TITLE: A methodology for assessment of long-term exposure to whole-body vibrations in vehicle drivers to propose preventive safety measures.

Abstract

Introduction: The appearance of musculoskeletal disorders (MDs) in professional drivers due to exposition to whole-body vibration (WBV) makes it relevant to assess this exposure. The European Directive 2002/44/EC establishes two methods for evaluating exposure to WBV (defined in ISO2631-1:2008). These methods evaluate the exposure associated with an 8-hour working day; however, MDs due to WBV could also be caused by accumulated exposure to vibrations over longer times, and so the methods defined in the European directive may be limited in their ability to ensure the safety of workers exposed to WBV in all years of employment. *Method:* A detailed comparison and discussion of methods defined in the European Directive and the ISO2631-5:2018 was used as a starting point of the main results of this paper. On this basis a new methodology for the management and organization of preventive measures is proposed to take into account the assessment of ISO2631-5:2018 standard and the full working life of workers. Experimental data to assess exposure to WBV in heavy equipment vehicle (HEV) drivers in different road surface conditions and range of velocities were considered to illustrate the process of the proposed methodology. *Results:* The methods defined in the standards provide different assessments leading to a different possible consideration of safe operations, when the risks associated with them may actually be high. The proposed methodology can be used with the aim of ensuring safety of workers throughout their working lives and providing an easy implementation of the calculations of ISO2631-5:2018 standard. *Conclusions:* A procedure to assess the health risk probability to which the HEV worker is exposed in terms of the exposure years and a different range of operational vehicle speeds is proposed and exemplified with a study case. *Practical applications:* This study provides a practical tool for management of WBV exposure related to work-tasks in HEV drivers. Safety managers should consider the global exposition to WBV throughout their working life and this research provides an easy tool to accomplish it.

Keywords: whole-body vibrations; ISO2631-5; vibration assessment; safety interventions; heavy equipment vehicles

1. Introduction

European workers reported that musculoskeletal disorders (MDs) are one of the main causes of work-related ill-health (Nielsen, Jørgensen, & Malgorzata Milczarek, 2018); and construction, agriculture, and transportation are among the industries with higher rates of MDs. For this reason, it is important to have health and safety requirements and strategies to limit, assess, and control specific risks associated with the appearance of MDs (Spielholz et al., 2008; Yazdani et al., 2018). There is epidemiological evidence that relates whole-body vibration (WBV) to MDs, such as low back pain (Bovenzi & Betta, 1994; Punnett & Wegman, 2004; Raffler et al., 2017), degenerative changes in the lumbar spine (Miyamoto, Shirai, Nakayama, Gembun, & Kaneda, 2000; Wilder et al., 1996), sciatica (Burström, Nilsson, & Wahlström, 2015), neck pain (Kim, Dennerlein, & Johnson, 2018; Milosavljevic, Bagheri, Vasiljev, Mcbride, & Rehn, 2011; Rehn, Nilsson, Lundström, Hagberg, & Burström, 2009), and disorders such as motor performance (Costa, Arezes, & Melo, 2014). In this sense, and within MDs, spine disorder is the most frequently reported group of diseases among workers in the construction industry (Bakusic et al., 2018; Health and Safety Executive, 2018). The most important single risk factor associated with low back pain was the amount of lumbar disc degeneration (Livshits et al., 2011), with overweight and obesity increasing the risk of appearance (Liuke et al., 2005; Shiri, Karppinen, Leino-Arjas, Solovieva, & Viikari-Juntura, 2009). Among individuals affected by low back pain, between 5.0% and 10.0% will develop a chronic pain problem, the prevalence of which increases linearly from 30 until 60 years (Meucci, Fassa, & Faria, 2015). These occupational diseases have a great impact on individuals and social care systems, as well as high treatment costs and sick absence (Woolf & Pfleger, 2003).

Professional drivers of heavy equipment vehicles (HEVs) are often exposed to WBV and mechanical shocks (Kittusamy & Buchholz, 2004; Johnson, Dennerlein, Ramirez, Arias, & Rodríguez, 2015; de la Hoz-Torres, López-Alonso, Ruiz & Martínez-Aires, 2017). In fact, their work tasks can be lead to WBV exposures among HEV operators (Blood, Rynell, & Johnson, 2012). A large number of the activities performed with HEVs are carried out on uneven surfaces, which are more likely to produce high levels of WBV and mechanical shocks as compared to activities performed on even surfaces (Kumar et al., 1999; Griffin et al., 2008; Milosavljevic, Bergman, Rehn, & Carman, 2010). Previous research has shown that the type of operation and ride conditions significantly affect the compressive stress on lumbar spine response (Singh et al., 2019). In addition, the type of seat suspension (active or passive) and seat suspension maintenance (Rahimdel & Mirzaei, 2020) significantly reduce WBV exposures. Since long periods of exposure to WBV can lead to health problems for drivers (Milosavljevic et al., 2010; Smets, Eger, & Grenier, 2010; Kia et al., 2020), in this research we focus specifically on this sector, with the aim of proposing a methodology that provides information on the risk of adverse health effects to the vertebral end-plates of the lumbar spine for seated individuals due to compression. Our procedure is based on the long-term exposition of workers to WBV and the analysis of the current standards. The proposed methodology, combined with medical, imaging, and biomechanical evaluation and health surveillance, has the potential to be a key tool to prevent possible negative effects on health.

On the basis of the above initial hypothesis, currently the most accepted and used method for assessing WBV exposure is that defined in ISO2631-1:2008. The methods defined in this standard are used to evaluate exposures in an 8-hour working day. However, the basic assessment method defined in this standard is only suitable for describing the severity of vibrations, in relation to their effects on human beings, for exposures with peak factors of the measured signal less than or equal to 9. In other cases, when the basic assessment method may underestimate the effect of vibrations, the standard refers to the use of a method based on the concept of vibration dose value (VDV).

Recently, ISO2631-5:2018 was published as a result of the revision of the previous standard (ISO 2631-5:2004). The new ISO2631-5:2018 standard defines two different methods in terms of the exposure regime (severe exposure regime and less severe exposure regime) and they assess the risk of chronic injury from exposure to repeated shock based on the predicted biomechanical response of the bony vertebral endplate (hard tissue). Now, the methods for calculating the acceleration transmitted to the spinal column is by means of a transfer function of a biomechanical model. Unlike the previous standard, neither method is limited by the signal crest factor. However, the limits in this new revised standard ISO2631-5:2018 remain unchanged compared to ISO2631-5:2004, although Eger et al. (2008) reported that the limits established in the Standard ISO2631-5:2004 may be set possibly too high. Previous research has also concluded that evaluation of the relationship between ISO 2631-1 and ISO 2631-5 parameters deserves further investigation (Blood et al., 2012; De la Hoz-Torres, Aguilar-Aguilera, Martínez-Aires & Ruiz, 2019).

In summary, there are two relevant standards, ISO2631-1:2008 and ISO2631-5:2018 for the problem addressed in this research. Both are important for evaluating the operation performances with HEVs, since these activities may expose drivers to WBV with a high amount of mechanical shocks. Although there are clear differences between the two standards, given the short lapse of time since the publication of ISO 2631-5:2018, very little research has been published related to it and there is a lack of information on how and when to use them and their feasibility.

This research has been undertaken to make a more comprehensive comparison of the evaluation methods described in ISO2631-1:2008 and ISO 2631-5:2018 in the context of HEV drivers, given their relevance. Based on this comparison, we propose a new a methodology for the management of WBV exposure in vehicle drivers (or other workers also exposed to WBV), with the aim of improving their quality of life both throughout their working lives and in their retirement. The methodology is then implemented in an illustrative case study to show and illustrate how the application of the proposed steps can be done in an experimental setup and a real case. The results for this illustrative case should not be automatically extended to other cases, since each driving activity must be analyzed on a case-by-case basis with the application of the proposed scheme. To achieve this objective, a collection of real data from a set-up field experiment (case study) was performed taking into account a typical variability in speed and surface conditions for HEV drivers. From this experiment, a total of 94 measured data sets were analyzed and then evaluated according to the standards. On the one hand, this data analysis allowed us to draw conclusions on the effect on the WBV magnitude calculation and the possible exceeding of the standard limits of both the different surface categories (e.g., on tarmac road), and vehicle speed. On the other hand, the data sets were also used to investigate the evolution of the risk factor over time, derived from cumulative exposure to WBV. From the analysis of this behavior, the proposed methodology allows us to manage WBV exposure for HEV drivers to keep them safe in a quick and easy way. In this context, it is worth noting that processes shown in this paper could be an essential tool to support many at-risk workers for those safety and health professionals who do not have a deep knowledge of WBV (Paschold & Sergeev, 2009).

The article is structured as follows:

- Section 2: preliminary concepts, definitions, and data processing techniques used in this research are featured. Thus, in this section the assessment parameters established by the ISO 2631-1 and ISO 2631-5:2018 standards are also reviewed, as well as the standardized limits to an 8-hour exposure reference period and the boundaries for the emergence of probable health effects derived from multiple shocks vibration exposure coming from the ISO 2631-5:2018. In addition, the data processing clustering method used as part of the proposed methodology is outlined in this section.
- Section 3: proposal of a methodology for health risk prediction assessment, a method is proposed to quickly assess the health risk probability to which the HEV worker is exposed in terms of the exposure years and a different range of speeds, taking into account the entire working life of the driver.
- Section 4: implementation of the proposed methodology to a HEV driver case, the overall process of the implementation of the proposed methodology is illustrated on the basis of a real case, from data collection to health risk prediction assessment.
- Section 5: conclusions, the main findings, conclusions and practical applications of this research are drawn.

2. Preliminary concepts, definitions, and data processing techniques

2.1. Whole-body vibration assessment

As noted in the introduction, ISO 2631-1 and ISO 2631-5 standards define methods of risk quantification. They used the recorded and measured acceleration on the seat surface to calculate the WBV exposure parameters. The procedure used in both ISO standards is summarized below:

2.1.1. ISO 2631-1:2008 parameters

This standard is based on the calculation of the root mean square (rms_w) of the weighted averaged acceleration (m/s^2) and the vibration dose value (vdv_w).

For calculating the first parameter, Butterworth filters are used to weight the acceleration in frequency according to the ISO 2631-1 standard. The x- and y-axes are weighted using weights denoted as W_d, and for the z-axis using W_k. The root mean square (rms_w) of the weighted averaged acceleration (m/s^2) is then calculated as the second power of the acceleration time history as the basis for the averaging process (Equation 1):

$$rms_w = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{\frac{1}{2}} \quad (1)$$

where a_w is the frequency-weighted instantaneous acceleration (W_d on x and y axes, W_k on z axis), and T is the time duration of the measurement.

The vibration dose value (vdv_w) is calculated as the fourth power of the acceleration time history (Equation 2), so this parameter is more sensitive to peaks than the rms_w:

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

In order to allow comparisons between different exposures, these parameters are normalized to reflect 4 hours of exposure to WBV for an 8-hour work cycle. The daily exposure value ($A(8)$)

(Equation 3) and the vibration dose value method (VDV) for each axis (Equation 4) are then calculated as follow:

$$A(8) = k\ rms_w \sqrt{\frac{T_{exp}}{T_0}} \tag{3}$$

$$VDV = k\ vdv_w \sqrt{\frac{T_{exp}}{T_{meas}}} \tag{4}$$

where k denotes the multiplication factor defined for each axis ($k_{x,y} = 1.4$ and $k_z = 1$), T_{exp} is the measurement period, T_0 is the reference duration of eight hours and T_{meas} is the daily duration of exposure to the vibrations. The calculated values can then be compared with the daily exposure action value ($A(8) = 0.50\ m/s^2$ and $VDV = 9.10\ m/s^{1.75}$) and the daily exposure limit ($A(8) = 1.15\ m/s^2$ and $VDV = 21.00 m/s^{1.75}$) established by the EU directive (Directive 2002/44/EC).

2.1.2. ISO 2631-5:2018 parameters

Unlike the basic evaluation method described in ISO 2631-1, this standard defines two assessment methods based on different exposure regime conditions. This research implements the method that addresses what the standard calls 'less severe conditions' since the exposures do not contain free-fall events.

As established by the standard, the analysis should be accomplished assuming the most unfavorable exposure conditions, taking into account the exposure time periods (hours per day, and days per year) and the life-time exposure history. Also, the Posture Group and the anthropometric characteristics of the drivers are used as input of the model. The intervertebral compressive forces and the daily compressive dose for the six disc levels of the lumbar spine (T12/L1, L1/L2, L2/L3, L3/L4, L4/L5 and L5/S1) were calculated as follows (Equation 5).

$$S^A = \left(\sum_i \left(\frac{c_{dyn,i}}{B}\right)^6\right)^{\frac{1}{6}} \tag{5}$$

where $c_{dyn,i}$ (N) stands for the sum of peak compressive forces acting on the vertebral endplate and B (mm^2) is the area of the vertebral endplate. The equivalent daily compressive dose is calculated considering the total duration of the exposure during a day (Equation 6).

$$S_d^A = \left(\sum_j S_j^{A6} \frac{t_{dj}}{t_{mj}}\right)^{\frac{1}{6}} \quad (6)$$

where S_j^A is the dynamic compressive stress of the lumbar spine due to vibration exposure, t_{dj} is the time period of the daily vibration exposure and t_{mj} is the time period over which S_j^A has been measured. The Risk Factor R^A is estimated at each vertebral level based on the S_d^A:

$$R^A = \left(\sum_{m=1}^{n} \left(\frac{S_d^A \, N m^{\frac{1}{6}}}{S_{ui}^A - S_{stat,i}^A}\right)^6\right)^{\frac{1}{6}} \quad (7)$$

$$S_{stat,i}^A = 6.765\ MPa - 0.067 MPA\ (b + i) \quad (8)$$

where N is the number of exposure days per years, n the number of years of exposure, S_{ui}^A is the ultimate strength of the lumbar spine for a person of age *(b+i)* years and $S_{stat,i}^A$ is the mean value of the compressive-decompressive force divided by the area of vertebra endplate.

2.1.3. Health guidance caution zone (HGCZ)

The European Directive 2002/44/EC specifies that the methods for assessing WBV exposure are those defined in ISO 2631-1 and it determines standardized limits to an 8-hour exposure reference period. In addition, ISO 2631-5:2018 defines boundaries for the emergence of probable health effects derived from multiple shocks vibration exposure (Table 1):

Table 1: Health guidance caution zone.

Directive 2002/44/EC	ISO 2631-5:2018
Exposure limit values and action values	Probability of an adverse health effect

Exposure Action Value (EAV)	$A(8) = 0.50\ \frac{m}{s^2}$	$VDV = 9.1\frac{m}{s^4}$	Low	$S_d^A < 0.5\ MPa$	$R^A < 0.8$
			Moderate	$S_d^A > 0.5\ MPa$	$R^A > 0.8$
				$S_d^A < 0.8\ MPa$	$R^A < 1.2$
Exposure Limits Value (ELV)	$A(8) = 1.15\ \frac{m}{s^2}$	$VDV = 21.0\frac{m}{s^4}$	High	$S_d^A > 0.8\ MPa$	$R^A > 1.2$

2.2. Data processing clustering method: unsupervised clustering

To obtain a grouping of the daily compressive dose to test the appearance of differences between different groups based on the mean velocity, a clustering process is performed as part of the proposed methodology. In our study, we have used the k-means++ algorithm, a variant of the original k-means algorithm. It is an unsupervised classification algorithm (Arthur & Vassilvitskii, 2007) in which the grouping is done by minimizing the sum of distances between each object to the centroid of its group or cluster. Given an initial number of data, the algorithm follows the following steps: (1) select an initial center using a uniform random variable. This first centroid is called c1; (2) calculate the distances for each point x to the centroid cj. The distance between the observation m and the centroid cj is denoted as D(Xm,C1)/D(x); (3) Select the next centroid (uniform random variable) cj, with the probability (Equation 9) [using a weighted probability distribution where a point x is chosen with the probability proportional to $D(x)^2$]:

$$\frac{d^2(x_m, c_1)}{\sum_{j=1}^{n} d^2(x_j, c_1)} \quad (9)$$

(4) Repeat step 2 and 3 until the centroids k are chosen.

In the next steps, the algorithm proceeds as in the original *k-means* algorithm, i.e.: (5) for each $i \in (1, \ldots k)$, sets the C_i cluster as the set of points in X that are closer to ci than to *cj* for all *j* other than i; (6) for each $i \in (1, \ldots k)$, sets ci as the center of mass of all points in C_i: $c_i=1|C_i|\sum x \in C_i x$; and finally (7) repeat steps 5 to 6 until there are no changes in the cluster assignment, or until the maximum number of iterations is reached.

To select the optimal number of clusters, in this work the Elbow and GAP methods (Tibshirani, Walther, & Hastie, 2001) have been used. The GAP method is based on comparing the intra-grouping dispersion with the expected one under a uniform distribution of points that plays the role of the null hypothesis. The number of groups that maximizes that difference is the optimal number of clusters.

The elbow method is based on minimizing the intra cluster variation (within-cluster sum of squares). Thus, it compares the within-clusters sum of squares with its expectation under a reference null distribution. In this method, the value of the so-called Elbow index decreases as the number of clusters increases. In this case the 'elbow' point on the graph becomes the optimal number of clusters, since the slope value on the graph is no longer important.

3. Methodology for health risk prediction assessment of human exposure to long-term whole-body vibration

The proposed methodology is based on ISO 2631-5:2018 standard and it assesses the impact of long-term exposure to WBV, unlike the methods used for the assessment of WBV in the Directive 2002/44/EC for evaluation of vibration exposure (based on A(8) and VDV parameters), which only assess the exposure associated with an 8-hour working day.

The methodology is articulated in six steps and they are summarized in Fig. 1. This procedure is a generalization of the process followed in this research, from data acquisition to risk factor evolution modelling. The key point is the generation of a color map of the Risk Factor evolution for each HEV and activity. Note that the strength of the proposed methodology is to ensure that vibration exposure is managed over the years so that the probability of occurrence of an adverse health effect remains low. Despite the initial effort required to implement the proposed methodology, the results obtained make it possible to guarantee the safety of the worker throughout their working life.

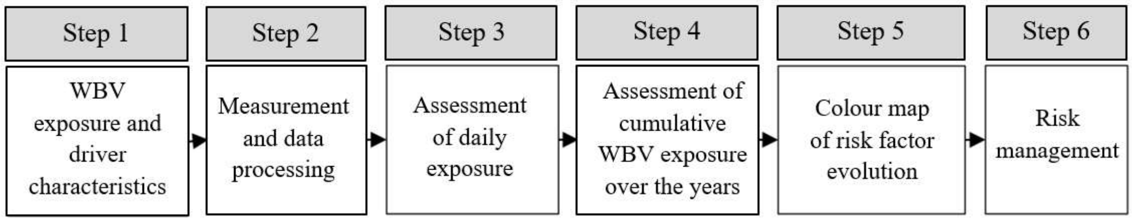

Fig. 1. Diagram of the proposed methodology.

Step 1. WBV exposure and drivers characteristics. In the initial step, data are collected from three different categories. Category I: the characteristics of the activity (surface, velocity and performance characteristics); Category II: the characteristics of WBV exposure (if the exposure contains multiple shock and duration); Category III: driver characteristics (age, height, weight and posture). The information collected during the initial phase of the process will be used as input of the methodology. The analysis of these data is used to define a measurement strategy in order to ensure that the WBV exposure is measured in representative situations. In addition to the measurement strategic requirements stated in ISO2631-1 and ISO2631-5, additional standards could be taken into account in the design of the experimental set up.

Step 2. Measurement and data processing. From the data obtained in the previous step, the measurement strategy has to be established. The speed of the vehicle and the acceleration at the interface between the seat and the driver must be measured. The number and duration of the measurement shall be sufficient to ensure that measured results are representative of the exposure.

Based on the data obtained in the measurement process, the parameters defined in ISO 2631-5 (S_d^A) and ISO 2631-1 (A8 and VDV) must be estimated. The daily compressive dose (S_d^A) (most unfavorable vertebra) and the average velocity must be used as input variables in a cluster data process. The objective is to obtain a grouping of the daily compressive dose to test the appearance of differences between different groups based on the mean velocity. The k-means++ algorithm is used in this process.

Step 3. Assessment of daily exposure. The parameter A8, VDV and S_d^A estimated in step 2 must be used to assess the daily exposure. For this purpose, these values have to be compare with the HGCZ values (Table 1). If the exposure exceeds the ELV or EAV or the probability of an adverse health effect is high, measures must be taken to limit exposure of drivers in order to ensure his safety.

Step 4. Assessment of cumulative WBV exposure over the years. For the data set of each cluster (estimated in step 2), the average value S_d^A must been calculated for the vertebral levels. From the value obtained for the most unfavorable level of vertebra, the probability of occurrence of an adverse health effect (R^A) is estimated. The evolution of the R^A parameter over the years is calculated considering the exposure lasts from the age of 20 to 70 years and the foreseen days of exposure per year (e.g., 240 days per years if a full working life with a typical length of the working day in this sector is considered). The values obtained have to be compared with the HGCZ values (Table 1) to assess the exposure over the years. In order to model the cumulative effect of WBV with the parameter R^A, the data obtained for each cluster must be fitted using polynomial fitting function. The parameterization of data allows the health risk probability to which the worker is exposed in any year to be determined, from a data set measured under specific velocity and surface conditions.

Step 5. Color map of risk factor evolution. Specifically the proposed method relies on the model the cumulative effect of WBV with the parameter R^A. Based on the data obtained, a bidimensional surface-type fitting must be carried out using a polynomial surface model, where the x-axis is the age of the worker and the y-axis represents the average speed at which the activity is performed.

Step 6. Risk management. The color map obtained in Step 5 can be used to manage WBV exposure. The safety manager can use it to perform an assessment of the long term cumulative WBV exposure. Based on the characteristics and speed at which the activity is performed, the safety manager can assess if the worker will reach a high probability of an adverse health effect (limit define in ISO2631-5:2018, Table 1) throughout his working life. In addition, the color map can be used by drivers as an information and training tool. It provides information that can be used to raise awareness of the importance of the performance characteristics of the activity and the impact of long-term WBV exposure.

This methodology can be applied to any activities carried out under less severe WBV exposure conditions such as those listed in Article 4(b) of ISO 2631-5:2018. HEVs are used in these types of activities, such as driving with tractors, forestry machines and mobile earth-moving machinery over rough surfaces (off-road, potholes, frequent crossing of railroad tracks, etc.). Given that the ride condition (i.e., surface condition and forward speed), type of operation and the use of machinery significantly affect the S_d^A value, therefore, the proposed methodology have to be applied on a specific case-by-case basis. In addition, as the type of crop may influence the operation performance and each country has set specific limits to WBV exposure, all these aspects have to be also considered when applying this methodology and the resulting risk management. The following section shows how to apply the proposed methodology to a given case, from the data collection step to the risk factor evolution and management.

4. Implementation of the proposed methodology to a HEV driver case

In order to illustrate the application of the proposed methodology, in this section the preceding proposed process steps are applied to a real study case to generate the color map for risk assessment as the final goal, according to the procedure proposed in Section 3.

4.1. Whole-body vibration and driver's characteristics. Step 1

4.1.1. Experimental set-up

An experimental data measuring campaign was designed with the aim of assessing the exposure to WBV in HEV drivers as a case study to test the implementation of the ISO standards and the proposed methodology. The magnitude to be measured was the acceleration at the interface between the seat pad and the ischial tuberosities. The experimental design included a monitoring of the exposure to WBV in a standardized test route comprising a variety of representative real surface conditions for HEV displacement. Previous studies analyzing the transmission of vibrations through the seat in agricultural tractors have considered different types of surfaces, such as tarmac and rough track (Adam & Jalil, 2017; Giordano, Facchinetti, & Pessina, 2015). In this case, the path and length of the routes were established to include the possibility of obtaining vibration data sets corresponding to different speeds representative of typical surface conditions found in HEV drivers (i.e.. the route included 1 km of off-road, 4 km of unpaved road and 5 km of tarmac road). The test locations were specifically chosen for two main reasons: (1) low traffic disturbance (to achieve a stable environment during the test and to minimize interference due to external interruptions); and (2) diversity and representativeness of the sample of road surfaces.

The same route was also used to evaluate the vibrations transmitted by the vehicle to the driver at a wide range of velocities. In this case, speed was monitored by a Global Positioning System (GPS) attached to the vehicle. The lowest speed value (5 km/h) was chosen in order to be able to reproduce realistic travel conditions with the usual lower speed. The highest speed value (25 km/h) was chosen because it is the maximum speed limit (HEV speed regulation). The vehicle used throughout the entire study was a tractor classified as Class II Category A according to the Directive 78/764/EEC (1978). As there are large variations in the magnitude of vibration depending on the type of vehicle (Paddan & Griffin, 2002), all measurements were performed with the same tractor to eliminate this variation, since the aim of this study case was to test the use of the standards to propose a methodology for exposure assessment.

The duration of the measurements was selected to provide enough data to be representative of the exposure in different conditions (surface and displacement velocity). The displacement through unpaved roads and tarmac roads are recurring tasks, therefore performing several subsequent measurements observing a minimum measurement time at an average speed (with a maximum speed dispersion of 5 km/h) is enough to ensure that the result is representative of driver exposure. However, off-road travelling is a non-repetitive task, so the terrain was studied and characterized in a first approach and successive measurements of sufficient duration were performed.

With regard to the driver, a healthy male adult was chosen to participate in this field study. The reasons for this option are mainly as follow: he fulfilled having more than 20 years of driving experience (HEV including trucks and agricultural tractors) without current pain and history of MDs; he was 48 years old and his height and weight were 1.85 m and 120 kg, respectively, with a body mass index of 35.06 kg/m^2. This high body mass index (>35 kg/m^2) indicates that this person suffers from obesity, and since body weight is related to spinal loading, this factor increases the risk of low back pain and lumbar disc degeneration (Liuke et al., 2005). Therefore, the subject belongs to a high-risk group for the development of MDs. Since the driver belongs to a high-risk group, a comparison of assessment methods in humans who may be at higher risk is of particular interest. It is worth noting that a high BMI (body mass index) within the highest body mass percentile range (BMI > 26,1 Kg/m^2 and 95th percentile, i.e. a body mass larger than 109 Kg), are those values defined in ISO 2631-5:2018 Annex A.3 that they maximize the spinal load, so it is an interesting study case for its specific characteristics. As regards posture groups classified in Annex A of ISO 2631-5, the driver's posture was the posture group number 3. Posture group 3 and the anthropometric characteristics of the driver were used as input of the model. As with the vehicle selection, all the measurements were performed by the same subject in order to eliminate the uncertainty associated with variables linked to the anthropometric characteristics of the operator.

4.1.2. Measurement equipment

A tri-axial accelerometer (SV38, SVANTEK) was used to measure the acceleration transmitted to the seat pad. The instrument enables the sampling of the experimental acceleration with a frequency of 6000 Hz in each direction: fore-to-aft (x axis), left-to-right (y axis) and buttocks-to-head (z axis). Raw unweighted acceleration signal was recorded and stored in a data logger (SV106, SVANTEK) connected to the accelerometer. According to the ISO2631-5:2018 standard, the sign of the acceleration signal was also recorded. The equipment meets the ISO 8041, ISO 10323-1 and ISO 2631 requirements for measurements. The time and position of the vehicle were also simultaneously recorded via a GPS logger.

4.2. Measurement and data processing. Step 2

The procedure adopted for the field testing consisted of three steps. Firstly, the sensors were installed: the accelerometer was placed on the seat surface and its position was adjusted to ensure the correct positioning of the axes. It was fixed with adhesive tape to avoid relative displacement between the seat surface and the sensor. In addition, the GPS was placed on the surface of the vehicle dashboard.

Secondly, the measurement with both sensors started simultaneously and the test started. During the measurements, the subject remained seated and did not lose contact with the seat surface (the subject was instructed and supervised not to get up from the seat just to ensure that the exposure did not include bad acceleration data measured during loss of contact). Moreover, the driver was monitored performing the activity under normal working conditions. In the case of a significant anomaly in the recorded test data occurring, the experiment was carried out again. The test was performed several times for each test section (at least three times) to reduce random errors. From the data obtained in each measurement, those with a length of more than 90 s and a maximum speed deviation of ±2.5 km/h were selected. In this data selection, we followed the recommendations of ISO 2631-1, which states that a minimum measurement duration of 108 s for a lower frequency limit of 1 Hz is required to assure an error less than 3 dB at a 90% confidence level. This data preprocessing step was intended to eliminate the vibration measurements in non-stable velocity periods and to ensure the minimum measurement duration to provide representative results of the exposure in tested conditions.

Finally, based on the acceleration data and other recorded data from the experiment, the daily compressive dose S_d^A is calculated according to Section 2. The acceleration measured at seat surface was used for the seat and backrest in the model. In order to compare different exposures, the same set of conditions is used to normalize the measured exposure to a typical/realistic daily exposure. In our test, the duration exposure conditions were chosen in such a way that they maximize the spinal load, as the values defined in Annex A.3 of ISO2631-5: the daily exposure duration were normalized to 4 hours in order to compare the results obtained in the different exposure conditions. An exposure of 240 days per year, for the ages from 20 to 70 years was considered as the lifetime exposure history.

The daily compressive dose (most unfavorable vertebra) and the average velocity were used as input variables (Fig. 2) and the objective is to obtain a grouping of the daily compressive dose to test the appearance of differences between different groups based on the mean velocity.

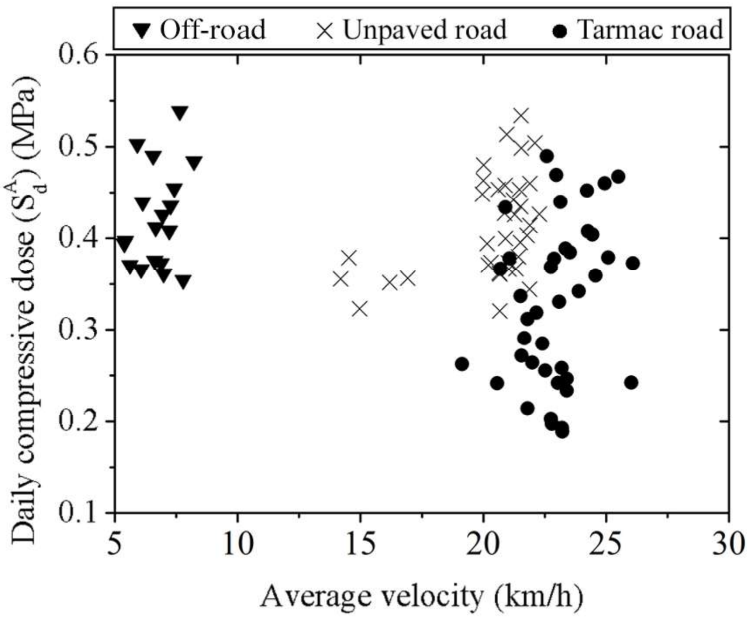

Fig. 2. S_d^A versus average velocity.

Therefore, a clustering process was carried out using the k-means++ algorithm in terms of the average velocity for different types or roads. As was commented on in Section 2, prior to the application of the algorithm, it is necessary to establish the number of clusters to carry out this process. For the selection of the optimal number of clusters, the Elbow and the GAP methods were used. Fig. 3 shows the results of the analysis using both methods. In this study, the optimum number of clusters obtained is $k = 4$, for both methods, according to the selection criteria given in Section 2.

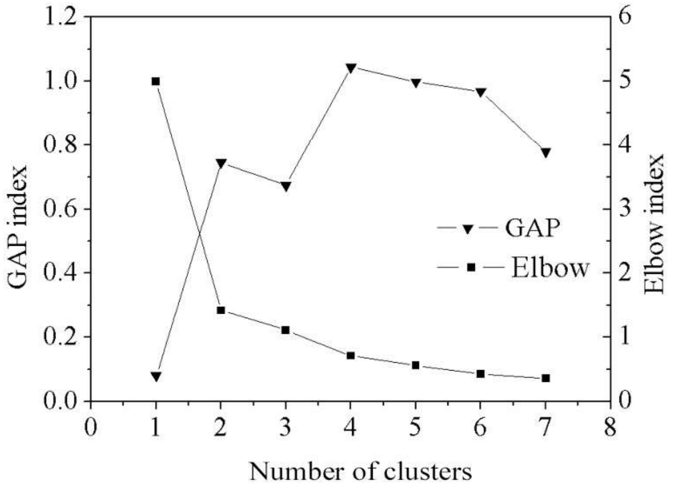

Fig. 3. Selection of the optimum number of clusters.

Once the optimum number of clusters was set up, the clustering process was subsequently applied. Fig. 4 shows the obtained results. The data set assigned to cluster 1 was recorded on off-road; cluster 2 contains data recorded on unpaved road and cluster 4 contains data recorded on tarmac road. Unlike the other clusters, cluster 3 contains data recorded coming from both unpaved and tarmac road. The mean travel speed for each cluster was also calculated ($\overline{v_{c1}} = 6.7\ km/h$; $\overline{v_{c2}} = 15.4\ km/h$; $\overline{v_{c3}} = 21.1\ km/h$; $\overline{v_{c4}} = 23.7\ km/h$).

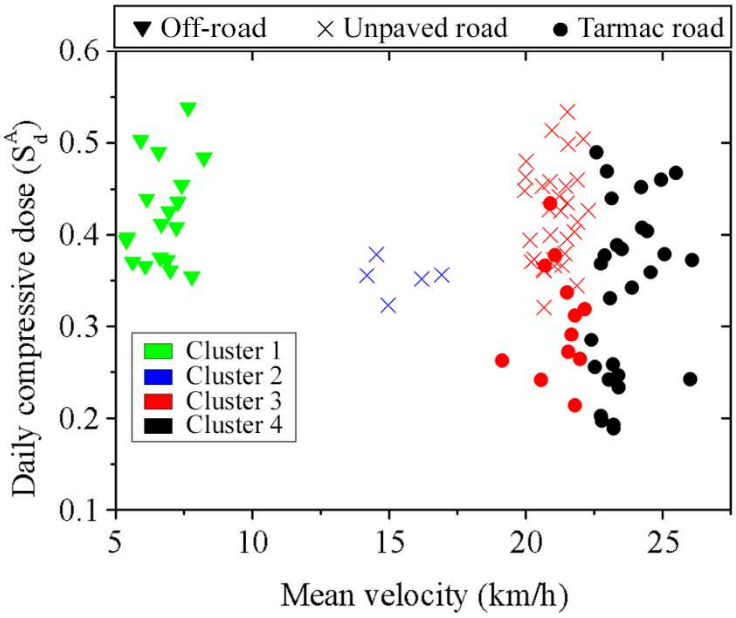

Fig. 4. K-means clustering of S_d^A in terms of mean speed.

In order to continue with this analysis, we can see that the driver clearly adapts his speed to the type of surface. Therefore, on 'off-road' the maximum speed the driver reaches is lower than on regular surfaces. On the other hand, it is observed that: (1) on the same type of surface, the higher the speed is, the parameter S_d^A increases; and (2) the greater the surface irregularity is, parameter S_d^A increases at the same speed.

4.3. Assessment of daily exposure. Step 3

On the basis of the acceleration data taken from the field experiment, methods defined in ISO 2631-1 based on A(8) and VDV parameters were applied, as explained in Section 2. With these parameters, we performed an analysis considering the different clusters obtained in the previous section. Firstly, the A(8) parameter and the highest S_d^A value of the vertebral level, calculated using the samples belonging to each cluster, were compared (Fig. 5), and their results have then been compared with those coming from the HGCZ boundaries associated with probabilities of adverse health effects. From this figure, it can be seen that there is a linear relationship between the two parameters and the results show similar assessments in clusters 2 and 4, regarding the values obtained for both parameters. Notably, two data are above the A(8) HGCZ boundary in cluster 1, and only one data is above the S_d^A HGCZ boundary in the same cluster. In addition, there are three data in cluster 3 that exceed the S_d^A HGCZ boundary and two data above the A(8) HGCZ boundary.

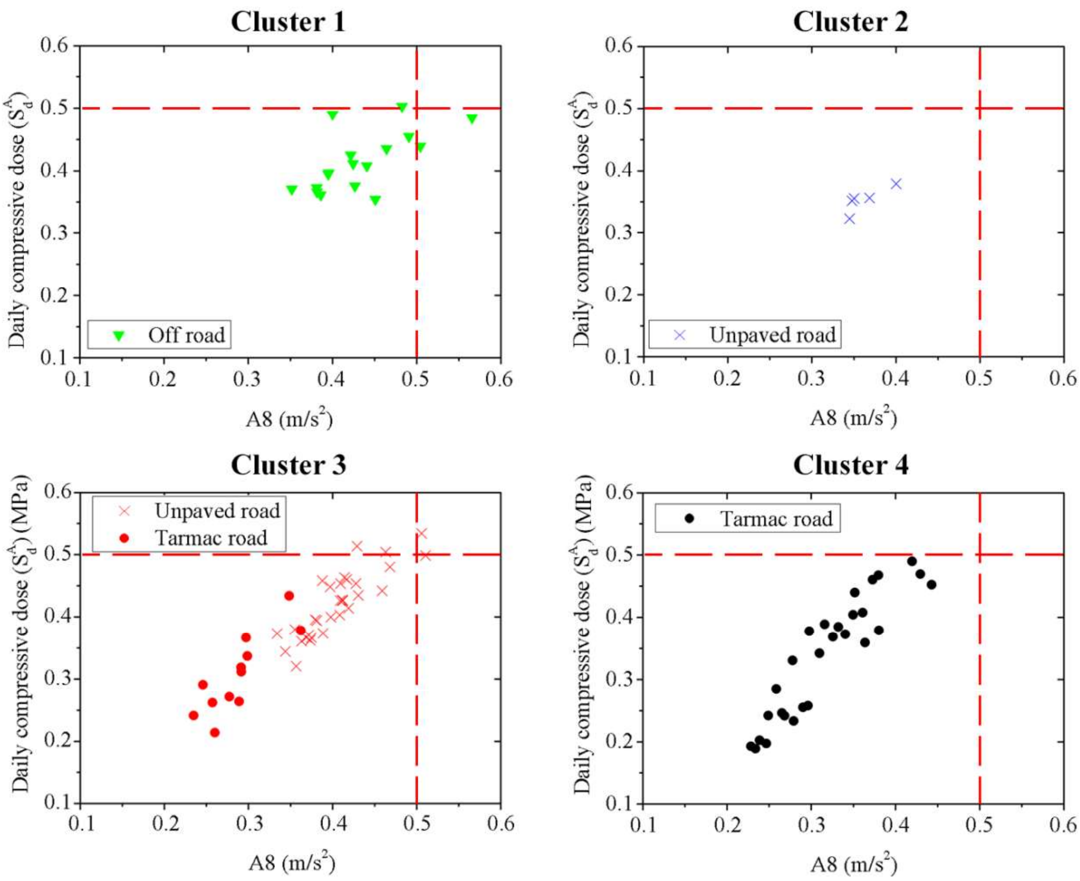

Fig. 5. Relationship between A(8) and S_d^A in the four generated clusters.

Secondly, the VDV parameter and the highest S_d^A value of the vertebral level were calculated. Fig. 6 shows the relationship between both parameters for each of the predefined clusters. Now, the general observation is that both parameters are correlated. In the case of the VDV, this methodology is more restrictive than that based on S_d^A. Thus, it can be seen that the data set of cluster 1 exceeds the VDV HGCZ boundary, as well as some data of clusters 3 and 4. It should be noted that only two samples of cluster 1 and three samples of cluster 3 exceeded the S_d^A HGCZ boundary with respect to the S_d^A.

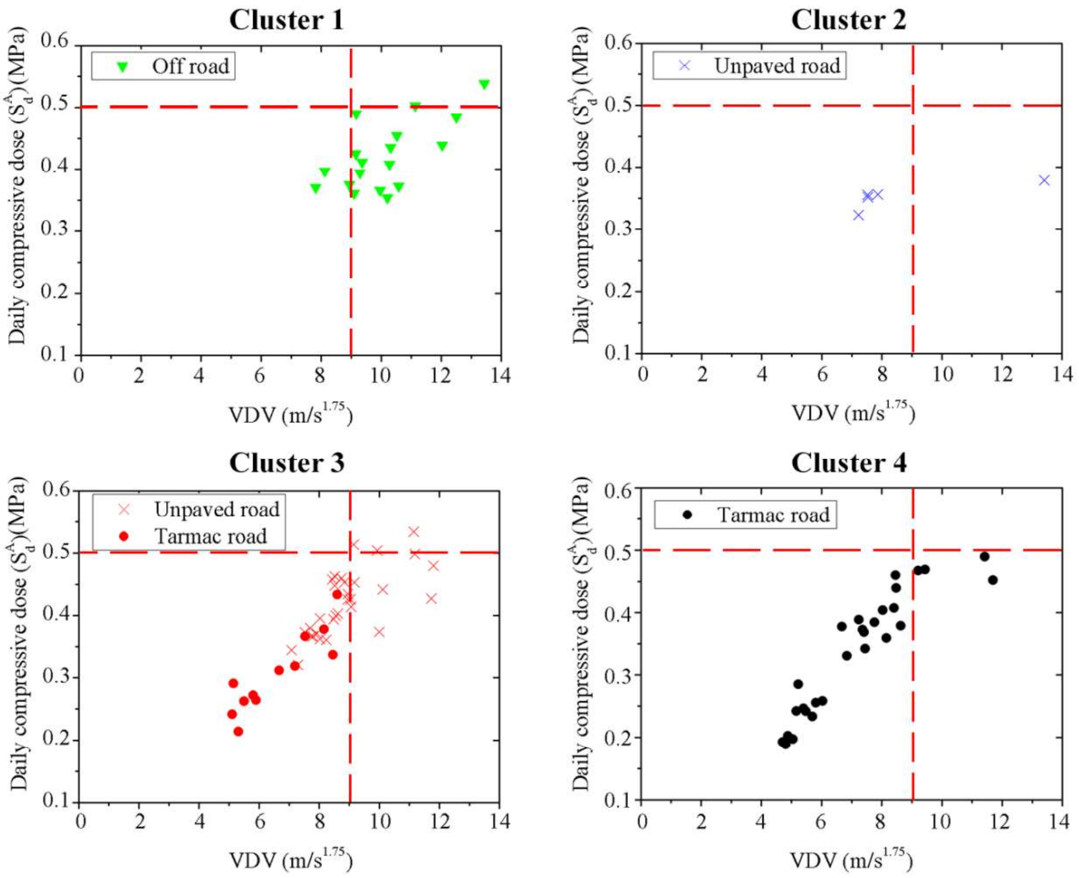

Fig. 6. Relationship between VDV and S_d^A in the four generated clusters.

Therefore, health risks predicted by the VDV assessment method are higher than those predicted by A(8)- and S_d^A-based methods. In our experiment, in which the worker exposure contains multiple shocks, this result can be explained since VDV values would be more restrictive than A(8) because the VDV method is more sensitive to shocks. However, there are two methods (VDV and S_d^A), both assessing WBV exposure but providing different assessments when data contain shocks. This can lead to a remarkable confusion since some operations could be considered safe when they are not, and vice versa, depending on the chosen assessment method.

In fact, similar results, but with previous standards, were provided by other research about the previous standard ISO 2631-5:2004 and ISO 2631-1 for load-haul-dump vehicles (Eger et al., 2008), railroad locomotives (Cooperrider & Gordon, 2006; Johanning et al., 2006), and front-end loader (Blood et al., 2012). Eger (2008) already suggested that research should be conducted to discuss whether the limits for low and high probabilities of adverse health effects suggested in

ISO 2631-5:2004 would require some revision. However, although the method of calculation of a compressive dose is different in ISO 2631-5:2018, the limits of low and high probability of an adverse health effect are the same as those published in ISO2631-5:2004, so this result backs this argument in a different context.

4.4. Assessment of cumulative WBV exposure over the years. Step 4

For the data set of each cluster, the average S_d^A value has been calculated for the vertebral levels T12/L1 to L5/S1 (Table 2), according to the surface on which they were measured. As the k-means++ method splits the data into non-overlapping groups, and the Elbow and Gap criteria have been applied to select the number of clusters, the data obtained are statistically different by the attributes used in the clustering procedure. If we compare the maximum values S_d^A with the HGCZ value, all values indicate a low probability of an adverse health effect to occur after vibration exposition. The maximum S_d^A value of each case has been used to calculate the R^A parameter as defined in Section 2, considering the exposure lasts from the age of 20 to 70 years for 240 days per year (full working life with a typical length of the working day in this sector). The evolution of the R^A values over exposure time is shown in Fig. 7.

Table 2: S_d^A values for the vertebral levels T12/L1 to L5/S1 for the defined clusters

Surface	Cluster		T12/L1	L1/L2	L2/L3	L3/L4	L4/L5	L5/S1	Max
Off-road	1	S_d^A	0.385	0.393	0.406	0.421	0.414	0.382	0.421
		σ	0.048	0.049	0.052	0.055	0.054	0.045	
Unpaved road	2	S_d^A	0.353	0.330	0.320	0.320	0.315	0.311	0.353
		σ	0.020	0.020	0.022	0.022	0.022	0.018	
	3	S_d^A	0.419	0.408	0.401	0.406	0.400	0.381	0.419
		σ	0.054	0.050	0.049	0.049	0.048	0.046	

Tarmac road	3	S_d^A	0.301	0.291	0.291	0.296	0.292	0.283	0.301
		σ	0.063	0.059	0.061	0.064	0.063	0.060	
	4	S_d^A	0.335	0.318	0.310	0.313	0.305	0.296	0.335
		σ	0.099	0.091	0.085	0.085	0.082	0.081	

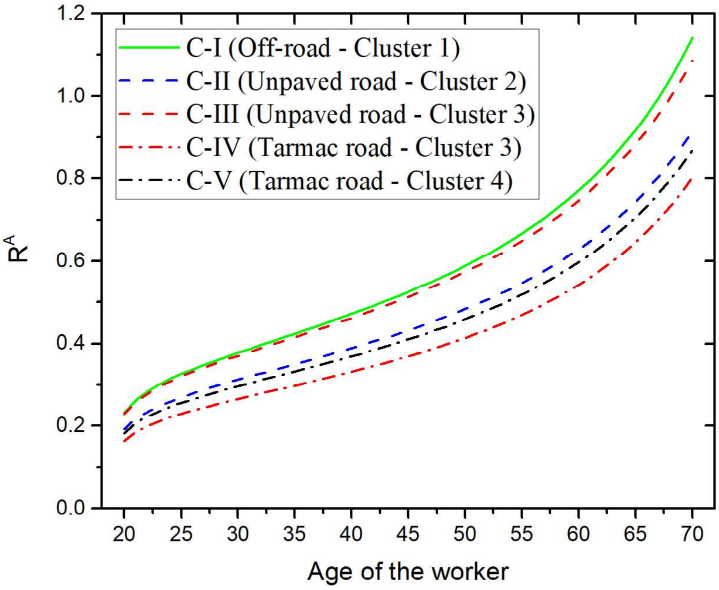

Fig. 7. Evolution of R^A values over the exposure time.

By analyzing the evolution of the R^A parameter over exposure time, the WBV exposure daily pattern per year allows us to predict when the subject will exceed the boundary values associated with low and high probabilities of adverse health effects. In this case, the curve C-I (off-road − cluster 1) reaches the limit when the driver is 61 years old, and C-II (unpaved road − cluster 3) reaches the limit when the driver is 62 years old. In none of the other cases is the boundary exceeded.

Further analysis and comparison on these curves, and specifically those corresponding to the same type of surface, also allow us to note how the slope of the curve increases as the speed increases. This implies a higher probability of occurrence of an adverse health effect. Therefore, speed is an important factor to take into account when trying to reduce the severity of the exposure. In addition, as the irregularity increases, so does the risk. The nature of the terrain and the characteristics of the activity have a great impact on the magnitude of the vibrations transmitted, and they are both very relevant factors. Although the off-road terrain is compressive in a majority of cases and accordingly the level of transmitted vibration would become lower, in our study the high surface irregularity and the unevenness of the off-road terrain result in an increased severity of the transmitted vibration in comparison to other surfaces, even though the forward speed is lower than in other surfaces. This fact is noted by comparing the curves CI (off-road), C-II/C-III (unpaved road) and C-IV/C-V (tarmac road).

Since this result deserves attention and will prove to be useful to establish a methodology to predict the probability of an adverse health effect, the data obtained were fitted using polynomial fitting tools in MATLAB software (Table 3) in order to model the cumulative effect of WBV with the parameter R^A. Equation (9) shows the equation of the general model polynomial fitting function applied to our data. The degree of the obtained polynomial fitting becomes three; this is due to the fact that greater degrees do not improve the goodness of the fit, causing an overfitting or badly conditioned problem.

$$R^A(t) = p1 \cdot t^3 + p2 \cdot t^2 + p3 \cdot t + p4 \quad (9)$$

t being the exposure time. The above polynomial functions can be used to predict the risk factor in terms of the exposure time of worker, depending on the type of road.

Table 3. Coefficients of the general model polynomial fitting model

	Curve	$p1$	$p2$	$p3$	$p4$	Goodness of fit R-square
C-I	Off-road Cluster 1	1.034e-05	-0.001123	0.04978	-0.3877	0.99
C-II	Unpaved road	8.094e-06	-0.00884	0.03966	-0.3043	0.99

	Cluster 2					
C-III	Unpaved road Cluster3	9.607e-06	-0.001049	0.04708	-0.3612	0.99
C-IV	Tarmac road Cluster 3	6.901e-06	-0.0007538	0.03382	-0.2565	0.99
C-V	Tarmac road Cluster 4	7.681e-06	-0.000839	0.03764	-0.2888	0.99

4.5. Color map of risk factor evolution. Step 5

Specifically, the proposed method relies on the analysis carried out to obtain Fig. 8 and 9. The parameterization of data in Table 3 allows the health risk probability to which the worker is exposed in any year to be determined, from a data set measured under specific velocity and surface conditions. Based on the experimental data for each type of road surface and exposure time, a bidimensional surface-type fitting has been carried out using a polynomial surface model, where the x-axis is the number of years of exposure and the y-axis represents the average speed at which the activity is performed, therefore the bidimensional polynomial models for surfaces are given by Equation (10). In this equation, the polynomial surface fitting coefficients and the goodness of fit statistics are shown in Table 4. The degree of the obtained polynomial fitting becomes three in the x-axis and one in the y-axis.

$$R^A = f(x, y) = p_{00} + p_{10} \cdot x + p_{01} \cdot y + p_{20} \cdot x^2 + p_{11} \cdot x \cdot y + p_{30} \cdot x^3 + p_{21} \cdot x^2 \cdot y \quad (10)$$

Table 4. Coefficients (with 95% confidence bounds)

	p_{00}	p_{10}	p_{01}	p_{20}	p_{11}	p_{30}	p_{21}	Goodness of fit R-square
Unpaved road	-0.4566	0.04434	0.006797	-0.001055	-5.324 e-05	8.85e-06	4.834e-06	0.99

Tarmac road	-0.4578	0.03717	0.008178	-0.000927	-6.406e-05	7.291e-06	5.816e-06	0.99

A graphic interpretation is useful to extract conclusions, and may do so by representing the z-axis by a color map that shows the R^A value. This analysis deepens into the evolution of the cumulative effect of WBV exposure for displacements in a wide range of velocities on different surface types. (Fig. 8 and Fig. 9).

It should be noted that this process has been carried out for displacements performed on unpaved road and tarmac road. As off-road operations take place in a reduced speed range because they demand continuous concentration and require conscious decision-making to choose the appropriate acceleration, trajectory, etc., off-road surface has not been included in the analysis.

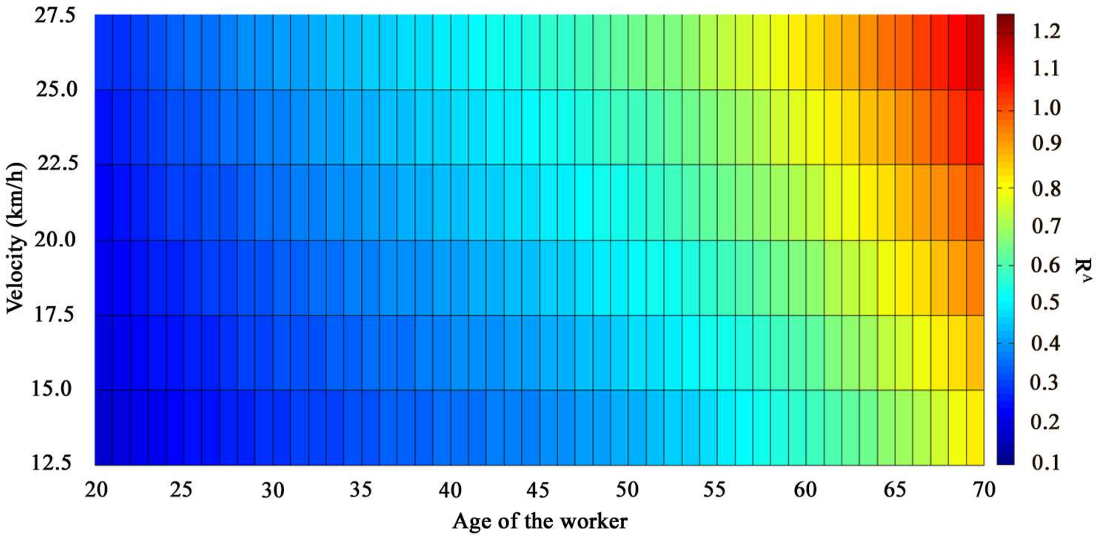

Fig. 8. Unpaved road.

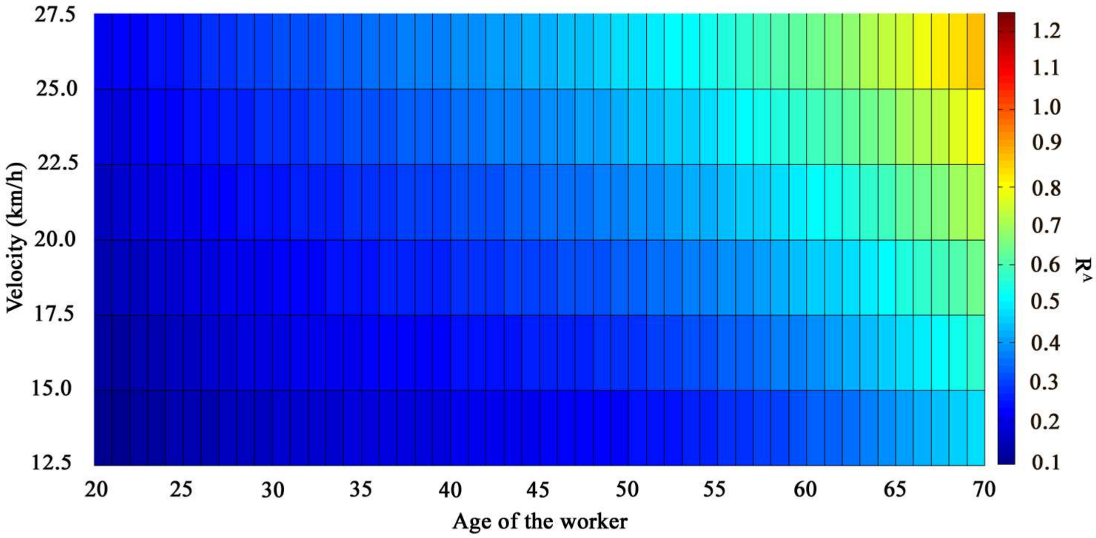

Fig. 9. Tarmac road.

It should be noted that Fig. 8 and Fig. 9 are the result of applying the proposed methodology to this study case. Therefore, the minimum speed was 12.5 km/h because it was the minimum forward speed when the real task was performed. Consequently, the results obtained in the illustrative case should not simply be generalized to other different activities. In any case, the risk assessment professionals should apply the proposed methodology following all the proposed steps when those activities require WBV risk management.

4.6. Risk management. Step 6

The proposed methodology relies on using Fig. 8 and 9 to estimate the health risk probability (based on the risk factor R^A) to which the worker is exposed in terms of the exposure years and a different range of speeds, with no need to calculate the dose, which is sometimes a hard task. Using the color maps obtained for each vehicle, the safety manager could perform a quick evaluation of the worker activity according to the average speed at which they are performed, with an entire working life perspective that covers the whole life of the subject. So, the characterization of the activities of the worker, together with the use of R^A curves and surfaces, allows for performing a quick analysis that guarantees the safety of the worker.

Finally, the objective of the proposed procedure is aligned with that defined in the Framework Directive 89/391/EEC, which states that the employer must implement measures to ensure an improvement in the level of protection of workers, as well as the establishment of the necessary organization and means. The application of this methodology provides vital information to ensure that WBV risk management is carried out correctly. Using these methodological basis, it will be very easy to perform an appropriate organization of the work and the design of the operations in an optimal way from the point of view of the worker health and safety in the long term. In addition, safety managers have a simple tool that allows them to define preventive organizational measures that should result in a reduction of WBV risk exposure. In this way, it is ensured that workers could carry out their operations by limiting themselves to the safe region given by this method, emphasizing that the whole working life of the subject has been taken into account in the development of this procedure.

5. Conclusions and practical applications

Musculoskeletal disorders have a high prevalence among occupational populations as well as a high economic and social impact. Whole-body vibration (WBV) exposure is related to the emergence of musculoskeletal disorders and degeneration of the lumbar spine, so international standards have focused on its assessment. In this sense, ISO 2631-1 and 2631-5 describe models for assessing exposure to WBV. In this research, WBV exposure was analyzed using both models to assess the WBV exposure associated with a HEV operation on a variety of surfaces and speeds. Based on the obtained results and the proposed modelling of the risk factor of occurrence of adverse health effects as established in the ISO 2631-5:2018 standard, a methodology was developed to perform a quick evaluation of risks due to the cumulative effect of WBV exposure associated with HEV operation as a function of HEV speed.

The research performed in this paper allows us to draw two main conclusions on the basis of the results and methods discussed in the previous sections:

The first main conclusion is that the results obtained in the evaluation with the A(8), VDV y S_d^A methods provide different assessments leading to different possible consideration of safe operations when the risks associated with them may actually be high. Although the ISO2631-5:2018 methods have been modified from ISO2631-5:2004, HGCZ boundaries should be revised for the sake of consistency.

The second main conclusion is that a method has been proposed to assess the health risk probability to which the HEV worker is exposed in terms of the exposure years and a different range of speeds. The methodology proposed in this study supports the design of activities performed with HEV, ensuring that the probability of an adverse health effect is low in the entire working life of the driver. In addition, this methodology reduces the computational time that would require recalculating the S_d^A and R^A values associated with other speed values, since they have been calculated from the parameterized R^A curves.

Furthermore, this methodology can contribute to improving the quality of life of professional drivers during and after their working life since this method can be applied from the start of the first job in which the worker is exposed to WBV. In the context of the increase in life expectancy and raising of retirement ages that make suffering from WBV-related diseases more likely, it is very important to consider the entire working life as this method does. Finally, the designed methodology contributes to the development of the EU Strategic Framework on Health and Safety at Work 2014-2020 (Brussels, 6.6.2014COM(2014)) in two of its three major health and safety at work challenges (i.e., it allows the improvement of the prevention of work-related diseases, taking into account the aging of the EU workforce).

Finally, the proposed methodology is designed and configured to be a practical tool to support safety and health professionals in their objective of assessing the global exposition to WBV throughout their all-working life. It should be noted that since other relevant factors contribute to the long term occupational health hazards, a comprehensive health surveillance to prevent possible negative effects on workers must always be conducted by professionals, supplementing the procedure described in this article.

Declaration of Competing Interest

The authors have no financial disclosures or conflicts of interest to report.

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