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RESEARCH ARTICLE

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Vibration analysis on driver's seat of agricultural tractors during tillage tests

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Abstract

The vibration of the driver's seat of agricultural tractors was investigated during three alternative tillage operations. Three tractors including a range of specifications were considered, at a range of forward speeds. The interactions between the tractors, implements and speeds were examined using the SPSS program and the GLM-ANOVA method. The results analysis indicated that the tractors played the first major role in vibration development in the lateral axis and was followed by the implements. In contrast, the implements played the first major role in the development of vibration in the horizontal axis and are followed by factor tractors. The statistically significant effect in vertical and horizontal axes shows the factor implements. In addition, the statistically significant effect in the vertical and lateral axes shows again the implements to be the most significant factor. Of the implements, the plough shows the highest vibration and displays statistically significant difference in comparison with the other implements.

Additional key words: ergonomics; transport; suspension system; piezoelectric acceleration sensor; implement; GLM-ANOVA test.

Abbreviations used: ELV (exposure limit value); GLM (generalized linear model); VDV (vibration dose value)

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Introduction

The vibration that occurs on agricultural tractors has an effect on the driver because of the reduced comfort, impaired activities and possible health degradation of the drivers. The limit values for exposure to vibration must not exceed allowed values referred to the protection of the drivers and shall be based on the European Parliament and Council Directive 2002/44/EC (OJ, 2002), and the International Organization for Standardization ISO 2631-1:1997 (ISO, 1997).

Important factors that significantly influence the whole body vibration are driving speed and ground unevenness (Oude Vrielink, 2009). The vibration transmitted from the ground to the driver's seat of a ballasted wheeled tractor, equipped with a front suspension axle and a suspended cab, have been measured and analyzed by Servadio & Belfiore (2013a). Two different tyres and two different forward speeds have been experimentally tested, during the simulation of the front agricultural implements transportation on a rectilinear plane tract of a conglomerate bituminous closed track. In addition, Servadio & Belfiore (2013b) studied the influence of the mechanical vibration on human health and assessed it with four methods: the health guidance caution zones, the estimated vibration dose value, the fourth power vibration dose value (VDV), and a combination of the methods. Fairley (1995), Buchholz *et al.* (1997), and Goglia *et al.* (2003) studied different forms of vibration and found that they are transmitted to the driver's body via the seat, to the feet via the floor, and to the hands via the steering wheel. Furthermore, exposure to high-frequency vibration for a long time period can cause health risks to the drivers such as: vascular, neurological and musculoskeletal disorders, which in most cases are usually permanent (Boshuizen *et al.,* 1990; Kumar *et al.,* 2001). The resonance behavior of the human body is very important in the identification of vibration frequencies and body postures associated with musculoskeletal problems (Park & Subramaniyam, 2013). The low-frequency vibration below 10 Hz results in various combinations of bending deformations of the spine, vertical motion of the viscera, axial and shear deformations of the buttocks tissue, pitching motion of the pelvis and pitching motion of the head (Bovenzi & Betta, 1994; Kitazaki & Griffin, 1998).

The reduction in vibration transmitted to the drivers of modern tractors was achieved by means of one or more suspension systems provided between the vibration source and the driver's body (*e.g.* cab, seat, and front axle suspension systems). Passive and active tractor suspension systems have been studied by many researchers. Marsili *et al.* (2002) adopted an innovative system that is able to reduce vibrations transmitted to the driver's seat using a front axle suspension system and a shock absorber for the implement connection. The front axle suspension system involved a large reduction of about 15% to 30% of acceleration. The shock absorber created a variable behavior depending on the test condition; it caused both attenuation and amplification, although when in combination with the suspension it often involved an average reduction in acceleration (24%). Shamshiri & Ismail (2013) described the design of a full-state active suspension control system with a feedback for the Kubota M110X agricultural tractor. The active suspension control system has the potential to improve ride comfort by dissipating the resulting oscillations within a settling time of less than five seconds and overshoot of about 10 % of the inputs disturbance.

Modern tractor seats are equipped with different type of suspension systems. The type of suspension systems may include pneumatic, hydraulic, mechanical, or combination of these suspension systems (Drakopoulos, 2008; Maciejewski *et al.,* 2010). The first seat suspension systems provided suspension only in the vertical axis based on a coil spring and telescopic hydraulic dampers. Many modern operator seats still utilize this design. During recent years, the majority of operator seats utilize an air spring and damper suspension systems in the vertical axis, as well as a mechanical spring and damper systems in the horizontal axis (Braghin *et al.,* 2011). Smart seats utilize electro-hydraulic and air suspension systems with electronic control of ride height and dynamic adjustment of suspension stiffness. Sankar & Afonso (1993) investigated the lateral ride performance of an off-road vehicle with a seat suspension having a dynamic vibration absorber. This prototype suspension system was tested in the laboratory under field conditions. The results showed that the seat suspension can significantly improve ride by 75 % and reduce peak relative displacement by 7 %. Paddan & Griffin (1988), studied the vibration in the three translational and three rotational axes of head motion during exposure to whole body random vibration. It was found that seat-to-head transmissibilities are shown up to frequencies of 25Hz for all six axes of head vibration.

A substantial proportion of tractor vibration resulted from the dynamic movement of a long, heavy implement such as a plough during road/track transport. These vibrations are transferred from the implement to the tractor chassis via the 3-point linkage. According to Scarlett *et al.* (2005), an effective dynamic ride control system can substantially reduce the ride vibration of the tractor-implement combination during road/track transport.

Loutridis *et al.* (2011) focused on the effect that the electronic engine speed regulator has on tractor ride vibration levels. A tractor with electronic engine speed regulator was driven on a predefined track in two basic series of tests. First, on a conglomerate bituminous track at speeds of 20, 25 and 28 km/h, and then on a rough farm track at speeds of 6, 7.5 and 9 km/h. Vibration was measured upon the surface of the driver seat simultaneously in the x*,* y and z axis. In the first case, the weighed r.m.s. acceleration was found to be between 8% and 8.6% higher for the case where operation with electronic speed adjustment had been selected. In the second case, the vibration levels with automatic speed adjustment were between 4.3 % and 8.6 % lower than when driving with normal foot pedal operation.

The aim of this work was to measure, record, and analyze in field conditions the vibration experienced by the tractor's seat during the seedbed preparation with different tractors, different implements and different speeds. The main effects of the factors to be considered were: tractors, implements and speeds. Additionally, the interaction was examined that occurs between: a) tractors and implements, b) tractors and speeds, c) implements and speeds, and d) tractors, implements and speeds.

Material and methods

The experimental tests were conducted at the Department of Biosystems Engineering at the Technological Educational Institute of Thessaly (Greece). The testing

Table 1. Technical specifications of the agricultural tractors.

Technical specifications	Tractor A	Tractor B	Tractor C
Engine type	1000.6 WT	1000.4 WT	BF6M1012C
Engine power, kW/HP	85/115	70/95	94/126
Max engine speed, rpm	2600	2600	2300
Speed regulator	Electronic	Electronic	Electronic
Gearbox type	Full synchronized	Full synchronized	Automatic power shift
Three point hydraulic linkage	Electronic	Electronic	Electronic
Wheel drive	4WD	4WD	4WD
Front axle suspension	No	No	Yes
Cab suspension	Silent-blocks	Silent-blocks	Pneumatic springs
Operators seat adjustment	Mechanical	Mechanical	Pneumatic
Driver's seat	Granular	Linear	Linear
Front power takeoff (PTO)	Yes	No	No
Front ballast weight, kg	500	320	600
Tyres dimensions (rear-front)	480/70R34-420/70R24	16.9R34-14.9R24	580/70R38-480/70R24
Tyres pressure, bar	1.6	1.6	1.6
Tractor dimensions (length × width × height), mm	4590×2250×2905	4123×2000×2660	4587×2304×2922
Wheelbase, mm	2750	2373	2647
Total weight, kg	5280	3650	5460

procedure was performed on the same field, which was uncultivated and contained grain remains from the previous crop year. The soil moisture content was 25 %, which remained constant during all of the experiment. The soil texture was sandy clay loam and the environment temperature was 22ºC. The implements working depth was kept constant to achieve comparable results.

For the experimental tests three different types of tractors and three different types of implements were used at four speeds. The full technical specifications of agricultural tractors are shown in Table 1. The tillage implements for seedbed preparation were: a) plough, b) disk harrow, and c) cultivator. The 3-furrow plough was reversible with hydraulic reverse, and the possibility to increase the maximum width of tillage to 1.50 m. The tillage depth was set to 0.20 m. The disk harrow consisted of 33 disks (0.50 m diameter). The working width was set to 3.20 m, and the working depth was 0.11 m. The cultivator consisted of five rows of S-type tines. In total 60 S-type tines were mounted on the cultivator frame with the possibility of setting the distance between them. The working width was at 3.0 m. At the rear end of the cultivator, two rows of adjustable rotating rollers were placed. Each row consisted of three pieces. The rollers had triangular teeth helically arranged into their periphery for better fragmentation of the soil. The tests were carried out at 4 different speeds: a) 5.0 km/h, b) 8.0 km/h, c) 12.0 km/h, and d) 16.0 km/h. The same driver was employed for all tillage tests.

The vibration of the seat was measured using piezoelectric acceleration sensors AS-065 from Brüel & Kjaer Vibro. Acceleration sensors technical data are provided in Table 2. The sensor was mounted to the metal base under the seat (Fig. 1) and measured the acceleration in three orthogonal axes (X, Y and Z). The reference axis system was defined according to ISO 5008:1979, ISO 2631-1:1997, ISO 10326-2:2001 and ISO 8041:2005 (ISO, 1979, 1997, 2001, 2005) with the X axis corresponding to horizontal direction (along of the tractor travel), the Y axis to lateral direction (across the tractor travel), and Z axis vertical direction.

Table 2. Technical data of the piezoelectric acceleration sensor with integrated charge amplifier (AS-065).

Type	Acceleration sensor
Transmission factor, mV/g	100 ± 5 %
Frequency range, Hz	1…15000 (± 3dB)
Resonance frequency, kHz	35 ± 3
Operating temperature range, °C	−50 … + 120

A portable instrument Vibrotest 60 from Brüel & Kjaer Vibro was used for data collection. The Vibrotest 60 has a vibration measurement accuracy ±2% of measured value. A sampling rate of 1600 samples per second was used and typically 120 s of data were acquired in each single experiment. The measurements were stored in a PC-card memory PCMCIA with a capacity of 32 Mbytes.

All data were transferred to a computer and analyzed using the SPSS software to verify differences among agricultural tractors, and implements, using the Generalized Linear Model (GLM) with analysis of variance (ANOVA) test. Details on GLM and ANOVA can be found in McCullagh & Nelder (1999) or Rutherford (2011).

Figure 1. Setup for measuring vibration in the Zm and Xm axes.

Results

Vibration analysis in the horizontal axis Xm

Table 3 presents the results of the tillage tests derived from maximum values of averages, for the different factors in the horizontal axis Xm. The analysis of model gives the opportunity to validate the significance of the main effects and interactions of field conditions in Xm. The inputs to the model were acceptable, because of the high value of the coefficient of determination R^2=0.698. Table 3 revealed the following points:

a) The factor “TRACTORS” has a statistically significant effect in Xm, (F(2,32)=8.190, p<0.001, η^2=0.339),

b) The factor “IMPLEMENTS” has a statistically significant effect in Xm, (F(2,32)=11.638, p<0.001, η^2=0.421),

c) The factor “SPEEDS” has no statistically significant effect in Xm, (F(3,32)=2.631, p=0.067, η^2= 0.198),

d) The 1st degree of interaction from factors “TRACTORS × IMPLEMENTS” was not statistically significant in Xm, (F(3,32)=1.934, p=0.144, η^2= 0.154),

e) The 1st degree of interaction from factors “TRACTORS × SPEEDS” was not statistically significant in Xm, (F(3,32)=0.861, p=0.471, η^2= 0.075),

f) The 1st degree of interaction from factors “IMPLEMENTS × SPEEDS” was statistically significant in Xm, (F(1,32)=0.8144, p=0.008, η^2= 0.203),

g) The 2nd degree of interaction from factors “TRACTORS × IMPLEMENTS × SPEEDS” was not statistically significant in Xm, (F(1,32)=0.411, p=0.526, η^2= 0.013).

The above (based on the values of η^2) lead to the conclusion that the greatest statistically significant effect in Xm shows the factor “IMPLEMENTS” and the “TRACTORS”.

Vibration analysis in the lateral axis Ym

Table 4 presents the results of the tillage tests derived from maximum values of averages, for the different factors in the lateral axis Ym. The inputs to the model was acceptable, because of the high value of the coefficient of determination R^2=0.732. Table 4 revealed the following points:

a) Factor “TRACTORS” has a statistically significant effect in Ym, (F(2,32)=14.096, p<0.001, η^2=0.468),

b) Factor “IMPLEMENTS” has a statistically significant effect in Ym, (F(2,32)=6.892, p=0.003, η^2=0.301),

c) Factor “SPEEDS” has no statistically significant effect in Ym, (F(3,32)=1.800, p=0.167, η^2= 0.144),

d) The 1st degree of interaction from factors “TRACTORS × IMPLEMENTS” was statistically significant in Ym, (F(3,32)=4.421, p = 0.010, η^2= 0.293),

e) The 1st degree of interaction from factors “TRACTORS × SPEEDS” was not statistically significant in Ym, (F(3,32)=1.102, p=0.363, η^2= 0.094),

f) The 1st degree of interaction from factors “IMPLEMENTS × SPEEDS” was not statistically significant in Ym, (F(1,32)=0.770, p=0.387, η^2= 0.024),

Table 3. ANOVA test results for the Xm.

Variables	Mean (m/s^2)	SD	df	F	p	η^2
TRACTORS	0.038	0.075	2	8.190	< 0.001	0.339
IMPLEMENTS	0.054	0.107	2	11.638	< 0.001	0.421
SPEEDS	0.012	0.036	3	2.631	0.067	0.198
TRACTORS × IMPLEMENTS	0.009	0.027	3	1.934	0.144	0.154
TRACTORS × SPEEDS	0.004	0.012	3	0.861	0.471	0.075
IMPLEMENTS × SPEEDS	0.037	0.037	1	8.144	0.008	0.203
TRACTORS × IMPLEMENTS × SPEEDS	0.002	0.002	1	0.411	0.526	0.013
Error	0.005	0.147	32			
Total		0.487	47			

R^2=0.698, R^2_{ads}=0.557, for $p \leq 0.05$ confirmed that there was statistically significant difference.

g) The 2nd degree of interaction from factors "TRACTORS × IMPLEMENTS × SPEEDS" was not statistically significant in Ym, (F(1,32)=0.869, p=0.369, η^2= 0.144).

Given the above (based on the values of η^2) we can conclude that the greatest statistically significant effect in Ym was from the "TRACTORS" while the factor "IMPLEMENTS" follows.

Vibration analysis in the vertical and horizontal (Zm and Xm) axes

Table 5 presents the results of the tillage tests derived from maximum values of averages, for the different factors in the vertical and horizontal (Zm and Xm) axes. The inputs to the model was acceptable, because of the high value of the coefficient of determination R^2=0.825. Table 5 revealed the following points:

a) Factor "TRACTORS" has no statistically significant effect on Zm and Xm, (F(2,32)=3.297, p=0.050, η^2=0.171),

b) Factor "IMPLEMENTS" has a statistically significant effect in Zm and Xm, (F(2,32)=44.383, p<0.001, η^2=0.735),

c) Factor "SPEEDS" has no statistically significant effect in Zm and Xm, F(3,32)=0.683, p=0.569, η^2= 0.060),

d) The 1st degree of interaction from factors "TRACTORS × IMPLEMENTS" was not statistically significant in Zm and Xm, F(3,32)=2.741, p=0.059, η^2= 0.204). This confirms that factors "TRACTORS × IMPLEMENTS" did not cause any significant worsening of the damping quality in Zm (vertical) and Xm (horizontal) axes.

e) The 1st degree of interaction from factors "TRACTORS × SPEEDS" was not statistically significant in Zm and Xm, F(3,32)=0.401, p=0.753, η^2= 0.036),

f) The 1st degree of interaction from factors "IMPLEMENTS × SPEEDS" was not statistically significant in Zm and Xm, F(1,32)=1.405, p=0.245, η^2= 0.042),

g) The 2nd degree of interaction from factors "TRACTORS × IMPLEMENTS × SPEEDS" was not statistically significant in Zm and Xm, F(1,32)=2.940, p=0.096, η^2= 0.084).

Table 4. ANOVA test results for the Ym.

Variables	Mean (m/s^2)	SD	df	F	p	η^2
TRACTORS	0.084	0.167	2	14.096	< 0.001	0.468
IMPLEMENTS	0.041	0.082	2	6.892	0.003	0.301
SPEEDS	0.011	0.032	3	1.800	0.167	0.144
TRACTORS × IMPLEMENTS	0.026	0.079	3	4.421	0.010	0.293
TRACTORS × SPEEDS	0.007	0.020	3	1.102	0.363	0.094
IMPLEMENTS × SPEEDS	0.005	0.005	1	0.770	0.387	0.024
TRACTORS × IMPLEMENTS × SPEEDS	0.005	0.005	1	0.829	0.369	0.025
Error	0.006	0.190	32			
Total		0.708	47			

R^2=0.732, R^2_{ads}=0.606, for $p \leq 0.05$ confirmed that there was statistically significant difference.

Table 5. ANOVA test results for the Zm and Xm.

Variables	Mean (m/s^2)	SD	df	F	p	η^2
TRACTORS	0.039	0.077	2	3.297	0.050	0.171
IMPLEMENTS	0.519	1.039	2	44.383	< 0.001	0.735
SPEEDS	0.008	0.024	3	0.683	0.569	0.060
TRACTORS × IMPLEMENTS	0.032	0.096	3	2.741	0.059	0.204
TRACTORS × SPEEDS	0.005	0.014	3	0.401	0.753	0.036
IMPLEMENTS × SPEEDS	0.016	0.016	1	1.405	0.245	0.042
TRACTORS × IMPLEMENTS × SPEEDS	0.034	0.034	1	2.940	0.096	0.084
Error	0.012	0.375	32			
Total		2.142	47			

R^2=0.825, R^2_{ads}= 0.743, for $p \leq 0.05$ confirmed that there was statistically significant difference.

Given the above (based on the values of η^2) we can conclude that the greatest statistically significant effect in Zm and Xm shows the factor “IMPLEMENTS” while the factor “TRACTORS × IMPLEMENTS” follows.

Vibration analysis in the vertical and lateral (Zm and Ym) axes

Table 6 demonstrates the results of the tillage tests derived from maximum values of averages, for the different factors in vertical and lateral (Zm and Ym) axes. The inputs to the model was acceptable, because of the high value of the coefficient of determination R^2=0.927. Table 6 revealed the following points:

a) Factor “TRACTORS” has no statistically significant effect in Zm and Ym, (F(2,32)=3.211, p=0.054, η^2=0.167),

b) Factor “IMPLEMENTS” has a statistically significant effect in Zm and Ym, (F(2,32)=118.955, p<0.001, η^2=0.881),

c) Factor “SPEEDS” has no statistically significant effect in Zm and Ym, F(3,32)=0.000, p=0.995, η^2= 0.002),

d) The 1st degree of interaction from factors “TRACTORS × IMPLEMENTS” was statistically significant in Zm and Ym, F(3,32)=4.946, p=0.006, η^2= 0.317),

e) The 1st degree of interaction from factors “TRACTORS × SPEEDS” was not statistically significant in Zm and Ym, F(3,32)=0.008, p=0.999, η^2=0.001,

f) The 1st degree of interaction from factors “IMPLEMENTS × SPEEDS” was statistically significant in Zm and Ym, F(1,32)=13.754, p<0.001, η^2=0.301,

g) The 2nd degree of interaction from factors “TRACTORS × IMPLEMENTS × SPEEDS” was not statistically significant in Zm and Ym, F(1,32)=0.012, p=0.169, η^2=0.058,

Given the above (based on the values of η^2) we can conclude that the greatest statistically significant effect in Zm and Ym shows the factor “IMPLEMENTS” while the factor “TRACTORS × IMPLEMENTS” follows.

In the following tables and histograms the effects of maximum values of vibration in axis Xm, for “TRACTORS”, “IMPLEMENTS” and the interactions of “IMPLEMENTS × SPEEDS” are given in detail.

Main effect of factor “TRACTORS” in the horizontal axis Xm

Table 7 and Fig. 2a show the effect of the factor “TRACTORS” in axis Xm and reveal that Tractor A had significant difference in comparison to the other two tractors.

Main effect of factor “IMPLEMENTS” in the horizontal axis Xm

Table 8 and Fig. 2b show the effect of the factor “IMPLEMENTS” in the Xm axis and reveal that:

Table 6. ANOVA test results for the Zm and Ym.

Variables	Mean (m/s^2)	SD	df	F	p	η^2
TRACTORS	0.019	0.037	2	3.211	0.054	0.167
IMPLEMENTS	0.693	1.387	2	118.955	<0.001	0.881
SPEEDS	0.000	0.000	3	0.022	0.995	0.002
TRACTORS × IMPLEMENTS	0.029	0.086	3	4.946	0.006	0.317
TRACTORS × SPEEDS	$4.59\cdot10^{-5}$	0.000	3	0.008	0.999	0.001
IMPLEMENTS × SPEEDS	0.080	0.080	1	13.754	< 0.001	0.301
TRACTORS × IMPLEMENTS × SPEEDS	0.012	0.012	1	1.977	0.169	0.058
Error	0.006	0.186	32			
Total		2.564	47			

R^2=0.927, R^2_{ads}= 0.893, for $p \leq 0.05$ confirmed that there is statistically significant difference.

Table 7. Main effect of factor “TRACTORS” in the Xm.

Tractors	Means (m/s^2)	SE	Confidence interval (95%)	
Tractor A	0.2095	0.016	0.177	0.242
Tractor B	0.269	0.023	0.223	0.315
Tractor C	0.256	0.015	0.226	0.286

Table 8. Main effect of factor "IMPLEMENTS" in the Xm.

Implements	Means (m/s²)	SE	Confidence interval 95%	
Plough	0.2945	0.020	0.255	0.334
Disk harrow	0.240	0.023	0.194	0.286
Cultivator	0.2175	0.013	0.191	0.244

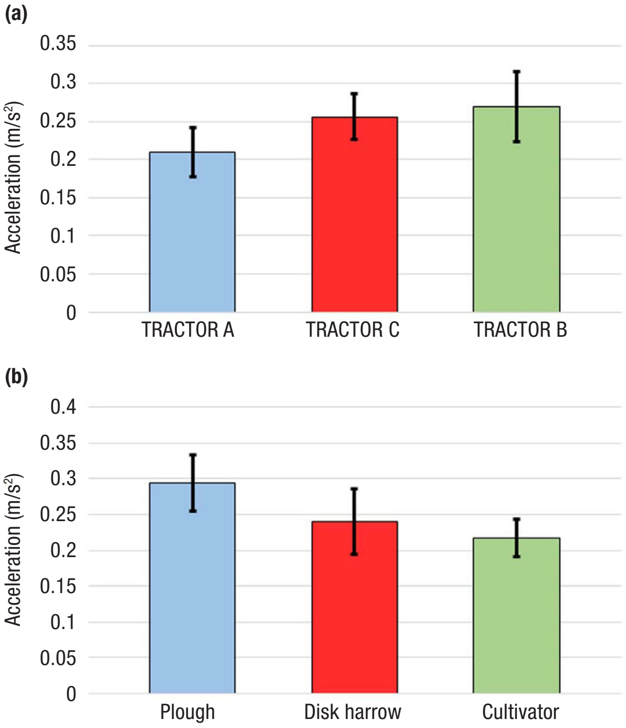

Figure 2. Main effect of factor "TRACTORS" (a) and of factor "IMPLEMENTS" (b) in the Xm.

a) The plough shows the highest vibration and shows statistically significant difference in comparison with the cultivator.

b) The cultivator shows the smallest vibration and displays no statistically significant difference in comparison with the disk harrow.

c) Values of vibration are within the standard permitted limits.

Main effect of factor "IMPLEMENTS × SPEEDS" in the horizontal axis Xm

Table 9 and Fig. 3 show the effect of the factor "IMPLEMENTS × SPEEDS" in axis Xm and reveal that:

a) The vibration when using the plough at 5.0 km/h shows smaller value and displays statistically significant difference compared to the developing vibration at 8.0 km/h.

b) The vibration when using the cultivator at 8.0 km/h shows smaller value and displays statistically significant difference compared to the developing vibration at 12.0 km/h.

c) The vibration using the cultivator at 8.0 km/h shows no statistically significant difference compared to the developing vibration at 5.0 km/h and 16.0 km/h.

d) Values of vibration are within the standard permitted limits therefore no further action required to take place for the driver's health.

Discussion

This research involved three agricultural tractors equipped with damped cabin and/ or front axle. One tractor with lower-power class (< 75kW) was included. In addition, we tried to select tractors of proper size to pull all implements. According to results from the analysis of vibration in the horizontal axis Xm, the factor "TRACTORS" had no statistically significant difference. However, tractor B with lower-power highlighted a poor general comfort level between the three tractors. This was probably due to the less power for the same implements.

In transport the tractor-implement system tends to oscillate and cause typical pitching movements. Using suitable control unit to monitor the force signals from the draft sensors on lift arm attachments, the dynamic implement oscillation control rapidly acts to dampen the oscillations by means of slight movements of the three-point linkage in the transport position. The shock absorbing function of the damping system is activated from the console. The power lift arms carrying the implement lowered from the position of maximum lift excursion by 4%. In this position, the device automatically keeps the oscillation inside 8% (peak-to-peak) of the maximum lift excursion (Marsili *et al.*, 2002). In this research, one of the tractors (Lamborghini R6.130) was equipped with electronic active damping system, while the other two tractors were equipped with conventional mechanical springs. The vibration analysis with mounted implements in three-point linkage during transport has not been investigated, because it is out of the goals of this study.

The manufacturers of agricultural tractors are trying to improve the level of comfort at the driver's cab by reducing both the production and the transmission of vibration. Tractor C (Lamborghini R6.130) was

Table 9. Interaction of factors "IMPLEMENTS × SPEEDS" in the Xm.

Implements	Speeds (km/h)	Means (m/s^2)	SE	Confidence interval (95%)	
Plough	5.0	0.2125	0.028	0.156	0.269
	8.0	0.3765	0.028	0.320	0.433
	12.0	–	–	–	–
	16.0	–	–	–	–
Disk harrow	5.0	–	–	–	–
	8.0	0.240	0.023	0.194	0.286
	12.0	–	–	–	–
	16.0	–	–	–	–
Cultivator	5.0	0.191	0.023	0.145	0.237
	8.0	0.174	0.023	0.128	0.220
	12.0	0.3225	0.028	0.266	0.379
	16.0	0.218	0.039	0.138	0.298

"-" means that we were unable to conduct tests using the specific implement and forward speed.

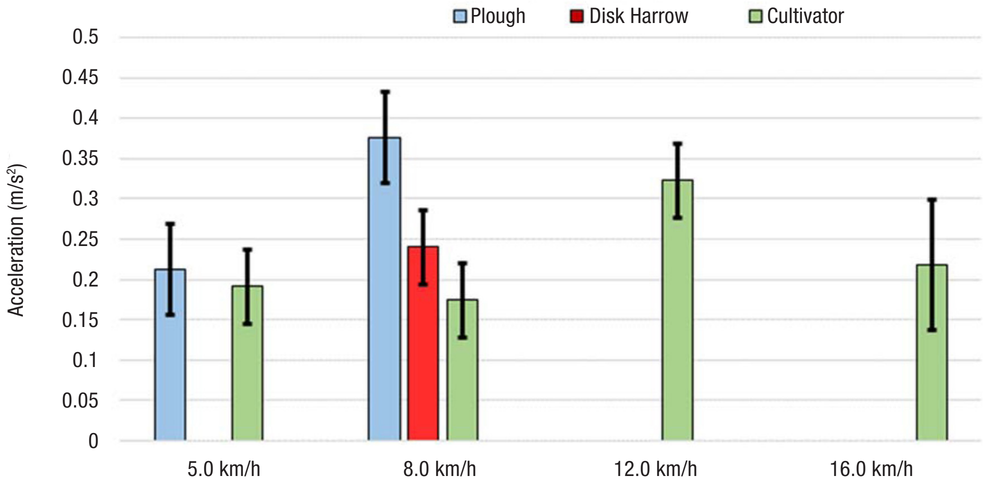

Figure 3. Interaction of factors "IMPLEMENTS × SPEEDS" in the Xm.

equipped with an integral cab suspension system. In the front part of the cab there were silent blocks, while in the rear there were pneumatic springs. The other tractors A and B were equipped with mechanical cab suspension system (the cab mounted on four silent blocks). The results obtained on the three types of tractors (Table 7) are particularly interesting. The tractor A with conventional cab suspension system performed better than tractor C equipped with self-levelling pneumatic cab suspension system.

Figure 3 shows the comparative results of the acceleration analysis for soil tillage with tractor-implement system at different travel speeds of 5, 8, 12 and 16 km/h. The tractor-cultivator system caused higher acceleration at 12 km/h than at 16 km/h. The higher acceleration value (0.3225 m/s^2) at 12 km/h was probably due to resonance phenomena of the tractor-cultivator system.

The International standards used were ISO 2631-1:1997, ISO 10326-2:2001, and ISO 8041:2005 (ISO, 1997, 2001, 2005) with which the estimation of vibration level is defined by two methods: a) the level of daily exposure to vibration A(8), which shows continuous equivalent acceleration at 8 hours working time, and b) vibration dose value (VDV), which represents cumulative dose. The ELV to whole-body vibration is 1.15 m/s^2 A(8) and the VDV is 21 $m/s^{1.75}$. In addition, the exposure action value to whole-body vibration is 0.5 m/s^2 A(8) and the vibration dose value (VDV) is 9.1 $m/s^{1.75}$. The value of ELV to the daily exposure to whole-body vibration A(8) in the "TRACTORS × IMPLEMENTS" was calculated to be 0.631 m/s^2.

The driver's exposure to whole body vibrations greater than the above allowable limits can cause health problems and may reduce the driver's ability to maintain control and stability of the tractors, causing accidents (Hinz *et al.*, 2010; Heidary *et al.*, 2013; Nupur *et al.*, 2013). The horizontal and vertical developing vibration which are coming from none well-matched tractor-implements combination should be avoided.

Manufacturers of agricultural implements should also provide construction elements which must have the possibility of eliminating the vibration which is transferred to the tractors.

In summary, results analysis generated significant effects and interactions on tractor in relation to the implements and speeds used during tillage test. More precisely: Factor "TRACTORS" plays the major role in vibration development in the axis Ym at the driver's seat and then follows the "IMPLEMENTS" factor. In contrast, factor "IMPLEMENTS" plays the first major role in the development of vibration in the axis Xm at the seat and is followed by the "TRACTOR" factor. The statistically significant effect in Zm and Xm axes shows the factor "IMPLEMENTS", and statistically significant effect in Zm and Ym axes, shows again the factor "IMPLEMENTS". There should be a proper selection of each agricultural implement which should be combined with the tractor to be used, given the ability for an "ideal" combination that minimizes the created vibration during tillage. Checks should also be carried out during cultivation with a tractor related to the working speeds, to control the vibration to a minimum level. Finally, tractors with three-point shock absorber for the implements should be used to provide attenuation of the vibration.

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