered as outliers (asterisks). The boxplot shows that vibrations are generally larger on the vertical axis. Also in this case, data variability is noteworthy, as pointed out by the large inter-quartile range with respect to the median. Similar data were obtained with different cars.

As per ISO 2631, the crest factor (*CF*) was used to investigate if the basic evaluation method is suitable for describing the harshness of vibrations. Because of the large *CFs*, the additional running RMS method was used and the $MTVV_i/a_{wi}$ ratio along the three axes was checked. The most common $MTVV_i/a_{wi}$ values (not reported in this study) during each single experimental session ranged from 3 to 4 for *x, y* and *z* directions, pointing out the non stationarity of vibration phenomena. Since one single shock in a whole day of travelling causes this ratio to be very large, $MTVV_i/a_{wi}$ was computed on each 10 s buffer. The statistics on such a short period are representative of occurrence of impulsive events. Results along the *z* axis (the most severe according to the basic ISO 2631 criterion) are summarized in Table 3, which points out that, approx. 50% of events exceed the 1.5 ratio. For all the cars, except for number 4, the percentage of events characterized by a $MTVV_i/a_{wi}$ ratio larger than 1.5 decreases with the speed. This means that driving on urban roads generally involves more frequent impulsive events than on the highways.

Probability density functions

Additional analyses were performed on the basis of the probability density function (PDF[16)]) of the vector sum acceleration a_v. The PDF describes the probability of the value falling within a particular interval and, consequently, provides a detailed overview of the values that the acceleration assumed

Table 3. Percentage of events in which the $MTVV_z/a_{wz}$ ratio (vertical axis, that is in general the most critical one) exceeded the 1.5 limit on a 10 s buffer

Speed Class	Car					
	1	2	3	4	5	Average
v_0	58%	62%	51%	58%	54%	57%
v_1	42%	59%	52%	44%	53%	50%
v_2	41%	56%	43%	43%	47%	46%
v_3	36%	48%	39%	57%	35%	43%
Average	44%	56%	46%	50%	47%	49%

during our tests. Data were analyzed in four speed classes; results are summarized in Fig. 3. Plots show some meaningful issues, which can be summarized as follows.

At low speeds (v_0) there are noticeable differences between the different car behaviors. The most frequent values of a_v range between 0.15 m/s^2 (car 5) and 0.45 m/s^2 (car 4). The difference is likely related to the different cars mechanical behavior; however, as already stressed, a comparative analysis between cars would require investigating the effects of the driver-car-path combination.

In the speed interval v_1 all the cars have very similar behavior. The most recurrent values are in the range between 0.25 m/s^2 (cars 2 and 4) and 0.35 m/s^2 (car 3). In the speed range v_2 the cars' behavior are still similar, with PDF maxima in the range 0.3–0.35 m/s^2. In the speed range v_3 there are again large differences between the car behaviors. The most frequent acceleration values range from 0.3 m/s^2 of car 1 to the 0.5 m/s^2 of cars 2 and 4. The discrepancies can be explained in this case considering the different roads on which the cars were tested. Cars 2 and 4 performed their test on highways in quite poor conditions; since the aim of this paper is not the comparison between different vehicles, but the identification of the measurement variability, it was chosen not to censure these data.

Maximum transient vibration value

Because of the non-stationary nature of the vibration (pointed out by the large CF and by the $MTVV_i/a_{wi}$ ratios), the "additional" evaluation methods based on *MTVV* or on *VDV* are expected to be more representative of the risks derived from the vibration exposure.

Results of Table 4 show that $MTVV_i$ ranges between a minimum value of 0.42 m/s^{2}and a maximum of 2.79 m/s^2. The mean of $MTVV_x$ (i.e. the arithmetic average of all $MTVV_x$ independently by the car type and by the speed) is 0.97 m/s^2 (SD=0.41 m/s^2); the mean of $MTVV_y$ is 0.81 m/s^2 (SD=0.23 m/s^2) and the mean of $MTVV_z$ is 1.56 m/s^2 (SD=0.46 m/s^2). It must be stressed that this parameter has only statistic relevance because the average has no meaning with respect to the exposure. Table 4 also shows that in nearly 50% of cases $MTVV_i$ ranges between 1 and 2 m/s^2. The *z* axis is the most critical independently from the car type and speed. In 70% of cases $MTVV_x$ is larger than $MTVV_y$.

Table 4 also shows that $MTVV_i$ depends on the car; for instance, $MTVV_x$ of car 2 is totally different from the others, $MTVV_y$ of car 5 has a huge variability with respect to the other cars and $MTVV_z$ of car 2 is larger than the one of

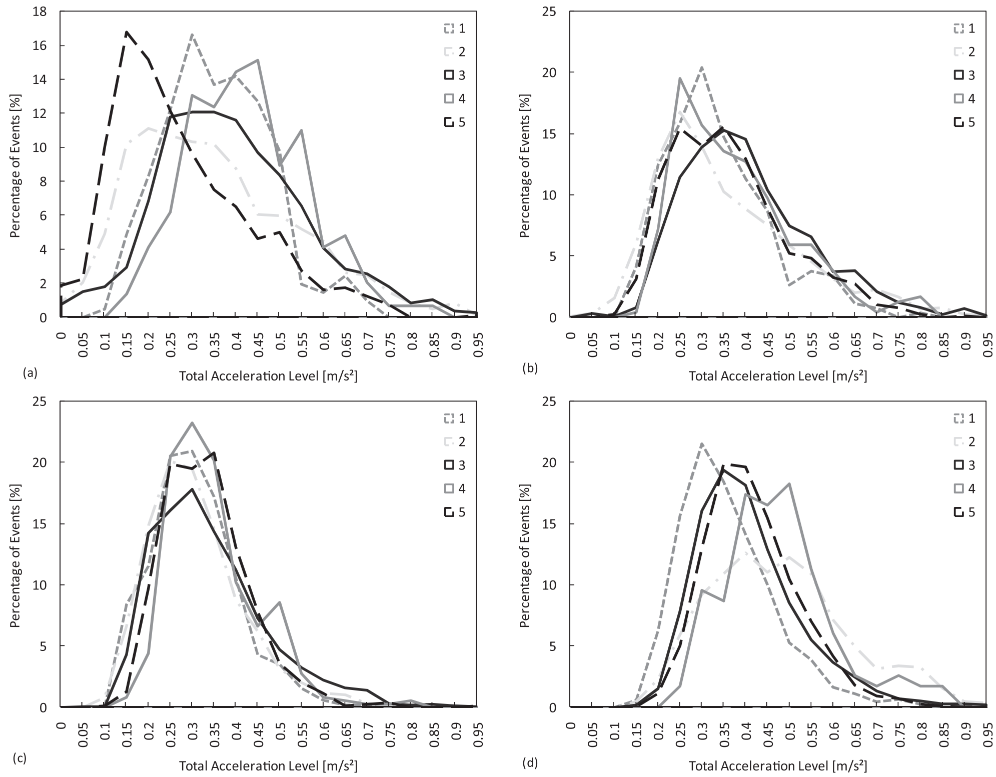

Fig. 3. Probability density functions of the acceleration vector sum $(a^{10s}_{v,j})_{v_\lambda}$ for four car speed ranges. (a) v_0, (b) v_1, (c) v_2, (d) v_3. The different plots identify the different cars that underwent our tests.

Table 4. Summary of the quantities describing the vibration exposure on different cars at different speeds. Reference period: eight hours of measurements for each driving condition. Weighted accelerations along the x and y axes include a multiplying factor of 1.4.

Car ID	Speed Class	$\left(\hat{a}_{v_\lambda}\right)_x$ [m/s^2]	$\left(\hat{a}_{v_\lambda}\right)_y$ [m/s^2]	$\left(\hat{a}_{v_\lambda}\right)_z$ [m/s^2]	$a_v\big\|_{v_\lambda}$ [m/s^2]	$MTVV_x$ [m/s^2]	$MTVV_y$ [m/s^2]	$MTVV_z$ [m/s^2]	$\left(VDV^{8h}_{v_\lambda}\right)_x$ [m/s$^{1.75}$]	$\left(VDV^{8h}_{v_\lambda}\right)_y$ [m/s$^{1.75}$]	$\left(VDV^{8h}_{v_\lambda}\right)_z$ [m/s$^{1.75}$]
1	v_0	0.22	0.24	0.23	0.40	0.72	0.68	1.10	3.59	3.80	5.35
	v_1	0.20	0.20	0.27	0.38	0.51	0.80	1.08	2.85	3.23	6.24
	v_2	0.15	0.18	0.24	0.35	0.55	0.62	1.42	2.37	2.87	5.66
	v_3	0.15	0.20	0.26	0.36	0.42	0.64	0.95	2.09	2.87	5.24
2	v_0	0.28	0.24	0.29	0.46	1.70	1.14	2.32	4.90	4.07	10.80
	v_1	0.25	0.22	0.31	0.46	1.41	1.10	1.70	4.20	3.77	6.89
	v_2	0.22	0.18	0.26	0.39	1.91	1.23	2.79	4.10	3.32	6.38
	v_3	0.28	0.17	0.31	0.45	1.51	0.94	1.66	4.47	2.72	5.95
3	v_0	0.22	0.22	0.28	0.43	1.08	1.00	1.87	3.75	3.74	7.59
	v_1	0.20	0.18	0.32	0.42	0.90	0.70	1.96	3.32	2.99	8.13
	v_2	0.18	0.14	0.27	0.36	0.79	0.71	1.64	2.92	2.26	6.87
	v_3	0.31	0.20	0.39	0.54	0.94	0.86	1.75	4.60	3.33	9.47
4	v_0	0.25	0.25	0.30	0.47	0.70	0.63	1.17	3.80	3.75	7.08
	v_1	0.21	0.22	0.32	0.44	0.83	0.56	1.44	3.29	3.30	7.44
	v_2	0.17	0.20	0.29	0.38	0.57	0.69	1.30	2.61	3.00	6.86
	v_3	0.27	0.28	0.35	0.52	0.70	0.53	0.93	3.92	3.82	7.34
5	v_0	0.18	0.20	0.21	0.34	1.22	1.27	1.29	3.63	3.63	5.66
	v_1	0.18	0.18	0.32	0.41	0.81	0.86	1.53	3.24	3.14	7.14
	v_2	0.17	0.15	0.29	0.37	1.12	0.89	1.53	2.91	2.66	6.40
	v_3	0.20	0.15	0.38	0.46	1.01	0.50	1.76	2.96	2.20	7.33

car 4. *MTVV* indication is only based on the worst event and completely neglects what happens at any other time[17]. Being this quantity strongly dependent on random phenomena that may occur during measurement, no further analyses were performed.

Vibration dose value

The daily vibration doses along the three coordinate axes $\left(VDV_{v_\lambda}^{8\,h}\right)_i$ are summarized in Table 4. The worst condition $VDV_{v_\lambda}^{8\,h}$ occurs along the z axis in the 95% of cases. The worst *VDV* is inside the "caution zone" (8.5–17 $m/s^{1.75}$) only in 10% of cases. The remaining 90% of the cases are characterized by levels lower than 8.5 $m/s^{1.75}$.

The *VDV* variability was investigated for the same 2 km path as before. Results are summarized with the box plots of Fig. 4. Similarly to what was previously found for the weighted vibration levels and for the $\left(VDV_{v_\lambda}^{8\,h}\right)_i$, the most severe axis is the vertical one in the majority of cases. The large VDV_z variability indicates that the effect of localized road faults is noticeable. As already pointed out, the *VDV* is a cumulative quantity and, consequently, non-normalized with respect to the time. Thus, a small fraction of the measurement variability can also be endorsed to the different time needed to cover the 2 km path (the ratio between the time standard deviation and the mean amounts to 8%).

The long term behavior of the vibration dose was summarized with the $VDV_{v_\lambda}^{10\,s}$ probability density function (Fig. 5). Results that can be drawn from this kind of analysis are very similar to the ones derived by the PDF of a_v. Within the v_0 speed group, the car generating lower vibrations with the a_v criterion (car 5) also generates lower vibrations with the vibration dose analysis. In the speed groups v_1 and v_2, the cars have similar behaviors, either with a_v or with *VDV* criteria. At high speeds (v_3) the car that exposes the driver to less severe vibrations with the a_v criterion is car 1, similarly to what happens with the *VDV*.

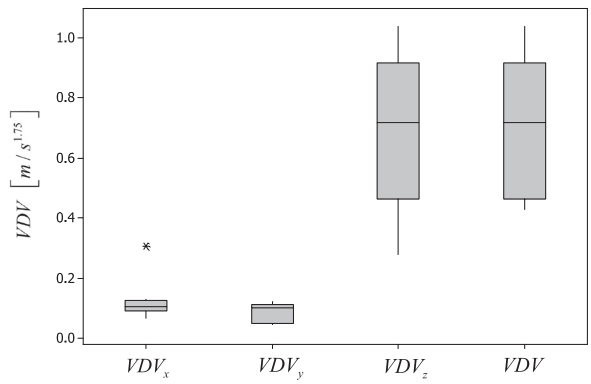

Fig. 4. Boxplots of *VDV* along the three measurement axes (VDV_x, VDV_y and VDV_z) and worst VDV measured in ten repetitions of the same path with the same car (car 2). The asterisk symbolizes the presence of an outlier.

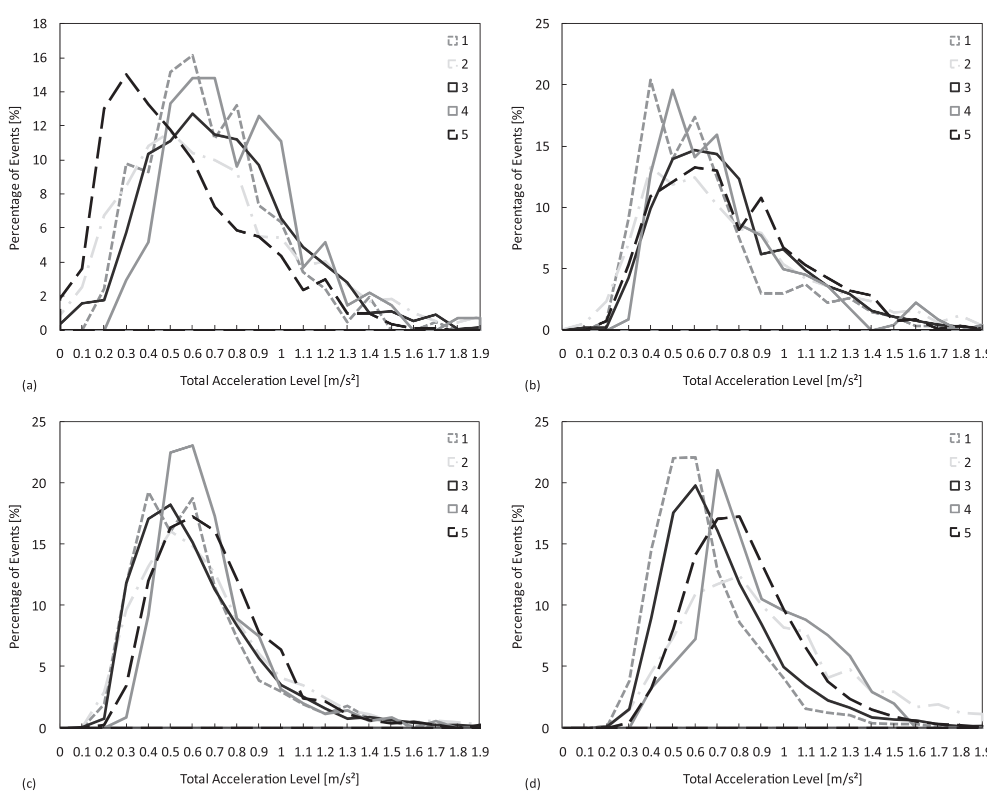

Fig. 5. Probability density functions of $VDV_{v_\lambda}^{10s}$ for four car speed ranges. (a) v_0, (b) v_1, (c) v_2, (d) v_3. Different plots identify the different cars that underwent our tests.

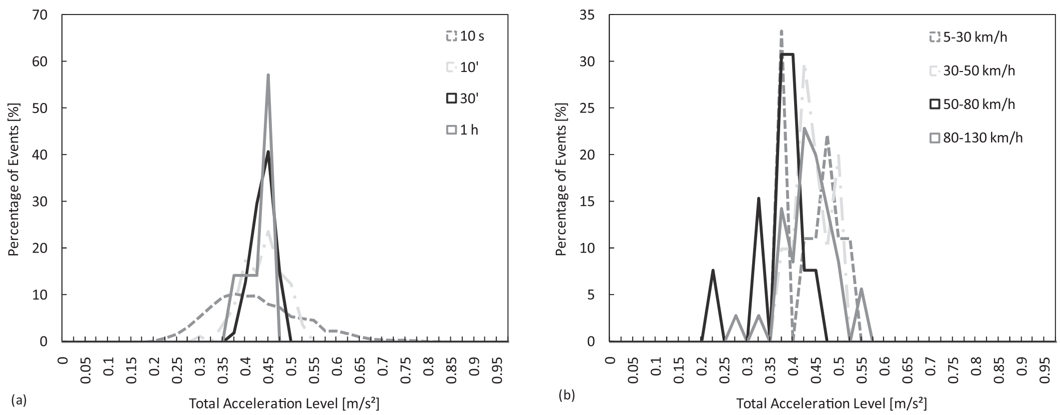

Fig. 6. Probability density functions of the vector sum acceleration. (a) single car (car 5), single speed class (v_3) and different time of analysis and (b) single car (car 3) same time of analysis (20') but different speed classes.

Discussion

Experimental results show that assessing a value summarizing the vibration exposure on vehicles travelling on urban paths is difficult for several reasons.

The first reason is that the ISO 2631 standard proposes several ambiguous alternatives to assess the vibration exposure, as evidenced by Griffin[17]. The use of different methods is quite cumbersome, especially when the adoption of the additional evaluation method is suggested by the standard itself. According to the ISO 2631 procedure, the expected weighted vibration is 0.30 m/s^2 along the z axis, with a standard deviation of 0.14 m/s^2. In case of eight hours per diem of exposure to vibration, *A(8)*[10] would be lower than the EAV[15]. Given that at low speeds (v_0) the weighted levels along the three axes are comparable (Table 2 and Table 4), it is possible to use the vector sum as the indicator of risk. Also in this case, 8 h of exposure would lead to an *A(8)* lower than the EAV. The $MTVV_z/a_{wz}$ ratio of 1.5 is often exceeded (even on very short measurement periods, Table 4) and, consequently, the alternative evaluation method should be used. In spite of the fact that measurements were performed on vehicles on normal roads – where transitory excitations should be limited – *MTVV* points out the non-steady nature of the vibration. Disappointingly, ISO 2631 standard does not define either warning thresholds for the *MTVV*, or how to use the quantity after its calculation[17]. Authors agree with the remarks of Griffin[17], i.e. that the *MTVV*, being based only on the worst vibration level, is unreliable for long lasting exposures and thus, in our work, no deep studies were performed about the *MTVV* variability. The specification of the 95% confidence interval of a_{wx}, a_{wy}, a_{wz} would provide for more reliable results with respect of the mere *MTVV*. The evaluation based on the *VDV* gives results consistent with those obtained through the a_v basic method; both criteria show that, in some speed conditions, eight hours of exposure may lead to possibly harmful conditions for the driver. The second reason that makes it difficult to assess the vibration exposure is the measurement variability. Data presented in this paper are based on a measurement-record of 10 s; such a duration is obviously too short to be representative of the driver vibration exposure. The long term analyses have shown (Table 2) that the expected a_v in generic speed condition is 0.43 m/s^2. The confidence intervals of a_v can be determined with integrations of the PDF to obtain the cumulative distribution function. Depending on the speed, the a_v 95% CI is [0.05–0.75 m/s^2] within the v_0 speed interval and [0.20–0.70 m/s^2] in v_3. PDF analysis showed that there are chances (5 to 45%, depending on the car and on the speed) of assessing that a_v is larger than 0.5 m/s^2.

Enlarging the buffer length obviously decreases the data variability: analyses were performed to identify a reasonable acquisition time to obtain a confidence interval of a_v within a particular range. For current purposes, 10-s buffers were randomly sampled from the entire population to create virtual measurements lasting 10, 30 and 60 min. Results of this analysis are shown in Fig. 6 (a), which represents the a_v PDF obtained with a single car (car 5) within the v_3 speed interval. The choice of the car and of the speed class was undertaken because of the largest number of 10-s buffers of this group. The first obvious conclusion was that, increasing the observation time reduces the data dispersion; with car 5 and within the v_3 speed interval, the 95% a_v confidence interval is 0.72 m/s^2 wide for measurements lasting 10 s, 0.15 m/s^2 for measurements of 10 min, 0.1 m/s^2 for 30' measurements and 0.05 m/s^2 for 1 h measurements. The choice of the measurement time depends therefore on the tolerated difference between the estimation of a_v and the one that would derive from an infinite-lasting measurement. If an accuracy of 0.1 m/s^2 can be accepted, the measurement should last at least 30' in each speed class, while if an accuracy of 0.05 m/s^2 is required, measurements should last 1 h per driving condition.

Figure 6 (b) shows that the PDF depends on the car speed, thus pointing out that the previously mentioned confidence intervals refer to the specific class speed. The conclusion here is that, in order to correctly assess the actual vibration exposure, a minimum measurement time of 30 min in each driving condition is required to limit the uncertainty below 0.1 m/s^2.

Conclusions

This article has presented the outcomes of a long term WBV monitoring campaign on five cars. Significant differences on the computed parameters (a_v, a_{wi}, $MTVV_i/a_{wi}$ and

VDV) were found for the different vehicle speeds and in some cases for the different cars on which tests were performed. It was shown that the vibration levels are, in most cases, not critical if the exposure period is eight hours per day. The large crest factor indicated that the a_v criterion may not completely characterize the exposure because of the presence of several random phenomena. This was confirmed by the $MTVV_i/a_{wi}$ ratio, which often exceeded the 1.5 limit suggested by the current standards. The measurements variability was investigated with the PDF analyses of the acceleration vector sum and on the VDV. An interesting outcome of the work was the minimum time requested to assess the driver exposure with a given confidence interval. If the exposure uncertainty has to be lower than 0.1 m/s^2, at least 30 min of measurement per each driving condition are necessary.

References

1) Gallais L, Griffin MJ (2006) Low back pain in car drivers: a review of studies published 1975 to 2005. J Sound Vib **298**, 499–513.
2) Bovenzi M, Hulshof CTJ (1999) An updated review of epidemiologic studies on the relationship between exposure to whole-body vibration and low back pain. Int Arch Occup Environ Health **72**, 351–65.
3) Seidel H, Heide R (1986) Long-term effects of whole-body vibration: a critical survey of the literature. Int Arch Occup Environ Health **58**, 1–26.
4) Griffin MJ (1990) Handbook of human vibration, Academic Press, London.
5) Wikstrom BO, Kjellberg A, Landstrom U (1994) Health effect of long-term occupational exposure to whole-body vibration: a review. Int J Ind Ergon **14**, 229–73.
6) Damkot DK, Pope MH, Lord J, Frymoyer JW (1984) The relationship between work history, work environment and low-back pain in men. Spine **9**, 395–9.
7) Chaffin DB, Park KS (1973) A longitudinal study of low-back pain as associated with occupational weight lifting factors. Am Ind Hyg Assoc J **34**, 513–25.
8) Svensson HO, Andersson GBJ (1989) The relationship of low-back pain, work history, work environment and stress: a retrospective cross-sectional study of 38- to 64-year-old women. Spine **14**, 517–22.
9) Bovenzi M, Rui F, Negro C, D'Agostin F, Angotzi G, Bianchi S, Bramanti L, Festa G, Gatti S, Pinto I, Rondina L, Stacchini N (2006) An epidemiological study of low back pain in professional drivers. J Sound Vib **298**, 514–39.
10) ISO 2631-1 (1997) Mechanical vibration and shock –Evaluation of human exposure to whole-body vibration – Part 1: General requirements. International Organization for Standardization, Geneva.
11) Okunribido O, Magnusson M, Pope M (2006) Delivery drivers and low-back pain: a study of the exposures to posture demands, manual materials handling and whole-body vibration. Int J Ind Ergon **36**, 265–73.
12) Okunribido O, Shimbles SJ, Magnusson M, Pope M (2007) City bus driving and low back pain: a study of the exposures to posture demands, manual materials handling and whole-body vibration. Appl Ergon **38**, 29–38.
13) ISO (1995) ISO Guide to expression of Uncertainty in Measurements (GUM). International Organization for Standardization, Geneva.
14) Rimell AN, Mansfield NJ (2007) Design of digital filters for frequency weightings required for risk assessments of workers exposed to vibration. Ind Health **45**, 512–9.
15) European Parliament (2002) Directive 2002/44/EC of the European Parliament and of the Council, On the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration), European Parliament, EU.
16) Montgomery DC, Runger GC (2003) Applied statistics and probability for engineers, John Wiley & Sons, New York.
17) Griffin MJ (1998) A comparison of standardized methods for predicting the hazards of whole-body vibration and repeated shocks. J Sound Vib **215**, 883–914.