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Assessment of whole-body vibration exposure using ISO2631-1:2008 and ISO2631-5:2018 standards.

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ABSTRACT

Whole-body vibration (WVB) exposure may likely become an occupational health problem for drivers of agricultural machinery. It is well established that frequent and regular exposition to WBV and shocks may cause health and safety risks to the driver (such as musculoskeletal disorders, low back pain or degenerative changes in the lumbar spine). The main source of WBV is the seat-body interface of drivers, although other important transmission points are the backrest, hands and feet. In this regard, Directive 2002/44/EC in the European Union establishes daily exposure limits with the aim of protecting workers from risks derived from vibrations. For this purpose, the different standards define some methods to assess the WBV exposure of workers and establishes several Health Guidance Caution Zones (HGCZ) associated with boundaries. This study presents a comparison of the assessment provided for both ISO 2631-1:2008 and ISO 2631-5:2018 Standards in the context of agricultural tractor operations. To accomplish so, predicted health risk associated with agricultural tractor operations have been determined and compared with the HGCZ boundaries. In the analysis we have considered different surface conditions of displacement and speed and finally some conclusions are drawn in terms of the different factors involved.

Keywords: Whole-Body Vibration, ISO 2631-1:2008, ISO 2631-5:2018
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1. INTRODUCTION

Whole-Body Vibration (WBV) exposure is a common physical risk presents in multiple industries. Tasks related to driving vehicles often expose drivers to potentially hazardous levels of WBV [1-3]. The WBV exposure produced by the movement of the vehicles may cause not only uncomfortable feeling in drivers, but also there are evidences of cognitive/motor impairment [4], standing balance [5], and musculoskeletal disorders such as low back pain, sciatica [6], neck pain [7] and degenerative changes in the lumbar spine [8].

The agricultural sector is one of the sectors that requires driving on surfaces of different nature. Agricultural tractors transmit vibrations to the driver's body through the seat pad, backrest, cabin floor and steering wheel [9]. Vibrations generated by the combustion engine and surface roughness may affect to the activity performance and endanger the safety of operation.

In order to prevent adverse health effects derived from WBV exposure, health and safety management should be carried out. The ISO2631-1:2008 [10] and ISO2631-5:2018 [11] Standards provide methods to perform the exposure assessment. Thus, ISO 2631-1:2008 defines methods for the measurement of periodic, random and transient WBV. Although this Standard does not provide exposure limits, the methods defined in ISO2631-1:2008 are used in the European Directive 2002/44/EC [12] in order to ensure the safety of workers.

In addition, International Standard Organization published the ISO2631-5 standard in 2004 [13] to address human exposure to WBV containing multiples shocks. The effects of cumulative exposure over time on the health of the lumbar spine are assessed by the method described in this standard. Recently, the new ISO2631-5:2018 has been published, where two exposure regimes (severe conditions and less severe conditions) are considered. Nevertheless, the limits established by ISO 2631-5:2004 remain unchanged compared to those defined in the ISO 2631-5:2018.

The purpose of this fieldwork investigation were threefold: (1) to compare both ISO 2631-1:2008 and ISO2631-5:2018 Standards in the context of agricultural tractor operations, (2) to analysis the influence of different conditions of displacements and speed and (3) to compare the results given by this evaluation procedure with the Health Guidance Caution Zones (HGCZ) boundaries.

2. MATERIAL AND METHODS

2.1 Measurement equipment and test tractor

The acceleration transmitted to the seat pad was collected with a tri-axial accelerometer (SV38, SVANTEK). This sensor enables to sample the acceleration with a frequency of 6000 Hz in x- (fore-to-aft), y- (left-to-right) and z- (buttocks-to-head) axes. The sign of the acceleration signal was recorded according to the ISO2631-5:2018 standard. Raw unweighted acceleration signal recorded was storage in a data logger (SV106, SVANTEK) connected to the accelerometer. The equipment meets the ISO 8041 [14] and ISO 2631 [10] requirements. The location and speed of the vehicle were measured simultaneously using a Global Positioning System (GPS).

The signals were downloaded to a computer and processed with Matlab® software (MathWorks, Natick, MA, USA).

In the experiment, a tractor was selected to perform the tests on different surfaces. According to the Directive 78/764/EEC [15], this tractor is classified as Class II Category A. The characteristics are shown in the Table 1.

Table 1: Tractor characteristics.

Dimensions		**Engine**	
Weight	3800 kg	Power	78 kW
Wheelbase	226 cm	Cylinder	4
Length	419 cm	Rear RPM	540/1000
Width	205 cm	Front tire	7.50-18
Height (cab)	266 cm	Rear tire	13.6R38

2.2 Test subject

Tests were developed by a highly experienced operator (more than ten years of tractor driver experience). This subject is a 48 years male with body mass index of 35.1 kg/m^2, weight of 120 kg and height of 1.85 m. In order to eliminate the uncertainty associated with variables linked to the anthropometric characteristic of the operator, all operations were performed by the same driver.

2.3 Route characteristics and measurements

This study took place in the city of Porcuna (37°52′11″N, 4°11′14″O). In order to establish the experimental setup, several agricultural tractor drivers working in the area were interviewed. The information obtained allowed us the identification of a typical work cycle of agricultural tractors and the location of the different road pavements. With these data, it was established a standard route for the test, representative of the full work cycle. This route comprises different surface nature (off road, unpaved road and asphalt) (Fig. 1) since the magnitude of the WBV transmitted to the operator is influenced by the characteristics of the displacement surface.

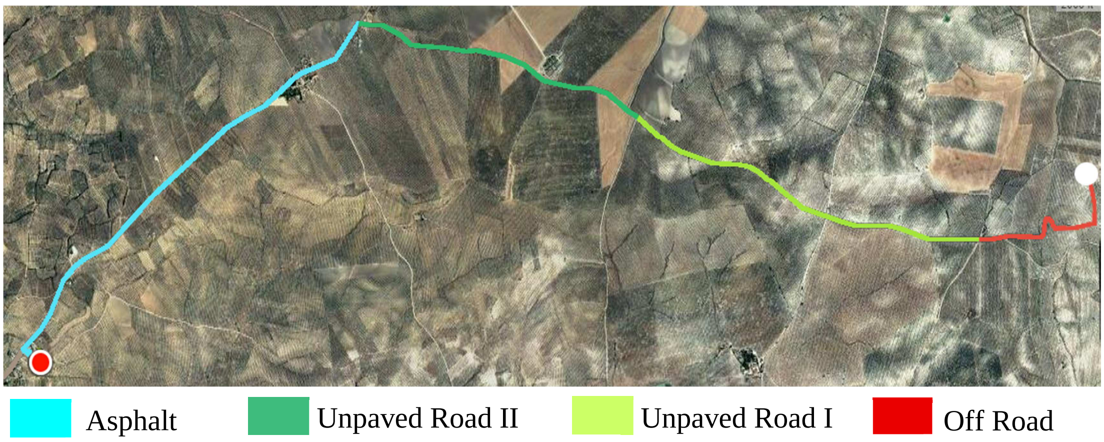

Fig. 1. Selected route for the test.

Once the route was established, it was set up some operational aspects of the experimental test. Agricultural tractors are widely used in different operations and these activities often require the use of interchangeable towed machinery or a trailer. Since we have to establish the performance of a representative task, the test tractor then used a trailer while the measurement were developed. The tests were also designed in such a way that their lengths allow us to obtain a representative result of the vibrations transmitted in each type of displacement. Another important variable was the speed: a forward speed was established for each type of surface. This selection takes into account several factors: the maximum measured road speed in different surface conditions and engine power (through the surface roughness parameter), and the legal maximum speed for agricultural tractors.

Taking into account the above criteria, for the off road case, the roughness for this pavement forces to keep the speed limited to ensure the safety of the driver, and so the forward speed ranges from 5 up to 10 km/h for agricultural tractors. In the case of unpaved roads, the typical forward speed range increases since the road surface is more regular than off-road. However, since unpaved roads can present a wide variety of roughness conditions, this category was split into two: "unpaved roads with a high roughness surface" (where forward speed ranges from 10 up to 15 km/h) and "unpaved roads with a low roughness surface" (where forward speed ranges from 15 up to 22 km/h). Finally, the average forward speed of the agricultural tractor in asphalt is higher than in other surfaces (from 20 up to 25 km/h). It should be noted that agricultural tractor legal speed limit is 25 km/h while using a trailer or interchangeable towed machinery.

Accordingly, since the roughness of the surface has to be calculated in this study to classify the different roads, we have chosen the IRI parameter for this regard and it has been widely used in multiple articles. The International Roughness Index (IRI) is a parameter defined by means of a quarter car model and it describes the roughness of surfaces. Ahlin and Granlund [16] derived IRI as a relationship between road roughness, speeds and vertical human WBV (Equation 1):

$$\frac{rms_z}{IRI} = 0.16 \left(\frac{v}{80}\right)^{\frac{1}{2}} \tag{1}$$

Where rms_z is the root-mean-square acceleration in the vertical direction (m/s^2) and v is the vehicle speed (km/h).

Once the test conditions were established, we have performed the measurements three times (the forward displacement and the acceleration along the three axis were recorded simultaneously) for each type of surface and speed, in order to reduce the risk of measurement error. Since all tests were performed by the same operator, the influence of the controller's anthropometric variables are no longer addressed in this experiment, and the results can be compared. All the above considerations applied to our measurements and we then analyzed the acceleration transmitted by the vehicle to the driver on different surfaces.

2.4 Analysis of WBV exposure

The obtained signal data allow us to calculate the parameters defined in the ISO 2631-1:2008 and ISO 2631-5:2018 and evaluate the WBV exposure according with these standards. The procedure becomes as follows:

ISO 2631-1:2008. This International Standard defines two method: the basic evaluation method using the effective value of weighted acceleration, the daily exposure value (A(8)) and the Vibration Dose Value method (VDV) (Table 2). Both methods evaluate WBV exposure for an 8 hour work cycle and require the application of frequency weighting filters to the obtained raw data (w_d for x- and y-axes and w_b for z-axis).

Table 2: Daily exposure value a(8) and Vibration Dose Value (VDV)

Daily exposure value A(8)	**Vibration Dose Value method VDV**
$rms_{ws} = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{1/2}$	$vdv_{ws} = \left[\int_0^T a_w^4(t)dt\right]^{1/4}$
$A(8)_s = k_s\, rms_{ws}\sqrt{\frac{T_{exp}}{T_0}}$	$VDV_s = k_s\, vdv_{ws}\sqrt{\frac{T_{exp}}{T_{meas}}}$
$A(8) = \max\left[A(8)_x, A(8)_y, A(8)_z\right]$	$VDV(8) = \max\left[VDV_x, VDV_y, VDV_z\right]$

On the one hand, the A(8) index is calculated based on the weighted rms acceleration. In Table 2, $rms_{ws}(t)$ is the weighted root-mean-square acceleration in the s-directions, T is the signal duration in seconds, k_s is the weighted factor associated with the direction ($k_x = 1.4$; $k_y = 1{,}4$; $k_z = 1$), T_{exp} is the daily duration of vibration exposure and T_0 is the reference duration set up to 8 hours. The $A(8)$ value is calculated as the highest value of $A(8)_x$, $A(8)_y$ and $A(8)_z$.

On the other hand, the VDV method uses the fourth power of the rms of the weighted acceleration instead of the second power. In Table 2, T_{meas} is the measurement duration time. The vibration dose value in a time equivalent to 8 hours ($VDV(8)$) is defined as the highest value of $A(8)_x, A(8)_y$ and $A(8)_z$.

ISO 2631-5:2018. The WBV evaluation methods defined in this standard are based on the calculation of the daily compressive dose value S_d^A and the Risk Factor R^A. In order to estimate the internal spinal force, the Standard defines two methods: one method for the severe conditions regime (defined as those exposures that contain free-fall events and the accelerations transmitted in the z-axis containing peaks that exceed $9.81 m/s^2$) and another method for the less severe conditions regime, which is that regime where the operator remains seated all the exposure and the exposition is not controlled by the accelerations in the z-axis.

In our assessment, the raw accelerations obtained in the three directions were used for the estimation using the less severe condition method. This method considers as possible inputs the acceleration transmitted through the seat, backrest, feet and hands. In this study, the acceleration measured at the seat surface were used as the same input for both the seat and the backrest. Several transfer functions, which depend of the body mass, posture and mass index, was then used in order to determine the compressive dose value $S^A(MPa)$ (Eq. 2) for every disc level (T12/L1, L1/L2, L2/L3, L3/L4, L4/L5 and L5/S1). In Eq. 2, $C_{dyn,i}(N)$ stands for the sum of peak compressive forces acting on each disc level, $B(mm^2)$ is the vertebral endplate surface and i stands for the year counter.

$$S^A = \left(\sum_i \left(\frac{C_{dyn,i}}{B}\right)^6\right)^{1/6} \quad (2)$$

The equivalent daily compressive dose of the lumbar spine is calculated based on the S_j^A (Eq. 3) of each exposure, which is associated to a daily exposure period t_{dj} and the duration of the exposure measurement time t_{mj}.

$$S_d^A = \left(\sum_j S_j^{A6}\,\frac{t_{dj}}{t_{mj}}\right)^{1/6} \quad (3)$$

The estimation of the Risk Factor R^A (Eq. 4) at each vertebral level is calculated based on the equivalent daily compressive dose of the lumbar spine S_d^A, the number of exposure days per years N, the number of years of exposure n, the ultimate strength of the lumbar spine for a person of age (b+i) years S_{ui}^A and the mean value of the compressive-decompressive force divided by the area lf vertebra endplate $S_{stat,i}^A$ (Eq. 5).

$$R^A = \left(\sum_{m=1}^{n} \left(\frac{S_d^A \, N_m{}^{1/6}}{S_{ui}^A - S_{stat,i}^A} \right)^6 \right)^{1/6} \tag{4}$$

$$S_{stat,i}^A = 6.765\ MPa - 0.067MPA\ (b + i) \tag{5}$$

It should be noted that the Risk factor is not a parameter of probability of failure. When $R^A = 1$ it indicates that the dynamic load of the shock reached the same order of magnitude as the ultimate strength that the vertebra is capable to resist.

2.5. Health Guidance Caution Zone (HGCZ).

The European Directive 2002/44/EC specifies that the methods for assessing the WBV exposure are those defined in ISO 2631-1 and it determines standardised limits to an eight-hour exposure reference period. In addition, ISO 2631-5:2018 defines boundaries for probable health effects derived from multiple shocks vibration exposure (Table 3).

Table 3: Health Guidance Caution Zone.

ISO 2631-1:2008 / Directive 2002/44/EC		**ISO 2631-5:2018**		
Exposure limit values and action values		Probability of an adverse health effect		
Exposure Action Value (EAV)	$A(8) = 0,50\ m/s^2$ $DV = 9,1\, m/s^4$	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)	$A(8) = 1,15\ m/s^2$ $DV = 21\, m/s^4$	High	$S_d^A > 0,8\ MPa$	$R^A > 1,2$

3. RESULTS AND DISCUSSION

In accordance to the previous sections, parameters IRI (Table 3), A(8) and VDV (Table 4) were calculated from the equations shown in the previous section. The driver was considered to carry out his activity for 4 hours during the working day.

Table 4. IRI index

Surface	**Off Road**	**Unpaved Road I**	**Unpaved Road II**	**Asphalt**
IRI (Avg)	10,15	12,90	7,32	4,30

Table 5: A(8) and VDV parameters in accordance with ISO 2631-1:2008

Surf.	**Nº**	**A_x (ms^{-2})**	**A_y (ms^{-2})**	**A_z (ms^{-2})**	**A(8) (ms^{-2})**	**Avg A(8)**	**VDV_x ($ms^{-1.75}$)**	**VDV_y ($ms^{-1.75}$)**	**VDV_z ($ms^{-1.75}$)**	**VDV**	**Avg. VDV**
Off Road	#1	0,50	0,38	0,34	0,50	0,43	11,53	8,77	9,14	11,53	9,98
	#2	0,41	0,33	0,33	0,41		8,83	7,50	9,27	9,27	
	#3	0,38	0,30	0,32	0,38		8,82	6,85	7,75	8,82	
Unpaved road I	#1	0,36	0,38	0,42	0,42	0,44	8,44	8,30	8,93	8,93	9,32
	#2	0,36	0,38	0,43	0,43		8,37	8,17	8,92	8,92	
	#3	0,36	0,41	0,48	0,48		8,60	8,52	10,11	10,11	
Unpaved road II	#1	0,36	0,39	0,47	0,47	0,43	8,56	9,49	10,20	10,20	9,43
	#2	0,34	0,39	0,44	0,44		8,08	9,28	9,60	9,60	
	#3	0,32	0,34	0,38	0,38		7,23	7,94	8,48	8,48	
Asphalt	#1	0,18	0,20	0,27	0,27	0,26	3,67	4,28	5,55	5,55	5,33
	#2	0,14	0,18	0,25	0,25		2,85	3,92	5,22	5,22	
	#3	0,14	0,21	0,26	0,26		2,90	4,26	5,23	5,23	

For the evaluation of WBV exposure according to ISO 2634-5:2018 shown in Table 4, the following considerations have been taken into account: the 48 year old driver was working in this job since the age of 20, performing this activity for 180 days per year. Our evaluation was made considering that this worker will continue with this activity until year 2035. The posture of the worker while carrying out the activity is that defined in the standard as Group 3. The obtained results are shown in Table 5.

Table 5: Factors $R^A$and S_d^A

Surf.	**Nº test**	**R Factor for lumbar spines in 2018**							
		T12/L1	**L1/L2**	**L2/L3**	**L3/L4**	**L4/L5**	**L5/S1**	**FR**	**Avg R^A**
Off Road	#1	0,55	0,57	0,60	0,62	0,61	0,54	0,62	0,61
	#2	0,50	0,51	0,52	0,54	0,52	0,47	0,54	
	#3	0,58	0,62	0,65	0,67	0,65	0,57	0,67	
Unpaved Road I	#1	0,59	0,59	0,61	0,62	0,61	0,55	0,62	0,62
	#2	0,56	0,56	0,57	0,59	0,58	0,52	0,59	
	#3	0,65	0,63	0,62	0,63	0,61	0,57	0,65	
Unpaved Road II	#1	0,60	0,58	0,58	0,58	0,57	0,54	0,60	0,56
	#2	0,56	0,55	0,53	0,53	0,53	0,50	0,56	
	#3	0,53	0,53	0,52	0,53	0,51	0,47	0,53	
Asphalt	#1	0,33	0,33	0,34	0,35	0,34	0,32	0,35	0,30
	#2	0,27	0,27	0,27	0,27	0,27	0,25	0,27	
	#3	0,28	0,28	0,27	0,28	0,27	0,26	0,28	

If the obtained results are compared with the limits established in the European directive (Fig. 2a, 2b), the VDV exceeds the EAV limit in the more irregular displacement surfaces (Off-road and unpaved road). However, if only the A(8) method is used, the exposure does not become so harmful to the worker's health because it does not reach the EAV limit.

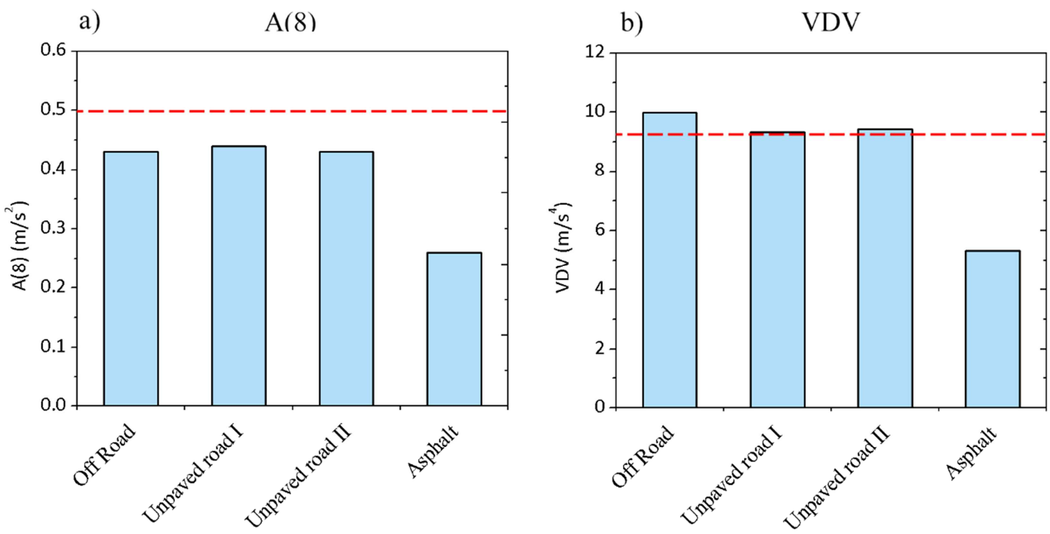

Fig. 2a. A(8) Exposure Value. 2b. Vibration Dose Value VDV

With regards to the evolution of the R Factor, i.e. R^A defined in ISO 2631-5:2018 (Fig. 3), the cumulative effect of exposure determines that the low limit of probability (LP) of suffering adverse effects on the spinal column ($R^A = 0{,}8$) is exceeded (Fig. 3a - 3c). If the evolution of the R Factor (R^A) is analyzed, it can be observed that the low limit of probability value is reached earlier in rougher surfaces than in others with a lower IRI value. The displacement on asphalt surfaces is the only one that transmit a level of WBV that does not reaches this limit ($R^A < 0{,}8$). The level of the more affected lumbar spine is the section L3/L4. In any case the limit of high probability (HP) is reached.

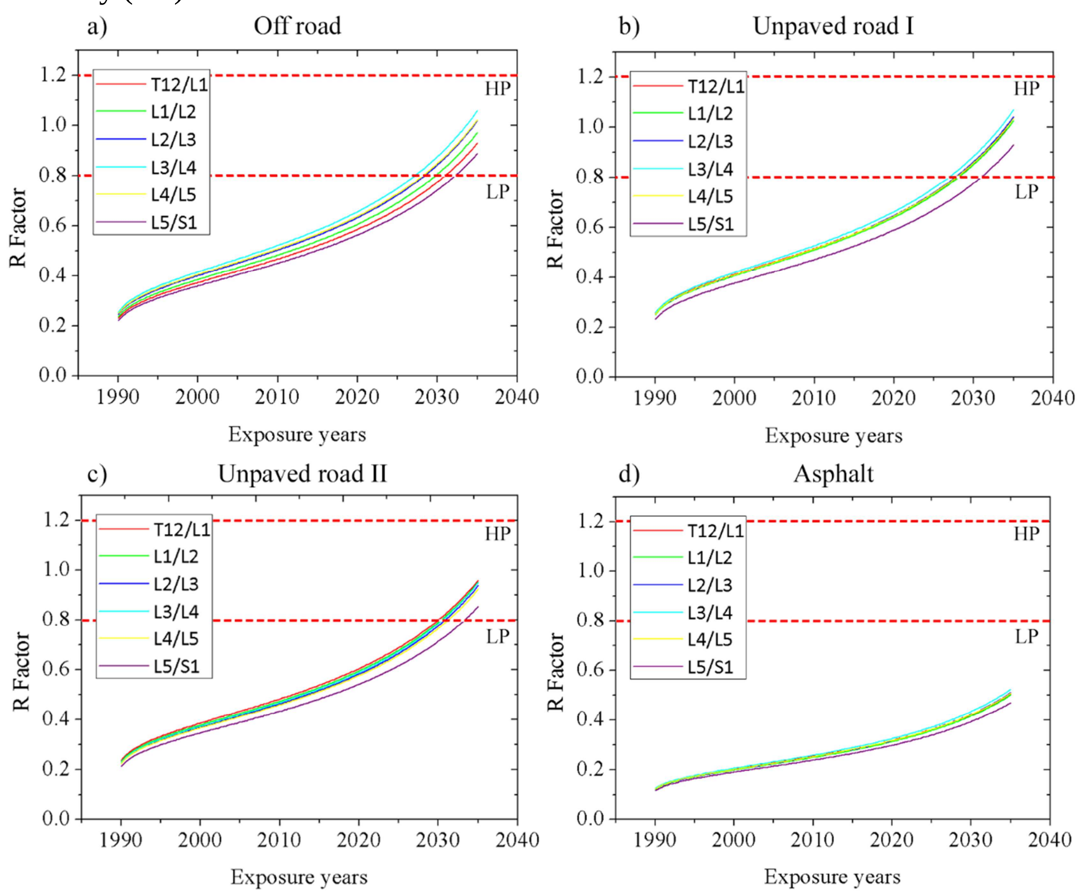

Fig. 3 Evolution of the R Factor 2631-5:2018

4. CONCLUSIONS

This study is a first approach to the characterization of the level of WBV exposure of drivers on different road conditions using standard models. Although many researchers have analyzed WBV assessment models during last years, the release of the ISO 2631-5:2018 standard meant an important step forward the way that the anthropometric variables of the driver and the different exposure regime are taken into account in the assessment.

In the present study, different models were used to make an assessment of the exposure to vibrations. Although the model defined in ISO2631-1:2008 is widely used, however the assessment is limited to the analysis of exposure for an 8 hour work cycle. This Standard does not consider the possible cumulative effects of continuous exposure across the working life of the driver. In contrast, the ISO 2631-5:2018 standard will allow us to consider the cumulative effects of WBV exposure in the lumbar spine and to determine whether the probability of damage becomes high or low.

In this work we have focused in the predicted health risk associated with agricultural tractor operations, comparing the results provided by the above mentioned standards. In the experiment, we have considered different surface conditions of displacement and speed and finally we get some conclusions in terms of the different factors involved. Thus, from the different tests performed in this study, we obtained that the WBV levels transmitted to the driver remain high in the off road and unpaved surface cases. In the cases of unpaved road, where roughness IRI index was lower, the transmitted WBV was similar to the off road case due to the increased of the forward speed. It should be noted that the driver really adjusted the speed and driving according to the conditions of the road, and these aspects were taken into account through the IRI of the surface and the forward speed in our study.

In the case of asphalt surface, the level of WBV is low despite being the surface with the highest speed associated and the lowest IRI.

Finally, it appears to be clear from our measurements that the level of WBV in roughness surface is an important factor that should be taken into account in the assessment. Vibration levels transmitted to the drivers may affect both their health and cognitive performance. For example, operations through off road surface demands continuous concentration in the road and they require taking decisions in order to choose the right speed, acceleration, trajectory, etc. This work suggests the need of including this index in the risk assessment for these category of workers.

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