Influence of tyres characteristics and travelling speed on ride vibrations of a modern medium powered tractor

Part II, Evaluation of the Health Risk

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Abstract: In this paper, according to ISO 2631/1, 1997, the influence of the mechanical vibrations on human health is evaluated and assessed with four methods: the health guidance caution zones (HGCZ), the estimated vibration dose value (eVDV), the fourth power vibration dose value (VDV), a combination of various methods presented in literature. The normative refers to the HGCZ, which involves the average RMS vibration emission level and its exposure time during a given working day. Values of crest factor for the operator seat showed that Z-axis was the more solicited, even if all the crest factor values are below 9. Results of mechanical vibration in respect of comfort and health, according with the method of the HGCZ, showed that only case B, at higher forward speed, does not exceed the lower boundary of the zone. According to the fourth power vibration dose method and ratios for comparison of basic and additional methods of evaluation, the results showed that only case A, at lower forward speed, does not exceeded 1.25.

Keywords: whole body vibration, tractor, comfort, health risk, tyres

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1 Introduction

Agricultural machinery is within the vehicle group with the highest vibration exposure and this certainly applies in the low-frequency range (1.5 – 5Hz) when driving under road conditions. In the first part of this investigation (Servadio et al., 2013), the analysis of the driving seat vibration has been considered. As is known, the vibration is transmitted to the body as a whole, through the supporting surfaces such as floors, seats, back rests and so on. However, the actual valuation of the damage on the human body depends not only on the quantitative vibration level but also on the time length of the vibration exposure. While RMS vibrations magnitude is a good representation of processes whose vibrations are continuous or intermittent rather than shock like, Vibration Dose Value (VDV) is a cumulative measure and therefore a well suited one to reflect the total exposure. A number of studies show that the musculo-skeletal system possesses a somewhat resonant response, with motion entering at the seat/buttocks interface being magnified at certain frequencies, and at certain location within the body. The resonance frequency varies between seats but is often approximately 2 Hz (Bovenzi and Betta, 1994; Servadio et al., 2007; Pessina et al., 2012). The frequency of maximum response (in the lumbar/thoracic region) to vertical motion is around 5 Hz and varying between different subjects, generally in the range (4−6 Hz); the low-frequency range (2−8 Hz) is crucial for good drivers'

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comfort and health, and work efficiency (Hostens et al., 2004).

The pressure distribution at human seat interface is affected by seat height, posture, type of cushion, frequency and vibration. Dhingra et al., (2003) found that: the dynamic pressure at interface is nearly sinusoidal in the vibration range of 1-10 Hz; under vibration excitation, increase in excitation magnitude causes increased maximum ischium pressure and maximum effective contact area around resonant frequency of 4.5 to 5.0 Hz. They concluded that: postural stress, whole body vibration and shocks are recognized as important factors, causing low back pain and this, however, can be reduced by provision of lumbar support, side support and suitable cushion type.

Increased low-frequency levels between 0.5 and 10 Hz are transmitted to the seat during field operation and cyclic motions like those caused by vehicles tyres hitting the road elevated the vibration levels in the frequency range of 2 − 20 Hz. The backbone is especially susceptible to severe physical damage in this frequency range. The damage is caused through cumulative trauma and is therefore difficult to be assessed (Scarlett et al., 2007).

There are several standards available for the evaluation of human exposure to whole body vibration which provides guidelines for minimizing the risk of physical damage due to exposure to high levels of vibrations (The international standard ISO 2631 for evaluation of human exposure to whole-body vibration was published in 1978. Revision version was than published in 1985 and 1997) or national standard (BS 6841, 1987) on whole body vibrations. Specific standards have been set up for the tractor both for laboratory measurements (ISO 5008, 1979) and for measurements on normalized track (ISO 5007, 1990). Griffin (1998) has carried out a comparison of standardized methods for predicting the hazard of whole-body vibration and repeated shocks offered in ISO 2631, 1974 and 1985; BS 6841, 1987 and ISO 2631, 1997. Paddan and Griffin (2002) have compared ISO 2631/1, 1997 and BS 6841, 1987 to evaluate the vibration efficiency of seating in different categories of work vehicles among the tractors. For the analysis of the vibration magnitude they have compared the two frequency weightings defined for evaluation exposures of seated person to vertical vibration: W_b as defined in British Standard BS 6841 and W_k as defined in ISO 2631/1, 1997 and two averaging methods R.M.S. and VDV. Results have shown that the seat values calculated using frequency weightings W_k (from ISO 2631/1, 1997) were slightly greater than those calculated using weightings W_b(from BS 6841, 1987) for both the R.M.S. and VDV methods of calculation. The average percentage difference for all vehicles was only 6%, both for the R.M.S. and the VDV methods of calculation.

General standards like ISO 2631 and BS 6841, used for all types of vehicles in which whole-body vibrations exposure occurs, were improved in a Vibration Directive (2002/44 EC) with exclusively prevention value. In order to set minimum standards for controlling the risk, the directive sets an 8 h reference period 'daily exposure limit values' 1.15 m s^{-2} or a vibration dose value $s^{-1.75}$ above which workers must not be exposed and 'daily exposure action values' of 0.5 m s^{-2} or a vibration dose value of 9.1 m $s^{-1.75}$ above which it requires employers to control the vibration risks. To meet this directive the development of adequate suspension systems in seat, cabin and axles need to be taken into account in the design or improvement of mobile machinery (Hansson, 2002; Deprez et al., 2005a).

Agricultural tyre characteristics have also been taken into consideration to predict vibration in some models, for example Deprez et al. (2005b) claimed that a series of measurements on a non–linear suspension has been illustrated for the sake of the minimization of the vibrations transmitted to the tractor pilot. Several other papers, for example, Clijmans et al. (1996), have done researches in the ground-tyre interaction by means of concentrated parameters models in order to evaluate seat vibrations. Stayner et al. (1984) have used a model to minimize the tractor vibrations by optimizing some technical parameters. An interesting discussion about the model degrees of freedom (DOF) has been also provided and it has been showed that sometimes 1 DOF models are good enough if only the vertical accelerations are to be simulated. Prasad et al. (1995) have compared different tractor's seat models and they showed that a proper seat suspension system is able to dampen considerably the accelerations, although this result doesn't apply to the low frequencies. Crolla and Horton (1984) and Crolla et al. (1990) have suggested two models to simulate the dynamic behavior and vibrations of a vehicle in off–road conditions. Such models can be used also in order to optimize some tractor properties. Finally, Kumar et al. (2001) has proposed other concentrated parameters which take into account some human body parts, for example, head, chest, diaphragm, abdomen and pelvis, and also the seat structure parts, stiffness and damping, and some effects of vibrations inside the human body have been simulated and investigated.

2 Procedures

Crest factor, one of the basic evaluation methods of the vibration Standard ISO 2631/1 (1997) was also used, and it is defined as the ratio of the maximum instantaneous peak value of the frequency-weighted acceleration signal to its R.M.S. value. The peak value shall be determined over the duration of measurement i.e. the time period T used for the integration of the R.M.S. value. The crest factor may be used to investigate if the basic evaluation method is suitable for describing the severity of the vibration in relation to its effects on human beings. For vibration with crest factors below or equal to 9, the basic evaluation method is normally sufficient.

3 Health risk of vibration

In this paper, according to Standard ISO 2631/1 (1997) a mechanical vibration of an operating tractors riding on rectilinear plain tract of a bituminous conglomerate closed track (Figure 1), in respect of comfort and health were evaluated and assessed with the following methods:

1. the health guidance caution zones (HGCZ) involving average R.M.S. vibration emission level and its period of use during a given working day,
2. the estimated vibration dose value (eVDV),
3. the fourth power vibration dose value (VDV) and
4. ratios for comparison of basic and additional methods of evaluation.

Figure 1 View of the tractor during the tests

The method of HGCZ involving average R.M.S. vibration emission level and its period of use during a given working day, within the limit of health guidance caution zone of 4 h (first exposure duration) and 8 h (second exposure duration). ISO 2631/1 (1997) standard, in Appendix B, shows a "health guidance caution zones" graph that is reported, for the sake of completeness, in Figure 2 (Figure B.1 of the Standard).

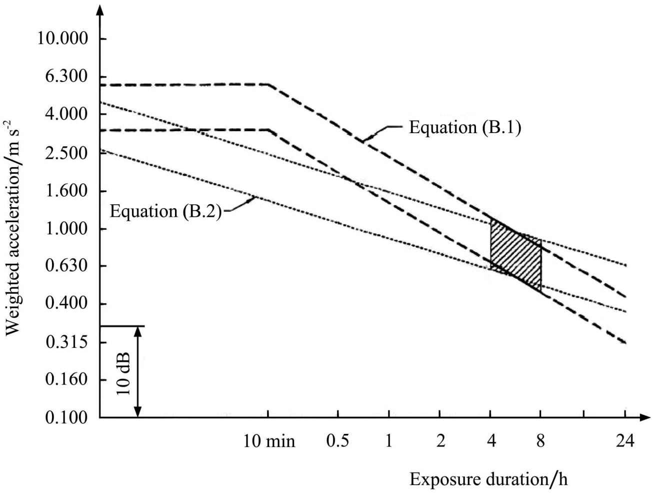

Figure 2 View of the Health Guidance Caution Zones graph (ISO 2631/1, 1997)

The method of 'health guidance caution zone' involves average RMS vibration emission level and its exposure time during a given working day. The HGCZ provides some indication about health vibration effects, mainly based on the response of the human body (in the sit position) to vibrations.

It is within the limit of health guidance caution zone of 4 h (first exposure duration) and 8 h (second exposure duration). Assuming responses are related to energy, two different daily vibration exposures are equivalent when Equation (1):

$$a_{w1} \times \sqrt{T_1} = a_{w2} \times \sqrt{T_2} \tag{1}$$

where, a_{wj} refers to the driver seat acceleration vector sum and T_{j} is the time measuring (for the two cases $j = 1$, 2).

A health guidance caution zone is indicated by dashed lines (Figure 2). The standard states that: for exposure below the zone, health effects have not been clearly documented and/or objectively observed; in the zone, caution with respect to potential health risks is indicated and above the zone, health risks are likely. This recommendation is mainly based on exposures in the range of 4 h to 8 h as indicated by shading in Figure 2. Shorter durations should be treated with extreme cautions.

Other studies indicate time-dependence according to the following relationship (Equation (2)):

$$a_{w1} \times \sqrt[4]{T_1} = a_{w2} \times \sqrt[4]{T_2} \tag{2}$$

This health guidance caution zone is indicated by dotted lines in Figure B.1. The HGCZ for Equation (1) and Equation (2) are the same for duration from 4 h to 8 h for which most occupational observations exist.

The R.M.S. value of the frequency-weighted acceleration can be compared with the zone shown in Figure B.1 at the duration of the expected daily exposure.

To characterize daily occupational vibration exposure, the 8 h frequency-weighted acceleration a_w can be measured or calculated according to the Equation (3) with 8 h as the time period T.

$$a_w = \left\{ \frac{1}{T} \int_0^T a^2{}_w(t)dt \right\}^{\frac{1}{2}} \tag{3}$$

where, $a_w(t)$ is the weighted acceleration in m s^{-2} as a function of time.

The estimated vibration dose value method defined as Equation (4):

$$eVDV = 1.4a_w \times \sqrt[4]{T} \tag{4}$$

Corresponding to the lower and upper bound of the zone given by Equation (2) are 8.5 m s$^{-1.75}$ and 17 m s$^{-1.75}$ respectively.

The fourth power vibration dose method is more sensitive to peaks than the basic evaluation method by using the fourth power instead of the second power of the acceleration time history as the basis for averaging. The fourth power vibration dose value (VDV) in m s^{-1} to the power 1.75 (m s$^{-1.75}$), or in rad s^{-1} to the power 1.75 (rad s$^{-1.75}$), is defined as Equation (5):

$$eVDV = \left(\int_0^T a_{wi}^4(t)dt \right)^4 \tag{5}$$

where, $a_{wi}(t)$ is the instantaneous frequency-weighted acceleration. Ratios for comparison of basic and additional methods of evaluation were used. Experience suggests that the additional evaluation methods are important for the judgment of the effect of vibration on human beings when the following ratios are exceeded (depending on which additional method is being used) for evaluating health or comfort (Equation (6)):

$$\frac{VDV}{a_{wi}} = 1.75 \tag{6}$$

With the VDV, the estimated vibration dose value can be substituted into the Equation (7), giving by Griffin (1998):

$$\frac{VDV}{eVDV} = 1.25 \tag{7}$$

The standard is therefore saying that the RMS accelerations value can be used unless the vibration dose value is 25% greater than the estimated vibration dose value (obtained from the RMS accelerations value). The RMS evaluation method produces a value which is an average vibration exposure adjusted to represent an 8-h working day, whereas the eVDV represents cumulative exposure to vibration over the working day. In fact the standard also states that: Increased duration (within the working day or daily over years) and increased vibration intensity mean increased vibration dose and are assumed to increase the risk, while periods of rest can reduce risk. There are not sufficient data to show a quantitative relationship between vibration exposure and risk of health effect. Hence it is not possible to assess whole-body vibration in terms of the probability of risk at various exposure magnitudes and durations. Regarding continued exposure to vibration, the standard states that: It generally takes several years for health changes caused by whole-body vibration occur. It is therefore important that measurements are representative of the whole exposure period (Scarlett et al., 2007 and Paddan and Griffin, 2002)

4 Results and discussion

4.1 Crest factor

Results which show high values of the crest factor on rear axle was not suspended (Table 1), and this means that the accelerations are impulsive with the prevailing lateral direction (Y-axis), for the tyre A and longitudinal direction(X-axis) for the tyre B. Values of crest factor for the operator seat showed that vertical Z-axis was the most solicited. However all the crest factor values for the operator seat are below 9 and according with Standard ISO 2631/1 (1997), for vibration with crest factors below or equal to 9, the basic evaluation method is normally sufficient.

Table 1 Mean values of crest factor for each axis, for the tests on tractor equipped with tyres A and B

Part	Axis	Tyre A		Tyre B	
		11.1 m s^{-1}	13.9 m s^{-1}	11.1 m s^{-1}	13.9 m s^{-1}
Rear-axle	*x*	11	19.14	20.00	17.50
	y	15.12	23.44	4.74	7.50
	z	5.85	22.50	8.57	8.19
Operator-seat	*x*	1.50	1.90	1.37	2.5
	y	1.05	2.00	1.60	2.53
	z	2.57	5.33	3.43	3.57

4.2 Health risk of vibration

Values of limit of health guidance caution zone and estimated vibration dose value (eVDV) according with ISO 2631/1 (1997) are shown in Table 2. In the specific test conditions, according with the method of the "Health guidance caution zone" (Figure 1.), an 8 h exposure to a magnitude over 0.93 m s^{-2} R.M.S. is required to exceed the upper boundary of the health guidance caution zone at 17 m s$^{-1.75}$, but an 8 hours exposure to a magnitude of only 0.47 m s^{-2} R.M.S. accelerations is required to exceed the lower boundary of health guidance caution zone, at 8.5 m s$^{-1.75}$. According to the results showed in Part I, dedicated to the analysis of the driving seat vibration, average value of the R.M.S accelerations obtained from the measurements carried out on tyre B at 13.9 m s^{-1} forward speed was smaller (0.44 m s^{-2}) than 0.47 m s^{-2}, and therefore (see Table 2) it was not exceeding the lower boundary of HGCZ (eVDV = 8.03 m s$^{-1.75}$). For this vibration emission level and exposure time, health effects have not been clearly documented or objectively observed.

Table 2 Values of limit of health guidance caution zone and estimated vibration dose value (eVDV) according with ISO 2631/1 (1997)

Tyre	Speed /m s^{-1}	a_w /m s^{-2}	Lower-boundary exceeding	Upper-boundary exceeding	eVDV /m s$^{-1.75}$
A	11.1	0.54	yes	no	9.85
A	13.9	0.48	yes	no	8.75
B	11.1	0.47	yes	no	8.57
B	13.9	0.44	no	no	8.03

Measurements carried out on tyre B at 11.1 m s^{-1} forward speed were similar in magnitude, 0.47 m s^{-2} R.M.S. (eVDV = 8.57 m s$^{-1.75}$), and measured carried out on tyre A, at the 13.9 and 11.1 m s^{-1} forward speed, were higher in magnitude (0.48 and 0.54 m s^{-2} respectively) then 0.47 m s^{-2} R.M.S. (eVDV = 8.75 and 9.85 m s$^{-1.75}$), exceeding the lower boundary of health guidance caution zone. In the HGCZ zone, caution with respect to potential health risks is indicated in all cases if the duration of exposure is 8 h within a 24 h period.

The results of the fourth power vibration dose value (VDV) and ratio for comparison of basic and additional methods of evaluation are shown in Table 3. This power vibration dose method is more sensitive to peaks than the basic evaluation method, and the results show (Table 3) that the ratios do not exceed 1.75 using additional method therefore, in these cases, additional evaluation methods will not be important for the judgment of the effect of vibration on human. The results also show (Table 3) that using additional method, in one case only (tire A at 11.1 m s^{-1} forward speed) the ratios don't exceeded 1.25. For all others treatments, the ratios exceeded 1.25 and according with the standard, the use of the additional evaluation methods is important for the judgment of the effect of vibration on human beings for evaluating health.

Table 3 VDV, ratios between VDV and $a_w T^{1/4}$, ratio between VDV and eVDV according with ISO 2631/1 (1997)

Tyre	Speed /m s^{-1}	a_{wi} /m s^{-2}	VDV /m s$^{-1.75}$	$\frac{VDV}{a_{wi}T^{1/4}} = 1.75$	$\frac{VDV}{eVDV} = 1.25$
A	11.1	0.89	11.6	1.00	1.18
A	13.9	1.20	15.6	1.03	1.78
B	11.1	0.96	12.5	1.01	1.46
B	13.9	1.33	17.3	1.05	2.16

Comparing the data of RMS accelerations on the driver seat in the vertical and lateral directions in the 1 − 80 Hz frequency range, some exposure criteria curves that defines equal fatigue-decreased proficiency boundaries has been detected. The values of limit fatigue for all treatments are bounded within the limit reported in Table 4.

Table 4 Values of limit fatigue according to Standard ISO 2631 (1978)

Tyre	Forward Speed/m s^{-1}	Limit fatigue/h
A	11.1	4
A	13.9	8
B	11.1	4
B	13.9	8

From Table 4, it is worth noticing that the highest risk applies at a lower speed both for tyre A and B. In fact, as described by Servadio et al., (2013), it appears that the shortest tolerable time range in case A is due to the highest values within the low frequencies vibrations range, form 1−2 Hz, probably due to rolling. Analogously, for case B, it can be shown that the shorter tolerable time exposure for 11.1 m s^{-1}, with respect to the 13.9 m s^{-1} speed, was due to the x-axis vibrations, perhaps due to pitch oscillations, which implies higher values in the 1.5 − 3.8 Hz range.

5 Conclusions

During farm operation, vibrations arising from the soil-tractor interaction and transmitted to the operator seat, can cause discomfort to the drivers who often are victims of backbone problems. The experimental campaign performed in Part I (Servadio et al., 2013) has shown that the tyres type can influence the ride vibration at different speeds. In fact, in the present Part II, the effects of the two different tyres and speeds on human health, have been evaluated in terms of vibration emission level and exposure time. According to the method of the health guidance caution zone, only case B, at higher forward speed, does not exceed the lower boundary of the zone. All the other test cases reenter in the HGCZ, witnessing potential health risks if the exposure duration is 8 h within a 24 h period.

At these elevated forward speeds, in order to assure a suitable reduction in driver's health risk, the obtained results would suggest a reduction in the total hours worked at less than 8 h per day. Comparing the stipulated values with the exposure criteria curves (Standard ISO 2631, 1978), at higher forward speed, the limit fatigue was equal to 8 h for both A and B cases. Moreover, in order to maintain the guidance efficiency of the driver along the whole working day at the best level, the improvement of the vibration comfort should be conveniently stressed, referring to the requirements suggested by 2002/44 EC Directive.

In conclusion, with forward speed increasing, further studies and measurements to improve the comfort and health on wheeled tractors are urgently required. Besides the seat equipped with a pneumatic suspension, a front swing axle and hydro-pneumatic height-controlled suspension, possible solutions could include the universal adoption suspension devices on both axles.

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