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Predictors of whole body vibration exposure in motorcycle riders

Estimadores de la vibración de cuerpo entero para motociclistas

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Abstract

Some occupations like police officers, paramedics, delivery and courier services, require professional motorcycle riders that may ride for many hours each day. In these cases, the employers, the riders themselves, and the occupational health physicians would benefit from the knowledge of the vibration transmitted to riders and the exposure time limits recommended for their activities. This paper presents an experimental design (2^4 Factorial Design) to determine the main effects caused on whole body vibration exposure limits by the following factors: motorcycle age, engine size, road type and rider weight. The results show that newer motorcycles allow 36.3% more riding time than older motorcycles before the Exposure Action time Value (EAV) is reached. Motorcycles with larger engine size (125 cc) allow 22.5% more riding time than motorcycles with small engine size. It is possible to ride 44% more time using fast roads than slow roads. The vibration measurements were performed according to ISO-2631 and, as a novel contribution, an artificial neural network was derived for estimating the vibration exposure time using the predictors as input variables. Neural Networks presented better correlation than multiple regressions.

----- *Keywords:* Whole Body Vibration, motorcycle, exposure time, ISO 2631, neural networks

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Resumen

Algunos oficios como los agentes de tránsito, agentes de policía o mensajeros requieren de motociclistas profesionales que puedan conducir sus motos muchas horas por día. En estos casos, los empleadores, los conductores y los médicos de salud ocupacional se beneficiarían al conocer la vibración transmitida a los motociclistas y los límites de tiempo de exposición recomendados para cada condición o actividad específica. Este artículo presenta un diseño experimental (Diseño Factorial 2^4) para determinar los principales efectos sobre el tiempo límite de exposición a vibraciones de cuerpo entero que tienen los factores: edad de la motocicleta, tamaño del motor, tipo de carretera y peso del conductor. Motocicletas nuevas permitieron conducir un 36,3% más de tiempo respecto a las viejas antes de alcanzar el límite de acción. Motocicletas con motor más grande (125 cc) permitieron un 22,5% más tiempo de conducción respecto a las de motor pequeño (100 cc). Es posible conducir 44% más tiempo usando vías rápidas respecto a las vías lentas. Las mediciones de las vibraciones fueron realizadas acorde a la norma ISO-2631 y, como contribución novedosa, una red neuronal artificial fue obtenida para estimar el tiempo de exposición a la vibración para llegar al límite de acción sugerido por la norma. Los factores bajo análisis fueron utilizados como entradas de la red neuronal. Las redes neuronales artificiales presentaron una mejor correlación respecto a las regresiones múltiples.

----- *Palabras clave:* vibración de cuerpo entero, motocicleta, tiempo de exposición, ISO 2631, red neuronal

Introduction

Most of these professional riders work for six to eight hours a day riding their motorcycles. Human response to vibration becomes a critical subject in these activities since overexposure may cause discomfort, may negatively influence their performance, or may even pose health risks.

Several studies have tried to evaluate the relation between vehicle vibration and some diseases. Bovenzi and Hulshof [1] published a review of epidemiologic studies on the relationship between exposure to Whole-Body Vibration (WBV) and low back pain. This review emphasized that WBV was related to the development of low back pain. Porter and Gyi [2] found that frequent car drivers suffered low back pain causing, in some cases, work absence. Mirbod et al [3] evaluated subjective symptoms in the hand-arm system in 119 traffic police motorcyclists and 49 male controls in a city located in the central part of Japan. They found that vibration exposure of traffic police motorcyclists might be considered a risk factor for suffering from hand arm symptoms.

Stark et al [4] studied one case of Raynaud´s phenomenon (white finger) caused by occlusion of the proper palmar digital arteries on the right hand and obstruction of the superficial palmar arterial arch on the left hand. They conclude that maybe excessive cross country motorcycle riding may induce Raynaud´s phenomenon. Mirbod et al [5] carried out studies on symptoms among motorcycling transit policemen in one city of Japan. They found that shoulder stiffness and low back pain were frequently encountered.

There is an evident need for developing preventive measures to address the WBV exposure. Although WBV is a complex phenomenon involving engineering, biomedical, and psychological issues, some measures can be taken based on averaged studies. The European Parliament, for example, has established the minimum requirements for the protection and safety of workers exposed to WBV (European Directive 2002/44/EC [6]). The frequency-weighted Root Mean Squared (RMS) acceleration, based on eight hours per day, is limited in this Directive to a Threshold Action Value (TAV) of 0.5 m/s^2 and a Threshold Limit Value (TLV) of 1.15 m/s^2. The European Directive suggests carrying out the measurements according to the International Standard ISO 2631-1 (Mechanical vibration and shock evaluation of human exposure to whole body vibration) [7].

Measurement of WBV exposure in garbage trucks was reported by Maeda and Morioka [8]. Their findings indicated that Japanese drivers of garbage trucks, under their work conditions at the time of the study, should limit their working hours to 2.5 per day. In a different study, WBV exposure levels experienced by freight truck drivers were investigated to determine whether the exposure of the driver exceeded the guidelines of ISO 2631. Their results indicated that, on average, the drivers did not increase their risk of adverse health effects as a result of exposure to vibrations. They found two significant factors that affected exposure time limits: road condition and truck type. The study suggested that future research should explore the effects of regular driving, larger vehicle age differences, suspension systems and driving situations [9].

There are many factors that affect WBV levels: speed, road conditions, vehicle maintenance, driving experience of the driver, vehicle weight, seat type, vehicle suspension, load, rider age, engine size, transit flow and driver weight [10-13]. Chen et al [14] found that, besides some of the factors mentioned before, the following also influenced WBV exposure: automobile manufacturer, use of seat cushion and transit flow conditions. Ozkaya et al. [11] found that track conditions of subway lines significantly affect the levels of WBV experienced by the operator. Bovenzi [12] reported that older buses are associated with greater levels of WBV.

Recently, Chen et al. [15] carried out a WBV exposure comparison between motorcycles and cars. They conclude that WBV exposure levels of common motorcycle riders are distinctively higher than those of cars. Wang et al. [16] also found that motorcycle riders have higher health risks than car drivers because they are sitting on a flat seat without back support causing greater energy absorption of vertical vibrations. These results highlight the need for studying the motorcycle WBV problem.

Matsumoto et al. [17] have studied the hand-arm vibration transmitted to motorcycle riders. They reported that acceleration levels at the handle-bars of motorcycles running on paved roads exceeded the ISO exposure guidelines.

This paper carries out a systematic experimental design to study the statistically significant effect of rider weight, road type, engine size, and motorcycle age, on the EAV. These factors will be used as inputs to a neural network for estimating the admissible exposure times. The trained network allows us to estimate the approximated exposure times without the need of particular measurements, i.e. riders can predict the admissible daily riding times depending on road type, engine size, rider weight, and motorcycle age.

Experimental design

The International Organization for Standardization, in its ISO-2631 standard, sets a procedure for evaluating human exposure to WBV, where the direction of measurements, durations, locations, sensors to use, and data to report, are detailed.

The aforementioned standard states that the acceleration signal should be measured with three-axis accelerometers in the frequency range from 0.5 Hz to 80 Hz. The signal is then subjected to weighting filters in order to take into account the greater or lesser influence of different frequencies in the human body.

The overall weighted acceleration shall then be calculated with equation 1.

$$a_w=\left[\sum_i (W_i a_i)^2\right]^{\frac{1}{2}} \qquad (1)$$

Where a_w is frequency-weighted acceleration, W_i is weighting factor for the i-th one-third octave band and a_i is the RMS acceleration for the i-th one-third octave band.

Since transversal vibrations (with respect to a body-fixed coordinate system for seated persons) create more discomfort than vibration along the body-fixed z axis (the axis running from hip to head), the transversal RMS components are magnified 40% whereas the "z" component is left unamplified. The directional weighting factors are then: kx=1.4, ky=1.4 and kz=1, and the weighted RMS acceleration is taken as the maximum of all three weighted components as indicated in equation 2.

$$a_v=\max\left[1.4a_{wx}, 1.4a_{wy}, a_{wz}\right] \qquad (2)$$

The European Parliament, based on studies from which average results may be inferred, limits the value of a_v for workers exposed to WBV during their eight hour shift. There is a threshold above which some action needs to be taken (to drive on paved roads, to use special dampers or to reduce the ride time), the TAV, which is set to be 0.5 m/s^2 in the European Directive 2002/44/CE , and another threshold which should not be surpassed, the TLV which is set to be 1.15 m/s^2 in this directive.

These limits can be increased when the exposure time is lower than eight hours per day or, equivalently, the calculated RMS acceleration (a_v) can be decreased to compare with the eight hour based thresholds TAV and TLV. When this second approach is taken, the reduced acceleration, referred to as A(8), is determined from equation 3.

$$A(8)=a_v\sqrt{\frac{t}{T}} \qquad (3)$$

Where a_v is overall weighted acceleration (equation 2), t is exposure time and

T is the reference time, 8 hours.

In general, a_v is determined from a time series which is statistically representative of the vibration but shorter than the overall exposure time. In this case, one may be interested in obtaining the time required to reach TAV or TLV. These times, referred to as EAV and ELV are readily obtained by comparing A(8) (equation 3) with either TAV or TLV, the resulting times are given in equation 4 and equation 5.

$$EAV=\left(\frac{TAV}{a_v}\right)^2 T \qquad (4)$$

$$ELV=\left(\frac{TLV}{a_v}\right)^2 T \qquad (5)$$

A multifactor experimental design was conducted to determine the influence of the following factors: motorcycle age, driver weight, engine size and road type on the diagnosis variable EAV (equation 4). Experiments were carried out for two levels of each factor and were replicated twice resulting in a total of 32 (2^4x2) experiments. The number of replicates was estimated based on similar previous factorial design. This number of replicates is enough to evaluate the random variability (or "pure error") and the repeatability. Each experiment yielded a long data signal to be analyzed. Proper randomization of the experiments was employed seeking independence (no correlation between factors). The statistical significance of each factor on the frequency-weighted RMS acceleration was assessed via an analysis of variance [18].

The levels for each factor are specified in table 1. The average weight of riders is taken to be 686 N (70 kgf), and this value allows us to differentiate between high weight (>686 N) and low weight (<= 686 N).

Table 1 Factors and levels used for experiments

Level/factor	*Motorcycle age*	*Cylinder volume*	*Driver weight*	*Road type*
1	> 3 years (Old)	100 cc	<= 686 N	Fast (F)
2	<= 3 years (New)	125 cc	> 686 N	Slow (S)

Selected riders

Our experimental design called for four riders to be recruited. All four of them were males with a mean weight of 712 N (Standard Desviation: 94.7 N). Two of the riders were heavier than 686 N (Rider 1= 813 N, Rider 2= 774 N), whereas the other two were lighter than 686 N (Rider 3= 627 N, Rider 4= 637 N).

Each motorcycle rider had at least 4 years of recent experience in motorcycle riding and was familiar with the test routes selected for this study. Background information for each rider was filled out by the support staff (contact information, weight, height, age, years of motorcycle riding experience, and health status).

Selected routes

Two different roads were used for experiments: the fast and the slow road. The fast road is composed of highways (Av. Regional), only a few stops, and flat and smooth lanes (10 km, 97% flat, 10 speed bumps, no traffic lights and mainly straight route). The slow road with many stops, sloped lanes and cracked asphalt (6.85 km, 80% sloped, including slope >10%, 14 speed bumps and 2 traffic lights and more than 15 turns in route located in Bello).

Selected motorcycles

Most motorcycles begin to show some wear after 3 years of work, and they are considered old after this time period. Frequently, 100 cc and 125 cc motorcycles are used for delivery and courier services in Medellín (more than 1.000.000 motorcycles with these engine sizes were sold in Medellín between 2004 and 2008, -www.publimotos.com/informes.html-). The motorcycles used are shown in table 2.

Table 2 Motorcycles used for experiments

Model	*Age*	*Motor size*
Motorcycle 1	1 year (New)	125 cc (Big motor size)
Motorcycle 2	3 years (New)	100 cc (Small motor size)
Motorcycle 3	5 years (Old)	125 cc (Big motor size)
Motorcycle 4	13 years (Old)	100 cc (Small motor size)

Data acquisition

The following devices were used for data acquisition: Quest VI-410 Advanced Analyzer with seat pad tri-axial accelerometer (sensitivity 100mV/g) for human exposure to WBV. Frequency range 0.5 Hz – 20 kHz. RMS, VDV and 1/1 and 1/3 Octave-Band analysis. W_d and W_k filters (ISO 2631). In figure 1 is possible to see the installation of the accelerometer on the motorcycle.

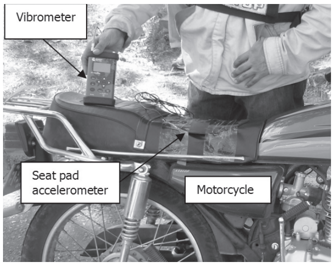


Figure 1 Seat pad accelerometer on the motorcycle.

Results and discussion

Acceleration records were acquired using the equipment described previously. The Exposure time limits (EAV and ELV) are readily obtained for each experiment.

Table 3 shows the nomenclature used for the experiments and table 4 shows the frequency-weighted acceleration (a_v) and the averaged values of EAV and ELV for each experiment. Consider, for example, the first experiment in table 4. The experiment is tagged NBHS which, according to table 4, means New motorcycle, Big engine, High rider weight and Slow road. In this experiment, the EAV was 1.9 hours and the ELV was 10.2 hours. An individual subjected to this type of vibration should take some action after 1.9 hours of riding, and should not exceed the 8 hour limit (although the ELV calculated was 10.2 hours). It is clear that in this case, the overall weighted RMS acceleration has to be between TAV (0.5 m/s^2) and TLV (1.15 m/s^2), and as seen in the table 4, a_v.=1.02 m/s^2.

Table 3 Nomenclature used for the experiments

Experiments nomenclature	
Age (N=0, O=1)	N(New <= 3 years) - O (Old >3 years)
Motor size (B=0, S=1)	B (Big = 125 cc) - S (Small =100 cc)
Driver weight (H=0, L=1)	H (High >= 70 kgf.) - L (Low< 70 kgf.)
Road type (f=1, s=0)	F (fast road) – S (slow road)
Example: NBHS	New, big motor size, high weight, slow road.

Table 4 Frequency weighted acceleration, averaged EAV and ELV for each experiment

Frequency-weighted RMS acceleration [m/s²] ***EAV*** ***ELV***				***Max Value [m/s²]***	***Exposure time***	
					EAV	***ELV***
Experiment	***1.4 ax***	***1.4 ay***	***az***	***av***	***[hours]***	
NBHS	0.75	0.30	1.02	1.02	1.9	10.2
NBHF	0.40	0.21	0.80	0.80	3.1	16.5
NBLS	0.76	0.32	1.09	1.09	1.7	8.9
NBLF	0.53	0.26	0.83	0.83	2.9	15.4
NSHS	0.61	0.27	1.24	1.24	1.3	6.9
NSHF	0.42	0.21	1.08	1.08	1.7	9.1
NSLS	0.69	0.38	1.09	1.09	1.7	8.9
NSLF	0.55	0.24	0.89	0.89	2.5	13.4
OBHS	0.56	0.16	1.31	1.31	1.2	6.2
OBHF	0.42	0.17	0.92	0.92	2.4	12.5
OBLS	0.60	0.33	1.30	1.30	1.2	6.3
OBLF	0.48	0.26	1.18	1.18	1.4	7.6
OSHS	0.51	0.15	1.19	1.19	1.4	7.5
OSHF	0.44	0.16	1.17	1.17	1.5	7.7
OSLS	0.76	0.40	1.33	1.33	1.1	6.0

Frequency-weighted RMS acceleration [m/s²] EAV ELV				Max Value [m/s²]	Exposure time	
					EAV	ELV
Experiment	1.4 ax	1.4 ay	az	av	[hours]	
OSLF	0.64	0.34	1.15	1.15	1.5	8.0
NBHS	0.74	0.26	1.09	1.09	1.7	8.9
NBHF	0.41	0.25	0.86	0.86	2.7	14.3
NBLS	0.68	0.34	1.04	1.04	1.8	9.8
NBLF	0.56	0.23	0.91	0.91	2.4	12.8
NSHS	0.57	0.25	1.23	1.23	1.3	7.0
NSHF	0.44	0.23	1.11	1.11	1.6	8.6
NSLS	0.75	0.43	1.15	1.15	1.5	8.0
NSLF	0.58	0.31	0.88	0.88	2.6	13.7
OBHS	0.62	0.16	1.37	1.37	1.1	5.6
OBHF	0.42	0.13	0.97	0.97	2.1	11.2
OBLS	0.54	0.32	1.17	1.17	1.5	7.7
OBLF	0.47	0.20	1.05	1.05	1.8	9.6
OSHS	0.50	0.19	1.24	1.24	1.3	6.9
OSHF	0.42	0.16	1.18	1.18	1.4	7.6
OSLS	0.77	0.43	1.24	1.24	1.3	6.9
OSLF	0.53	0.27	1.16	1.16	1.5	7.9

The analysis of variance decomposes the variability of EAV into contributions due to each factor, having removed the effects of all others. The ANOVA table shows the results of the statistical tests conducted to determine which factors have a statistically significant effect on EAV. Table 5 shows the results for the experiments. The F-test is used to identify the significant factors [18], and since three P-values are lower than 0.05, they have a statistically significant effect on EAV at 95% confidence level.

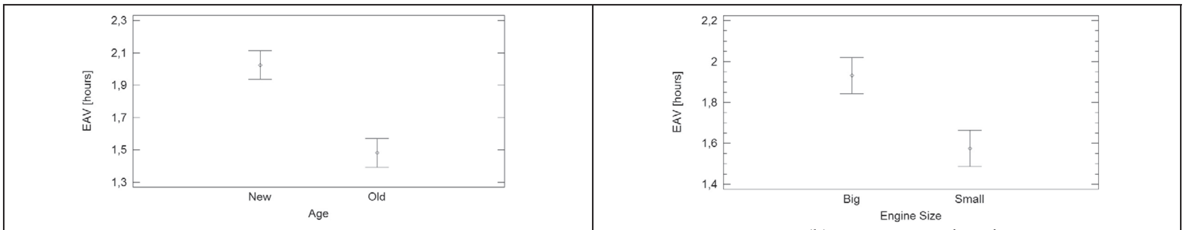
Table 5 Analysis of Variance for EAV - Type III Sums of Squares

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Main effects					
A:Age	2.38	1	2.38	45.41	0.0000
B:Eng size	0.95	1	0.95	18.15	0.0003
C:Road	3.35	1	3.35	63.94	0.0000

Source	*Sum of Squares*	*Df*	*Mean Square*	*F-Ratio*	*P-Value*
D:Weight	0.02	1	0.02	0.41	0.5280
Interactions					
AB	0.17	1	0.17	3.28	0.0845
AC	0.30	1	0.30	5.80	0.0253
AD	0.25	1	0.25	4.86	0.0388
BC	0.41	1	0.41	7.88	0.0106
BD	0.36	1	0.36	6.96	0.0154
CD	0.01	1	0.01	0.25	0.6244
Residual	1.10	21	0.05		
Total (corrected)	9.33	31			

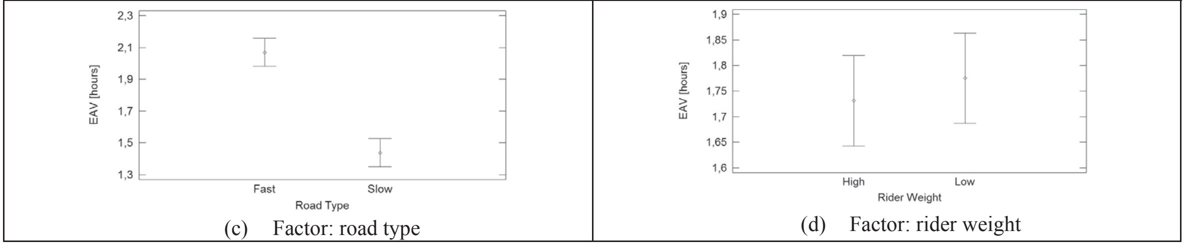
The first, second and third factors had significant influence on EAV. The ANOVA results show some interaction between factors. Presence of interaction means that the difference in response between the levels of one factor is not the same at all levels of other factors. It is necessary to check the interaction plot to understand the interacting factors behaviour.

Figure 2 shows the mean values of EAV for each factor at the 95% confidence level. EAV is higher for newer motorcycles, fast roads and big engine size. The driver weight doesn't have a significant effect on EAV. This figure is very useful because it provides the reference values for recommended exposure times. From the figure, one may conclude, for example, that a new motorcycle can be ridden about 2.02 hours per day before reaching the EAV while an old motorcycle only can be ridden about 1.48 hours. In the same way, it is possible to ride about 2.06 hours on fast roads while only about 1.43 hours in slow roads.



(a) Factor: Motorcycle age

(b) Factor: engine size

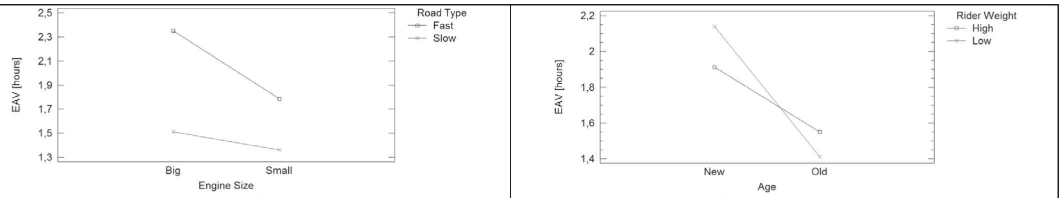


(c) Factor: road type

(d) Factor: rider weight

Figure 2 EAV behaviour with factors: (a) Motorcycle age, (b) engine size, (c) road type and (d) rider weight

The interaction plot must be analyzed to support the comparison between the main effects. Otherwise, misleading conclusions may be drawn. For example, Figure 3a shows that EAV variations due to “engine size” are larger when the road is “fast route” type. As another example consider Figure 3b. The plot shows that EAV variations due to “motorcycle age” are larger when “rider weight” is lower than 686 N.



(a) Road type and engine size

(b) Road type and driver weight

Figure 3 Interaction plot: (a) Road type and engine size. (b) Motorcycle age and rider weight

Data from table 4 can be processed by multiple regressions to obtain a mathematical expression that helps obtain the estimated EAV and ELV for different combinations of parameters: motorcycle age, engine size, road type and rider weight. The regressions we obtained are written in equation 6 and equation 7. For example, to estimate the EAV and ELV for case NBHS (New motorcycle, Big engine size, High rider weight, Slow road) one has to plug in the following values in equations 6 and 7: Age=0, Cylvol=0, Weight=0 and Road=0 according to the values and levels defined in table 3. The results are EAV=1.86 hours and ELV= 9.9 hours (for convention, the maximum ELV value for reporting is 8 hours), which are very similar to the measured values shown in table 4 (EAV=1.9 hours and ELV= 10.2 hours). These results derived from multiple regressions are only valid when applied to the type of experiments from which they were obtained.

$$\text{EAV} = 1.86 - 0.54 \cdot \text{Age} - 0.35 \cdot \text{Cylvol} + 0.63 \cdot \text{Road} + 0.04 \cdot \text{Weight} \quad R_2 = 71\% \tag{6}$$

$$\text{ELV} = 9.90 - 2.93 \cdot \text{Age} - 1.87 \cdot \text{Cylvol} + 3.37 \cdot \text{Road} + 0.22 \cdot \text{Weight} \quad R_2 = 71\% \tag{7}$$

The correlation coefficients in these regressions are low due to transient and non linear processes which occur during vehicle transportation, and due to the strong interactions between different factors. A better approach would be to use artificial neural networks (ANN) instead of multiple regressions.

Neural networks are models inspired by biological neurons and the nervous system. Large number of interconnected processing elements (neurons), working as “weighted regression coefficients”, try to learn by example for solving specific problems. The ANN structure usually has one input layer, some hidden layers and one output layer. Neurons located in hidden layer sum the weighted inputs and apply the specific activation function f(∑) (linear, sigmoid, step, Gaussian, etc.).

Data samples must be selected, from suitable examples, so that ANN can learn the process and be trained in this manner. During training, inputs and target outputs are set, and the weights and bias values are adjusted (in ways that depend on the training method) in several iterations.

The results show that, using part of the data from table 4 for estimating EAV and ELV, Neural Networks had higher correlation than multiple regressions. A two layer feed-forward network with 20 sigmoid hidden neurons and linear output neurons was trained with Levenberg-Marquardt back-propagation algorithm, using 32 samples from table 4, 22 samples for training, 5 samples for validating, and 5 for testing. Table 6 shows the correlation R^2 for EAV and ELV estimations obtained using the ANN described in this paragraph.

Table 6 Neural networks results

Results	*Samples*	*R^2 EAV*	*R^2 ELV*
Training	22	99.1	97.8
Validation	5	93.9	99.3
Test	5	95.7	94.9

Sample size and experimental replicates required were calculated using the type II error probability of a statistical test (previous variance was available) [18]. Two replicates of all possible combinations were enough in this case. Neural networks show significant improvement over linear regression because the ability to handle complex data sets with many inputs and few data points [19].

Conclusions

Multifactor experimental design has been proven useful to analyse the main effects of factors such as motorcycle age, engine size, road type and driver weight on EAV. Experiments conducted in Medellin have been performed to determine the statistical significance of each factor. The results were used to evaluate the main effects in the factorial experiments and to estimate the exposure time action value for all possible combination of factors. This is a valuable and novel contribution since EAV and ELV can now be estimated using the results in this paper without the need of specific measurements for the case under consideration. The estimation can be achieved by means of multiple regressions or by neural networks. Multiple regressions are easier to calculate but yields lower correlation factor.

The motorcycle condition severely affects the exposure action time and exposure limit time for WBV. The most unfavourable combination of factors is the following: old motorcycle, small engine, and slow road. In this case, EAV=1.1 hours and ELV = 6.0 hours. However, the lesser EAV and ELV reported in table 4 are EAV=1.1 hours and ELV= 5.6 hours for the case OBHS. This is possible because the interaction between engine size and rider weight was reported in table 5.

On the other hand, the most favourable combination of factors is: new motorcycle, big engine, and fast road. In this case, EAV =3.1 hours and ELV=16.5 hours.

EAV is higher for newer motorcycles, fast roads and large engine size. Newer motorcycles allow 36.3% more riding time than older motorcycles before the EAV is reached. Motorcycles with larger engine size (125cc) allow 22.5% more riding time than motorcycles with smaller engine size. It is possible to ride 44% longer using fast roads than slow roads. In terms of acceleration, old motorcycles, with small engines and using slow roads, expose the rider to higher vibration.

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