Industrial Health 2010, **48**, 628–637 **Original Article**

Assessment and Prediction of Whole-body Vibration Exposure in Transport Truck Drivers

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Received June 3, 2009 and accepted June 21, 2010

Abstract: The European Directive 2002/44/EC on the minimum Health and Safety prescriptions regarding the exposure of workers to vibrations, was implemented in Italy through the Legislative Decree 187/2005, recently amended by the Legislative Decree 81/2008. The Decrees contain legal obligations and minimum requirements for the evaluation by direct measurement, which is the reference method, although not always appropriate or necessary, and by means of vibration data banks or information provided by equipment manufacturers. The values assessed must be representative of the actual working environment: in order to adapt assessed values to real working conditions it may be useful to adopt some statistical models. Statistically significant relationships were observed by means of a multiple linear regression on a limited set of measures on different models of trucks, in different operating conditions and settings: the relative influence of predictor variables was then assessed. Finally a short digression about the evolution of the suspension fitting has been made in order to briefly describe the historical context of WBV exposure level reduction and the state of the art of industrial vehicle comfort improvement technologies.

Key words: Whole-body vibration, Vibration exposure assessment, Vibration exposure prediction, Truck drivers, Statistical analysis, Empirical models, Linear regression

Introduction

The Legislative Decree 81/2008[1)], the Italian implementation regulation of many European Social Directives, prescribes the minimum requirements for the worker protection against health and safety risks. More specifically, having also adopted the 2002/44/EC Directive[2)], it covers risks arising from the exposure to mechanical vibrations, stating the thresholds: the action and limit values. The Decree confirmed most of the provisions of the EC regulations, except for some limited exceptions, and has effected the choice regarding the evaluation of the daily level of exposure to WBV, expressed as the equivalent continuous acceleration over an eight-hour period A(8), instead of the (Fourth Power) Vibration Dose Value VDV. In our opinion this choice was necessary because the A(8) should not be considered as an alternative choice with respect to VDV, as the latter is not equivalent, but rather an additional and complementary WBV exposure evaluating parameter[3)], to be measured in some cases (transient vibration, occasional shocks, etc.).

The Decree, in compliance with the EC regulation, reports the obligation to evaluate operator's exposure, which can be carried out by means of the more onerous direct measurement, or through reference to appropriate information on the probable entity of the vibrations of the equipment used. Furthermore, the Decree refers expressly to data source such as ISPESL's Data Bank, as well as to the data released by manufacturers.

As far as the last values are concerned, it is necessary to keep in mind that the operative conditions in which the measurements are carried out are standardized according to specific procedures set for each machinery by harmonised European vibration test codes, produced by European or International standards bodies, and often differ from conditions of normal use. In addition, it should also be noted that in the WBV field very few machine specific standards are actually available. The standard EN 13059: 2002[4)] has been adopted for the industrial trucks: the standard is in accordance with the general one EN 1032: 2003[5)], but it cannot be used to assess the operator's vibration exposure in real work conditions.

The qualified data banks[6)] are a first valid reference point for an evaluation of the exposure to vibrations, especially when they adopt standardized measurement protocols and when they report the main characteristics of the machines examined and the operative conditions in which the measurements were carried out, the main descriptive statistical variables (average, min, max, standard deviation, etc.), as well as the uncertainty of measurements. These values, in order to be considered representative of the activity taken into consideration, cannot be applied uncritically, but must be adjusted to the actual working conditions. In fact, the limit of these

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information sources are the operative conditions in which the measurements presented are carried out, that can differ from the *specific* working conditions that the Employer must refer to in conformity with the Legislative Decree 81/2008, during the evaluation of the exposure to vibrations.

The application of the direct measurement method is not always appropriate or necessary, because of the complexity and practical difficulties in identifying representative conditions for measurement, and also for economic reasons as well as the high degree of related uncertainty, of the not so negligible execution time, and also for the scarcity of good professionals in this field[7]. In some cases, however, it may be necessary to take measurements of the vibration magnitudes: in this case, it is important that whoever takes the vibration measurements has sufficient competence and experience. Moreover human exposure to WBV should be evaluated using the method defined in International Standard ISO 2631-1: 1997[8] and detailed practical guidance on using the method for measurement of vibration at the workplace is given in EN 14253: 2003[9]. With regards to this last method, the importance of the assessment of the uncertainty of vibration exposure evaluation should be highlighted: the uncertainties associated with the evaluation of A(8) can range from 20% above the true value to 40% below[10].

The study herein, with reference to some measurements carried out during test sessions on trucks, attempts to supply an aid for the evaluation and forecast of the level of exposure to vibrations. By means of the setting up of a statistical model, it is in fact possible to minimize the number of measurements that must be carried out and therefore minimise costs and time in order to carry out a more accurate forecast, that is, with a fixed degree of uncertainty of the results.

The aid presented can be useful for those employers of transport companies for whom the evaluation carried out solely through direct measurements is onerous and, however, unnecessary. Furthermore, through the assessment of statistical parameters of the model, it is possible to evaluate which factors most influence the level of exposure in question according to an ordinal scale of significance, in order to implement well targeted interventions and preventive measures.

Evaluation of the WBV exposure in the road transport industry

In the road transport industry, exposure to WBV is complex because it is strongly influenced by various factors. There is insufficient information in national literature to characterize the exposure to WBV of road transport operators and, generally speaking, very little research has been conducted internationally on the assessment of the influence of the aforementioned factors[11–13]. These factors can, however, be classified from an occupational health point of view, that is with reference to the exposure to the level of the target organ, in three categories: those concerning truck features, the operating conditions and the characteristics of the driver. Of the first, generally speaking, reference should be made to the type and class of vehicle, the position of the cabin (Cabin Over Engine, Conventional Cab, etc.), the make and model of manufacture, the anti-vibration features (undercarriage, cabin and seat suspension typology, etc.), the age and upkeep of the vehicle, the weight of the vehicle, the power source (diesel, petrol, electric, etc.), the typology, the wear and the inflation pressure of the tyre. Of the second, reference should be made to speed, road conditions and the extent of the load transported. Finally, of the final category, the anthropometric features of the driver (height, weight, etc.), the biomechanical features (transmissibility, mechanical impedance and apparent body mass) as well as driving experience and style. Obviously not all the factors have the same importance and therefore only a few of them are important in evaluating the exposure to the WBV in the case in study.

The vibrometric data examined in the study herein have been kindly supplied by IVECO S.p.a. - T. C. - S. F. - Vehicle Testing Labs: the observations mentioned, dated back a few years, were aimed at verifying the driving comfort of some of the truck models produced and, therefore, the best quality of a certain production fitting through the evaluation of the "K-factor". The measurements were carried out through the equivalent level of the weighted vibration energy in frequency and integrated on the measurement timing:

$$L_{eq} = 20 \cdot \log \sqrt{\frac{1}{T}\int_0^T \left(\frac{Awz\ (t)}{10^{-6}}\right)^2 dt}$$

with: $Awz\ (t)$ = vertical weighted acceleration as a function of time (m/s^2)
T = measured time interval (s)
L_{eq} = equivalent continuous acceleration level, determined over a measured time interval T (dB)
From this indication one can measure the "K-factor":

$$K = 20 \cdot 10^{\left(\frac{L_{eq}}{20} - 6\right)}$$

that is, in actual fact, the equivalent acceleration times 20.

The measurement equipment system included a triaxial ICP (of PCB Group Inc.) seat pad accelerometer placed on the seat in accordance with the 1997 ISO 2631-1 guidelines and a Larson Davis HVM 100 vibration meter.

This set of data was chosen because it was considered to be of particular interest: in fact, the vibrometric data is measured during operating and in strictly controlled conditions (road roughness, load, speed) ensuring, at the same time, an optimal field of variability.
The measurements were carried out by varying the following operating conditions:
- with a fully loaded vehicle and with an empty box;
- on a smooth test track (comparable to a highway road) and

Fig. 1. Heavy duty trucks.

Table 1. Whole-Body Vibration (WBV) measurements on trucks.

	Awz (m/s^2)	Model	Load	Speed (km/h)	Road conditions	Front suspensions	Rear suspensions
1	0.375	A	Empty	60	Highway	Semi-elliptic springs	Semi-elliptic springs
2	0.315	A	Empty	60	Highway	Parabolic springs	Parabolic springs
3	0.335	B	Empty	60	Highway	Parabolic springs	Pneumatic
4	0.535	A	Empty	80	Highway	Semi-elliptic springs	Semi-elliptic springs
5	0.400	A	Empty	80	Highway	Parabolic springs	Parabolic springs
6	0.400	B	Empty	80	Highway	Parabolic springs	Pneumatic
7	0.535	A	Empty	40	Provincial	Semi-elliptic springs	Semi-elliptic springs
8	0.420	A	Empty	40	Provincial	Parabolic springs	Parabolic springs
9	0.535	B	Empty	40	Provincial	Parabolic springs.	Pneumatic
10	0.660	A	Empty	60	Provincial	Semi-elliptic springs	Semi-elliptic springs
11	0.565	A	Empty	60	Provincial	Parabolic springs	Parabolic springs
12	0.750	B	Empty	60	Provincial	Parabolic springs	Pneumatic
13	0.335	A	Full	60	Highway	Semi-elliptic springs	Semi-elliptic springs
14	0.335	A	Full	60	Highway	Parabolic springs	Parabolic springs
15	0.250	B	Full	60	Highway	Parabolic springs	Pneumatic
16	0.475	A	Full	80	Highway	Semi-elliptic springs	Semi-elliptic springs
17	0.375	A	Full	80	Highway	Parabolic springs	Parabolic springs
18	0.315	B	Full	80	Highway	Parabolic springs	Pneumatic
19	0.375	A	Full	40	Provincial	Semi-elliptic springs	Semi-elliptic springs
20	0.375	A	Full	40	Provincial	Parabolic springs	Parabolic springs
21	0.400	B	Full	40	Provincial	Parabolic springs	Pneumatic
22	0.600	A	Full	60	Provincial	Semi-elliptic springs	Semi-elliptic springs
23	0.565	A	Full	60	Provincial	Parabolic springs	Parabolic springs
24	0.600	B	Full	60	Provincial	Parabolic springs	Pneumatic

a slightly rough test track (comparable to a provincial road);
- at speeds of 40 and 60 km/h on slightly rough test track and 60 and 80 km/h on the smooth one.

Both truck models examined (A and B) presented suspended cabins (Cab Over Engine type), pneumatic driver seats and similar Gross Vehicle Weight Ratings (about 15 metric tons of weight). The data reported (Table 1) refers solely to the vertical component, which is the dominant one in the field of interest, as well as that more sensitive to the operating variables described and the fitting's changes.

Subjects and Method

Statistical analysis of the vibrometric data

A statistical analysis of the data presented in Table 1 was carried out: the (least square) multiple linear regression method was adopted, because, compared to other methodologies, it requires fewer observations to obtain a significant statistical sample.

The independent (or predictor) variables were chosen in order to "explain" the values observed by the dependent variable (or explained) *Awz* and that is: road roughness, load, suspension fitting and speed, leaving the evaluation of the quality of the assumed regression model to the statistical analysis.

The current choice of the predictors in the empirical models is based solely on the improvement of the fit. However, the physical meaning of this choice is still under investigation.

The driver during the test was always the same: so no variable was introduced in order to take the characteristics of the driver into account. Instead, the difference between the two truck models (A and B) was not considered relevant: however, this supposition was verified in retrospect. Therefore, *dummy* variables were defined in order to represent the "nominal" (or categorical) variables, that are not characterized by measurements but by qualitative evaluations (road roughness, load, and suspension fitting).

Through Table 2, which includes the *dummy* variables defined, with the respective average values and standard deviations of the accelerations measured, it is possible to deduce qualitatively the influence of the following variables: the road roughness, the absence of load and the presence of semi-elliptic springs (compared to the parabolic or pneumatic ones) on the increase in the magnitude of the vibrations. Instead, at first sight, the pneumatic suspension does not seem to influence directly the vibratory phenomenon observed.

On the basis of the descriptive statistical analysis it can be seen that the distribution of the sample of Awz is asymmetrical, has a wide range, and by graphical analysis no outliers (Fig. 2): this is important in verifying the suitability of the following statistical tools.

Results and Discussion

The statistical model M1 assumed can be represented as follows:

$$\hat{A}_{wz} = m_F \times F + m_C \times C + m_V \times V + m_S \times S + m_P \times P + b \quad \text{(M1)}$$

$\hat{A}_{wz}$ = Awz predicted (m/s^2)
F = Road condition (F=1 : Rough ; F=0 : Smooth)
C = Load condition (C=1 : Empty ; C=0 : Full)
S = Semi-elliptic springs
(S=1 AND P=0 : Semi-elliptic springs)

Table 2. Definition of the dummy variables for truck data analysis

Nominal variable	Operating conditions	Dummy variable	Average (m/s^2)	SD (m/s^2)
Road roughness	Provincial	F=1	0.532	0.119
	Highway	F=0	0.370	0.076
Load	Empty	C=1	0.485	0.134
	Full	C=0	0.417	0.117
Suspension fittings	Semi-elliptic springs	S=1	0.486	0.117
	No semi-elliptic springs	S=0	0.433	0.133
Suspension fittings	Pneumatic suspensions	P=1	0.453	0.109
	No pneumatic suspensions	P=0	0.448	0.167
Model	A		0.453	0.109
	B		0.448	0.167
Global average			0.451	0.128

Awz	Max	Min	Range	Avg	SD	Median	Q1	Q3	IQR
m/s^2	0.750	0.250	0.500	0.451	0.128	0.400	0.365	0.543	0.178

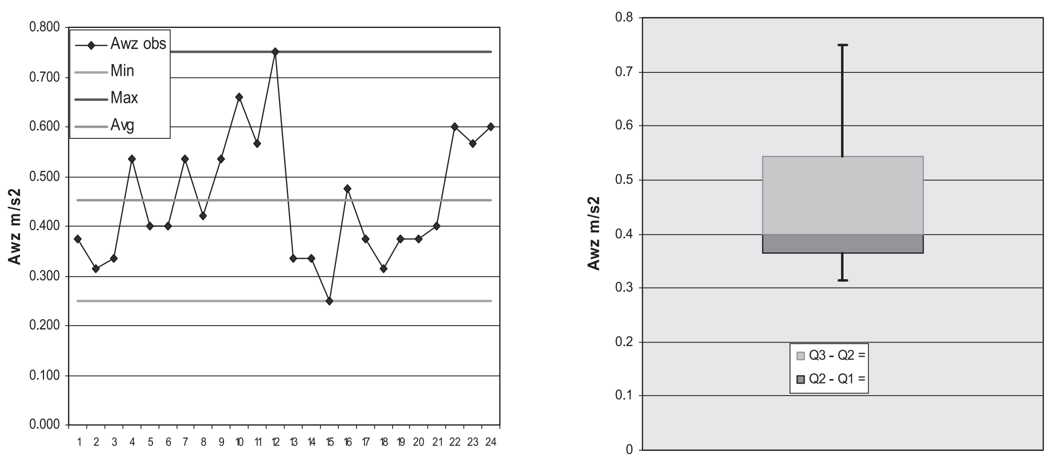

Fig. 2. Some elements of descriptive statistics.

P = Pneumatic (rear) suspensions
(S=0 AND P=1 : Pneumatic (rear) suspensions)
(S=0 AND P=0 : Parabolic springs)
V = Velocity (in km/h)
m_i *= Regression coefficient of i variable*
b = Intercept

and the results of the multiple linear regression, carried out through the least-squares method (Table 3), are exposed. In model M1 correlation coefficient equal to R=0.9193 shows a significant linear relation between the independent variables and the dependent variable; even the standard error equal to s=0.05678 shows a good approximation to the estimated values.

It is, furthermore, possible to use statistic F to determine whether the quality of these results, with such a high R, is a coincidence. The null hypothesis (H_0) stating that any partial regression coefficient is equal to zero can be tested by using a standard *F*-test that verifies the equivalent null hypothesis stating that the global coefficient of correlation is zero. This *F*-test has $\nu_1 = K = 5$ and $\nu_2 = N - K - 1 = 18$ degrees of freedom (with N being the number of observations and K being the number of predictors).

The value of the significance of *F*, equal approximately to 1 E-6, shows that it is extremely difficult to observe these results in a random sample of such population, and therefore the null hypothesis (H_0) can be rejected, i.e. that there is no relation, and conclude instead that there is a significant linear relation (alternative hypothesis H_1).

In a multiple regression model the coefficients are called *partial regression coefficients* m_i (or simply *regression coefficients*). In other words it is possible to notice for example how for every 10 km/h of increased speed the value of *Awz* increases on average by approximately 0.07 m/s^2 (when the other variables are maintained fixed).

Another hypothetical test will prove that each *regression coefficient* is actually useful in predicting the dependent variable through the examination of their significance value according to a *t*-distribution.

In fact, more precisely, since the significance values calculated represent the probabilities in a two-tailed *t* test, and since

Table 3. Model M1 - Regression statistics

SUMMARY OUTPUT					
Multiple R	0.919346921				
R Square	0.845198761				
Adjusted Square R	0.802198416				
Standard Error	0.056777873				
Observations	24				
ANOVA TABLE	*df*	*SS*	*MS*	*F*	*F Significance (p-value)*
Regression	5	0.316821875	0.063364375	19.65562776	1.00554E-06
Residual	18	0.058027083	0.003223727		
Total	23	0.374848958			
	m_i = *Regression coefficients*	s_i = *Standard Error*	*Stat t (m_i/si)*	*t Significance (p-value)*	
b = Intercept	–0.178958333	0.085166809	–2.101268495	0.049966068	
P = Pneumatic	0.029375	0.028388936	1.034734078	0.314495561	
S = Semi-elliptic	0.0675	0.028388936	2.377686819	0.028710195	
C = Load	0.06875	0.02317947	2.965986769	0.008274741	
V = Speed	0.006895833	0.001158973	5.949949215	1.24885E-05	
F = Road roughness	0.299166667	0.03278072	9.126299385	3.57731E-08	

Table 4. Model M2 - Regression statistics

SUMMARY OUTPUT					
Multiple R	0.946475973				
Square R	0.895816767				
Adjusted Square R	0.866876981				
Standard Error	0.04657907				
Observations	24				
ANOVA TABLE	*df*	*SS*	*MS*	*F*	*F Significance (p-value)*
Regression	5	0.335795982	0.067159196	30.95450472	3.07741E-08
Residual	18	0.039052976	0.00216961		
Total	23	0.374848958			
	m_i = *Regression coefficients*	s_i = *Standard Error*	*Stat t (m_i/s_i)*	*t Significance (p-value)*	
b = Intercept	–0.172440476	0.068938223	–2.501376868	0.022244261	
$P \times F$ = Pneumatic × Road roughness	0.098035714	0.030493159	3.215006789	0.004801398	
S = Semi-elliptic	0.077321429	0.02156192	3.586017826	0.002111867	
C = Load	0.06875	0.019015826	3.615409642	0.001978205	
V = Speed	0.006895833	0.000950791	7.252730858	9.61857E-07	
F = Road roughness	0.266488095	0.028749226	9.26940058	2.83284E-08	

we assess a positive relation between *Awz* and the explanatory variables (depending on the choice made concerning *dummy* variables), we could use in a more profitable manner a one-tailed (right) t test: therefore the actual significance values are half of those stated. Through the examination of statistic t it is possible to deduce how the significance value of the coefficient of the variable P is higher than the generally accepted significance values (p>0.05). It is therefore possible to deduce that variable P is not actually useful to determine the estimated value of *Awz*, that has already been proven, from a qualitative point of view, while examining the average values and standard deviations of the *Awz* compared to the *dummy* variables.

This does not necessarily mean that there is an absence of any relation between the variable P and the dependent variable *Awz*, but only the non-existence of a direct linear relation. We can therefore assume a second linear regression model M2: the examination of the data suggests the following hypothesis:

$$\hat{A}wz = m_F \times F + m_C \times C + m_V \times V + m_S \times S + m_{PF} \times P \times F + b \tag{M2}$$

Even in this case the results of the statistical analysis produce an excellent correlation (Table 4). In fact, in this case there is a correlation coefficient equal to R=0.9465 and a standard error equal to s=0.04658, better than the previous case. Furthermore, all the coefficients have significance values lower

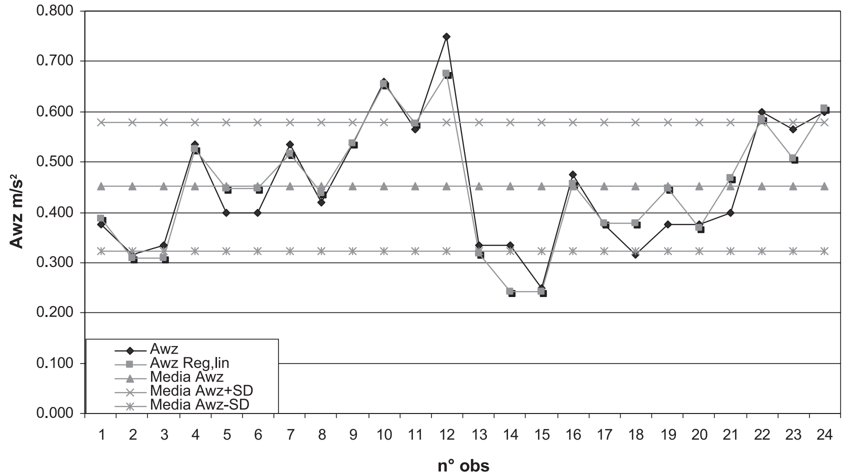

Fig. 3. Model M2 - Graphic of Awz_{estim} compared to Awz_{obs}.

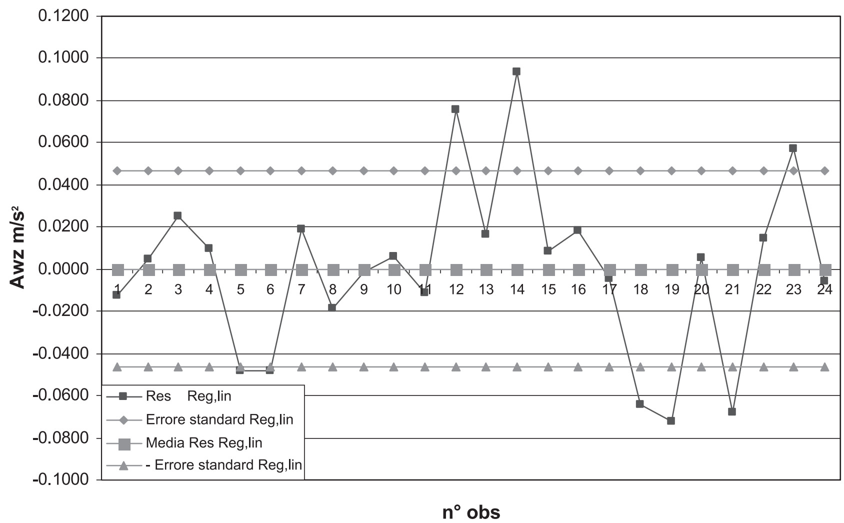

Fig. 4. Model M2 - Graphic of Awz_{estim} residuals compared to Awz_{obs}.

than those generally accepted ($p<0.01$), a fact that confirms the usefulness of all the new *regression coefficients*.

In graph (Fig. 3) it is possible to verify how the validated linear regression model approximates the values of *Awz* observed in a more accurate manner than the simple Awz_{avg} (± SD), that the estimated values are contained mainly within the standard errors values, with an average tending to zero (Fig. 4), and how the residue patterns are unsatisfactory because of a lack of a quadratic term in the model (Figs. 5 and 6).

The statistical linear regression model that has just been validated is characterized by both its simplicity, and accuracy, but it is not the only one that "explains" statically the sample of data observed. In fact it is possible to assume some slightly more complex models that, on the other hand, enable more accurate prediction.

Let's examine the following statistical model M3:

$$\hat{A}\mathrm{wz} = m_F \times F + m_C \times C + m'_V \times V + m''_V \times V^2 + m_S \times S + m_{PF} \times P \times F + b \qquad \text{(M3)}$$

In this model the results of the statistical analysis give the best correlation (Table 5). In fact the value of the correlation coefficient is very high R=0.9638, and the standard error is equal to s=0.03961: we can declare that the vibratory phenomenon observed through the measurements of the samples taken has been statistically "explained" thoroughly.

By means of the graphs above it is possible to verify how the validated linear model M3 approximates the values of *Awz* observed (Fig. 7), as well as the patterns of residuals which are fully satisfactory this time (Figs. 8 and 9). Moreover it is possible to represent graphically (Fig. 10) the quality of the adjustment of the regression model M3 and the very high correlation between the estimated *Awz* and those observed, as well as the almost normal distribution of the residuals (Fig. 11).

Finally, we would focus on the problem about which the predictor is more important. There have been some attempts to come up with a purely statistical answer, but they are unsatisfactory. The question can be answered only in the context of a specific research question by using subject matter

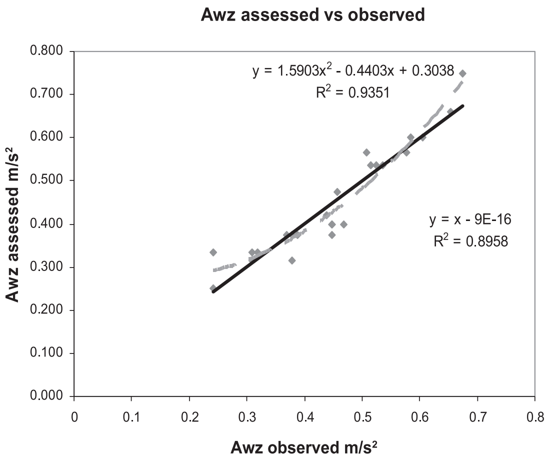

Fig. 5. Model M2 - Correlation between Awz_{estim} compared to Awz_{obs}.

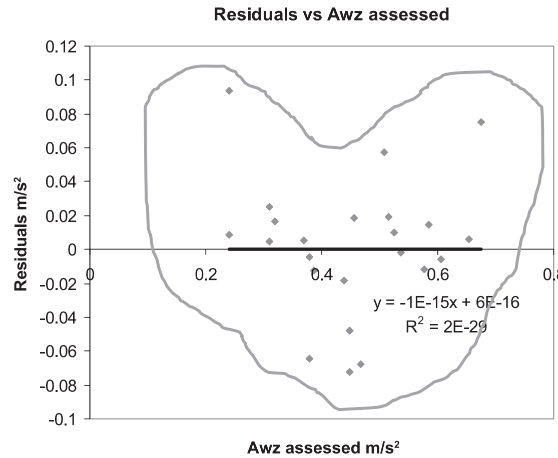

Fig. 6. Model M2 - Scatter plot of Awz_{estim} residuals compared to Awz_{obs}.

Table 5. Model M3 - Regression statistics

SUMMARY OUTPUT					
Multiple *R*	0.963759744				
Square *R*	0.928832843				
Adjusted Square *R*	0.903715023				
Standard Error	0.039613526				
Observations	24				
ANOVA TABLE	*df*	*SS*	*MS*	*F*	*F Significance (p-value)*
Regression	6	0.348172024	0.058028671	36.97903895	7.67599E-09
Residual	17	0.026676935	0.001569231		
Total	23	0.374848958			
	m_i = *Regression coefficients*	s_i = *Standard Error*	*Stat t* (m_i/s_i)	*t Significance (p-value)*	
b = Intercept	–0.558482143	0.149444057	–3.737064928	0.001640356	
P × *F* = Pneumatic × Road roughness	0.098035714	0.02593314	3.780325618	0.001493289	
S = Semi-elliptic	0.077321429	0.018337499	4.216574316	0.000580488	
C = Load	0.06875	0.016172154	4.251134317	0.000538802	
V = Speed	0.020520833	0.004918569	4.172114812	0.000638953	
F = Road roughness	0.266488095	0.024449999	10.89930902	4.31979E-09	
V^2 = Speed^2	–0.000113542	4.04304E-05	–2.808325094	0.012091623	

knowledge. One possibility is to measure the importance of a variable by the magnitude of its regression coefficient. This approach fails because the regression coefficients depend on the underlying scale of measurements[14)].

One other possibility of solving the problem of units of measurement is through the ratio between the *regression coefficients* and the respective *standard errors* (m_i/s_i). At present, a simple and reliable method is by means of standardized regression coefficients. Before fitting the multiple regression equation, all variables dependent and independent are standardized by subtracting the mean and dividing by the standard deviation. The *standardized regression coefficients*, then, represent the change in response for a change of one standard deviation in a predictor. In our case study calculating the *standardized regression coefficients* as follows:

$$\beta i = bi \times \frac{\sigma i}{\sigma y}$$

$\beta\iota$ = i predictor variable standardized regression coefficient
b_i = i predictor variable (non standardized) regression coefficient
σi = i predictor variable standard deviation
σy = dependent variable standard deviation
it is possible to arrange the influence of the different explanatory variables on the dependent variable according to the following hierarchical order:

Road roughness > Speed > Susp. Fitting > Load

In fact regression M1 (see Table 6) does not contain all predictor variables having a direct linear relation with the predicted one, regression M2 contains all the predictor variables and is sufficiently accurate (see Table 7) and

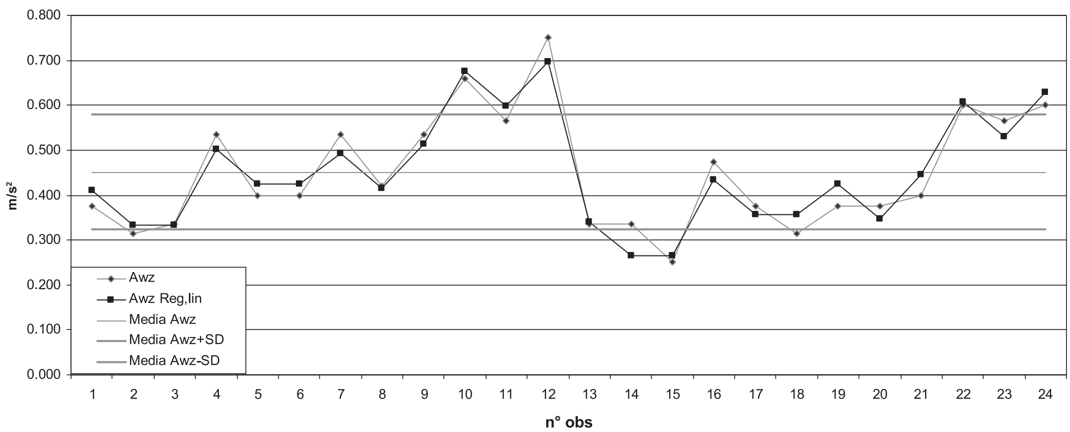

Fig. 7. Model M3 - Graphic of Awz_{estim} compared to Awz_{obs}.

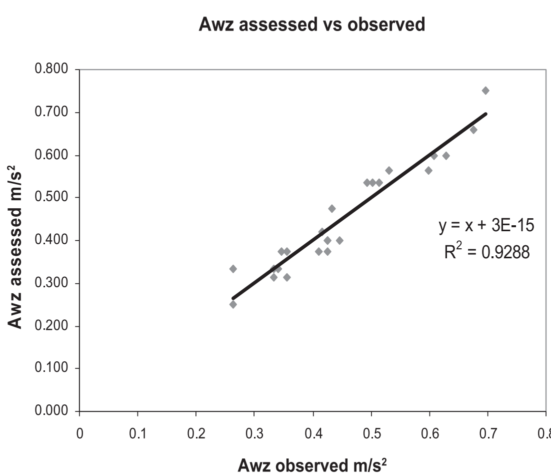

Fig. 8. Model M3 - Scatter plot of correlation between Awz_{estim} compared to Awz_{obs}.

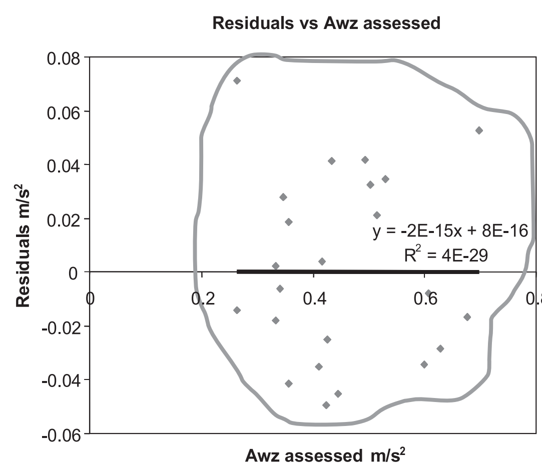

Fig. 9. Model M3 - Scatter plot of Awz_{estim} residuals compared to Awz_{obs}.

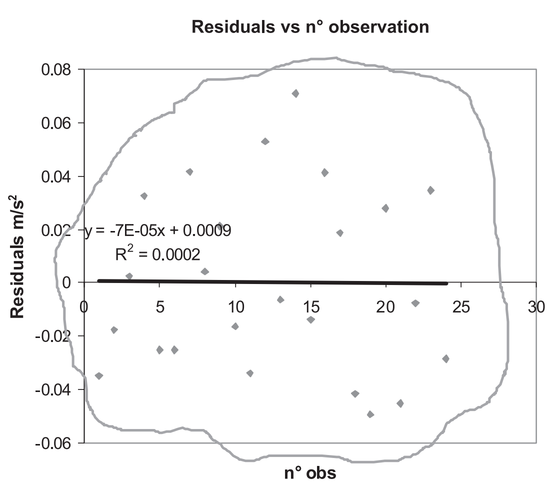

Fig. 10. Model M3 - Graphic of Awz_{estim} residuals compared to n° observation.

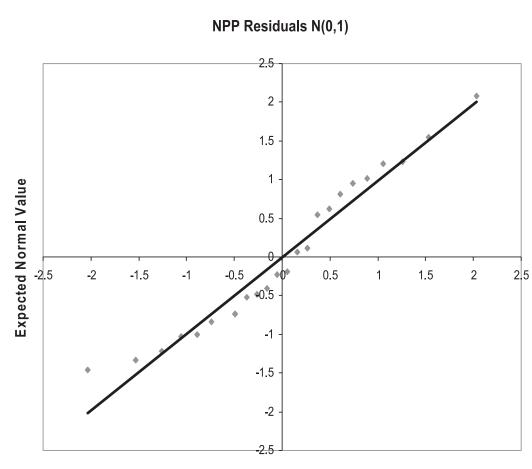

Fig. 11. Model M3 - Normal Probability Plot of Awz_{estim} residuals.

Table 6. Model M1 - Relative importance of predictors variables

	m_i = *Regression coefficients*	s_i = *Standard Error*	*Stat t* (m_i/s_i)	*SD*	β_i
Awz				0.127662762	
P = Pneumatic	0.029375	0.028388936	1.034734078	0.481543412	0.110802379
S = Semi-elliptic	0.0675	0.028388936	2.377686819	0.481543412	0.254609722
C = Load	0.06875	0.02317947	2.965986769	0.510753918	0.275055399
V = Speed	0.006895833	0.001158973	5.949949215	14.446302370	0.780331648
F = Road roughness	0.299166667	0.03278072	9.126299385	0.510753918	1.196907735

Table 7. Model M2 - Relative importance of predictors variables

	m_i = *Regression coefficients*	s_i = *Standard Error*	*Stat t* (m_i/s_i)	*SD*	β_i
Awz				0.127662762	
$P \times F$ = Pneumatic × Road roughness	0.098035714	0.030493159	3.215006789	0.380693494	0.292344909
S = Semi-elliptic	0.077321429	0.02156192	3.586017826	0.481543412	0.291656110
C = Load	0.06875	0.019015826	3.615409642	0.510753918	0.275055398
V = Speed	0.006895833	0.000950791	7.252730858	14.446302370	0.780331647
F = Road roughness	0.266488095	0.028749226	9.26940058	0.510753918	1.066167116

Table 8. Model M3 - Relative importance of predictors variables

	m_i = *Regression coefficients*	s_i = *Standard Error*	*Stat t* (m_i/s_i)	*SD*	β_i
Awz				0.127662762	
$P \times F$ = Pneum × Road roughness	0.098035714	0.02593314	3.780325618	0.380693494	0.292344909
S = Semi-elliptic	0.077321429	0.018337499	4.216574316	0.481543412	0.29165611
C = Load	0.06875	0.016172154	4.251134317	0.510753918	0.275055399
V = Speed	0.020520833	0.004918569	4.172114812	14.446302370	2.322134964
F = Road roughness	0.266488095	0.024449999	10.89930902	0.510753918	1.066167117
V^2 = Speed^2	–0.000113542	4.04304E-05	–2.808325094	1745.553356886	–1.552473363

regression M3 (see Table 8) has twice the speed variable (one positive and the other, square, is negative) with the opposite sign, and so it is not immediately apparent which one of them prevails.

In our opinion, however, the question is still open and will be subject to further attempts to solve the problem.

Evolution of the suspension fitting

Research carried out by the commercial vehicle manufacturing companies has favoured the technological evolution of the models developed and produced, achieving notable levels of the health and safety conditions of the driver's seat. The design standards of the fittings by leading industrial vehicle manufacturing companies have, for many years, aimed, not so much at the reduction of vibration exposure levels from an occupational health point of view, but rather to the continuous improvement in driving comfort.

The main evolution in industrial vehicle suspension in the last few decades is represented by the change from multiple leaf springs, with a constant thickness, to springs with fewer leaves with variable thickness and parabolic profile, up to the pneumatic suspension.

It is, however, necessary to keep in mind that, at the moment, all three suspensions are used:

- semi-elliptic multi-leaf suspensions: off-the-road use and work sites (as well as normal roads);
- parabolic suspensions: road use;
- pneumatic suspensions: mainly highway tracks.

Obviously other industrial vehicle components have also changed through the years and particularly as far as the vehicle comfort is concerned, we could mention:

- cabin suspension: apart from improvements made to traditional suspensions (shock absorbers and springs with the best features), for those vehicles belonging to a "higher" standard pneumatic cabin suspensions that are adjustable to any load condition have been introduced;
- the seat: there has been a change from mechanical suspension seats (spring adjustable according to the driver's weight), longitudinal seat adjustment and back rest tilting, to more sophisticated pneumatic seats, lumbar adjustment of the back rest and the possibility of longitudinal and vertical seat adjustment; all these characteristics must be added to a longitudinal damper that intervenes during the start and/or pickup of the vehicle, contributing strongly to the attenuation of the "knocks" felt by the driver.

All three principal suspension systems (undercarriage damping, suspension cabs and seat suspension) are designed to cover a specific frequency range: there is a critical frequency over which they amplify vibration and an incorrect selection of the correct device could increase exposure to vibration. In general, undercarriage suspension is designed to reduce higher-level frequencies, cabin suspension to reduce lower frequencies and the suspended seat to reduce the lowest frequencies of vibration.

As far as the superiority of the pneumatic suspensions compared to the mechanical ones is concerned, some researchers claim that the pneumatic suspensions in general transmit lower levels of WBV: such conviction is not universally accepted. However, against a higher initial investment, from a more general point of view the pneumatic suspensions are advantageous, enabling an optimal levelling independently from the road, less use on road, higher average duration of the frame, more stability on slopes, humps and in the case of overturning.

The evolution of the fitting design introduction of all these adjustments has obviously influenced the vehicle comfort contributing strongly to its improvement.

Conclusions

This study shows how it is possible to establish a statistical model through a sample of vibrometric data: the statistic model is not univocal because, according to the requirements, a more complex application could be required, with a higher accuracy in the predictions: often the linear model (more or less articulate) is chosen because it is adjustable to the data and requires a limited number of representative samples of the phenomenon taken into consideration.

It is possible to notice that, under the hypothesis for validity of multiple linear regression model and in the range of the original data, speed increases vibration exposure: the relationship seems to be linear at first sight and quadratic after a more accurate analysis. Moreover road roughness, semi-elliptic fitting (instead of parabolic) and the absence of the load, increase vibration exposure too, but, at the moment the analytical relationship is unknown. Finally, pneumatic fitting has no direct relationship with Awz, but is, in some way, also dependent on road roughness.

Furthermore, it is important to stress the conceptual differences between physical laws and empirical models. In our case the models created do not represent a physical law that enables us to explain the relation between the dependent variable (*Awz*) and independent variables, but are empirical models. The models that we validated obviously do not mean to represent in general the vibratory phenomenon that can be felt on the driver's seat of a truck, but they are limited to the fields of variability of the explicative variables: their results can therefore be considered *useful* in explaining the vibratory phenomenon examined. If an empirical model was extended and validated on a representative number of samples of the entire population of checkable vibratory phenomena, then it could earn the rank of physical law: in such a case its results could be considered *true*.

But this approach lies outside the purposes of this study. Our aim was to prove that, by creating a statistical model, the realization of a limited number of measurements or the aid of reliable data (vibration data banks), which reflect the main characteristics of the machines examined and the operating conditions in which the measurements were carried out, it is possible to describe the exposure to WBV in certain working environments, in *specific* working conditions. We honestly hope that we have succeeded in our intent.

Acknowledgements

A special thank you to IVECO S.p.a. - T. C. - S. F. - Vehicle Testing Labs (FIAT Group) for their help and cooperation: in particular to M.Sc. Enrico Durelli and M.Sc. Massimo Mazzarino.

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