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Comfort Efficiency of the Front Axle Suspension in Off-Road Operations of a Medium-Powered Agricultural Tractor

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Abstract

The whole-body vibration transmitted through the seat of a 4WD modern tractor of 81 kW max power, equipped with seat, cab and front axle suspension systems were measured and analysed according to the official relevant Standards. The test conditions involved the travelling speed (from 1.11 to 4.44 m s⁻¹), the surface feature (field and rough track), the type of task (tractor alone and coupled with a towed slurry tank) and the front axle suspension condition (working or locked).

After their statistical validation, the results highlight a good efficiency of the front axle suspension in reducing the vibration levels of the tractor alone, while when coupled with the slurry tank the benefit is less evident, especially in the back-front direction.

The lower limit provided by the 2002/44 EC Directive (“action value”, 0.5 m s⁻²) is generally exceeded in all the three axes, apart when travelling at the lowest speed.

Vice versa, the vibration levels exceed the higher limit (“limit value”, 1.0 m s^{-2}) only if the overall RMS values are considered, in the field at 2.22 m s^{-1} and on the rough track at 4.44 m s^{-1} .

Keywords: whole-body vibration, comfort, front axle suspension, agricultural tractor

1 Introduction

Agricultural operator’s comfort has become a key factor institutionally recognized and led to prescriptive and preventive actions, funded by the European Commission [Agri-ergonomics.eu, 2014]. In this context, it is widely recognized that tractor drivers are exposed to high levels of whole-body vibration (WBV) during typical farm operations. Low-frequency tractor ride vibration, the resultant problem of driver discomfort and the possibility of spinal injury became recognised issues during the ‘60s of the last century, but only many years later has legislation been introduced to limit worker exposure to vibration, be it whole-body or hand-arm. [Scarlett et al., 2007]. On agricultural tractors, low-frequency vibration is produced mainly by the interaction between the tractor and the terrain, depending upon the terrain type and the speed of travel [Cuong et al., 2013]. Also the tyre inflation pressure and the soil moisture content can affect sometime remarkably the RMS acceleration values at the driver’s seat, because on tractor having no suspension system the tyre is the unique elastic element able to reduce tractor vibration [Cuong et al., 2014]. The demand for higher forward speeds in agricultural tasks and the increasing use of specialised transport-oriented vehicles have introduced new technical problems related to dynamic behaviour, such as general deterioration associated with high speeds. Furthermore, an increase in operational speeds increases vibration levels and, consequently, reduces driver performance [Anthonis et al., 2000, 2002].

On modern agricultural wheeled tractors, many devices have been fitted to improve ride vibration comfort. Apart from the driver’s seat, equipped with a passive or sometimes with an active electronically controlled pneumatic suspension, pneumatic or hydraulic suspensions on the cab and on the front axle have recently been fitted. Moreover, a more elastic tyre wall combined with a low inflation pressure can improve operator comfort, especially on hard surfaces at high speed [Pessina, 1993].

In particular, the type of seat suspension, and above all its correct adjustment (related to the driver’s mass), also have a remarkable impact on the level of vibration [Nuccitelli et al., 1993, Stein et al., 2011]. Furthermore, the ride comfort is also very sensitive to the stiffness of the rear suspension of the cab [Uys et al., 2007]; the hydropneumatic type can significantly improve the situation [Hammes and Meyer, 2010]. In particular, the active or semi-active cab suspension is able to reduce the level of vibration with respect to the traditional means [Deprez et al., 2005].

The tractor axle suspension has been widely studied through simulation models [Hansson, 1996; Melzi et al, 2014], as well as carrying out field tests [Marsili et al., 2002; Servadio et al., 2007]. The main manufacturers adopted different technical solutions, in particular for the suspension of the front axle fitted on conventional tractors. Considering the very complex driveline of an agricultural tractor, to obtain an anti-dive behaviour, in case of 4WD models the non statically determined torque distribution between front and rear axles requires a proper tuning of the geometry of the front arms, particularly of their slope [Gobbi et al., 2014]. Moreover, also the vineyard/orchard narrow-track tractors have been recently equipped with a front axle suspension, overcoming finally the lack of available space [Uberti et al., 2014].

In any case, the front axle suspension is the means typically devoted to decrease the back-front vibration of the tractor when travelling at maximum speed on public road, especially if it is coupled with a towed implement. In fact, in the range between 35 to 44 km h⁻¹ (about 10 to 12.5 m s⁻¹) the angular velocity of the rear wheels is often quite close to the natural frequency of the tractor, so producing a resonance due to the tyre and rim non-uniformity.

The aim of this research is to measure the benefit on operator's ride comfort of the front axle suspension system fitted on a medium powered 4WD tractor, when working in off-road operations.

2 Materials and method

2.1 Tractor and implement

A medium-powered 4WD agricultural tractor, make Deutz-Fahr model 5110 TTV was investigated for the survey. The main technical features are shown in tab. 1.

Make, model	Deutz Fahr, 5110 TTV
Type	4WD
Engine type	diesel, common rail with turbocharger
Engine model	Deutz TCD 3.6 L04 T4i
No. of cylinders - displacement	4 - 3 620 cm ³
Max. power	81 kW (at 2 000 min ⁻¹)
Max. torque	440 Nm (at 1 600 min ⁻¹)
Transmission	
- type	continuously variable transmission
- no. of speeds	infinite
- max. nominal speed	40 km h ⁻¹ (11.1 m s ⁻¹) (in Eco Mode)

Wheelbase	2 430 mm	
Tyres	front	rear
- labelling	440/65 R 28	540/65 R 38
- overall diameter	1 290 mm	1 687 mm
- inflation pressure	200 kPa	160 kPa
Mass		
- front axle	2 230 kg	
- rear axle	2 930 kg	
- total	5 160 kg	

Tab. 1: Main technical characteristics of the tested tractor

The tractor version selected for the survey was equipped at the top level for the vibration reduction: apart the seat pneumatically suspended, the cab was fitted with a rear mechanical suspension and the front axle was connected to the tractor body through a hydraulic suspension completed with two nitrogen accumulators.

In detail:

- the *seat pneumatic suspension* was auto-adaptive, i.e. was able to adjust automatically its stiffness to the driver's mass, in order to assure the best vibration comfort;
- the *cab rear suspension* was a mechanical type, based on a spring-damper combination. In the front part, the cab was equipped with a couple of traditional silent-blocks, ring-shaped;
- the *front axle was suspended with two hydraulic cylinders* completed with two nitrogen accumulators, providing each a total vertical displacement of 150 mm, controlled with some position sensors. The axle oscillation in the lateral plane is $\pm 9^\circ$; the max steering angle is 55° . The hydraulic circuit works at a max pressure of 20 MPa. To obtain the better efficiency in some agricultural tasks, the suspension system can be locked: in this case, the hydraulic cylinders are completely closed, so reducing at a minimum the distance between the front axle and the tractor body.

The implement coupled to the tested tractor was a towed slurry tank, equipped with two conjugated axles. The main technical features are shown in tab. 2.

Make, model	F.lli Menegari, mod. 2
Type	2 conjugated axles
Tyres	
- labeling	385/55 R22.5
- inflation pressure	350 kPa
Mass	
- with empty tank	2 350 kg (2 080 kg on the axles; 270 kg on the tractor hitch)
- with full tank	8 490 kg (6 720 kg on the axles; 1 770 kg on the tractor hitch)

Tab. 2: Main technical features of the slurry tank coupled to the tested tractor



Fig. 1: View of the tractor alone and with slurry tank, travelling on the rough track

2.2 Test conditions

The vibration levels at the driver's seat were measured by executing different test sessions, in order to highlight the tractor front axle suspension performance in agricultural tasks different from the travelling at high speed on the public road, being this last the main reason of its fitting. In detail the following conditions were investigated:

1. tractor alone travelling on an unpaved rough track, at two different speed values, 2.22 and 4.44 m s⁻¹;
2. tractor alone travelling on a transitional meadow (in the following named "field"), at two different speed values, 1.11 and 2.22 m s⁻¹;
3. tractor coupled with a slurry tank travelling on an unpaved rough track, at two different speed values, 2.22 and 4.44 m s⁻¹;
4. simulation of a slurry distribution on a transitional meadow, at two different speed values, 1.11 and 2.22 m s⁻¹.

The measurements were repeated with the front suspension axle system switched on and off (tab. 3). Three repetitions were carried out for each condition surveyed. The averaging time of each vibration measurement was 60-100 s, depending on the travelling speed.

Condition no.	Surface type	Front axle suspension	Travelling speed
1	field	on	1.11 m s ⁻¹
2		off	
3		on	2.22 m s ⁻¹
4		off	
5	rough track	on	2.22 m s ⁻¹
6		off	
7		on	4.44 m s ⁻¹
8		off	

Tab. 3: Summary of the test conditions

2.3 Instrumentation used and analytical method

The vibrations transmitted through the seat to the driver were measured along 3 orthogonal axes, with the origin centered on the contact surface between the seat and the driver [ISO 2631, 2014]. The axes were oriented as follows: X back-front, Y lateral and Z vertical. Whole-body values were measured on the driver's seat, using a triaxial accelerometer Dytran 5313M2 (mass 11 g, sensitivity 99.3 mV/g) operated by a 4-channel human vibration meter (Quest Technologies HAVPro) complying with ISO 8041:1990 standards. Data elaboration took into consideration the provisions of the European Union Directive 2002/44/EC (European Commission, 2002) concerning:

$$a_{wmax} = \max [1.4 a_{wx}; 1.4 a_{wy}; a_{wz}]$$

As an alternative, the previous ISO 2631-1:1997 standard was also considered, as follows:

- single axes values: a_{wx} ; a_{wy} ; a_{wz}
- overall root mean square (RMS) value:

$$a_{wsum} = [(1.4 a_{wx})^2 + (1.4 a_{wy})^2 + a_{wz}^2]^{1/2}$$

The Italian Decree No. 81/2008 currently in force concerning the evaluation of vibration provides the comparison of the limits with the a_{wmax} value obtained. However, the present study considered both the single axes (in terms of $1.4 a_{wx}$; $1.4 a_{wy}$; a_{wz}) and the a_{wsum} values, because this last in authors' opinion represent better the real disturbance caused by vibrations to the agricultural tractor's driver. The rough data were then statistically analyzed: the T-Student test was used for the coupled data comparison, while using the release 17 of the Minitab software a multiple ANOVA variance analysis and a multiple Tuckey Pairwise Comparisons were carried out.

In order to highlight the best statistical significance, the data coming out from each vibration axis were analysed in a stand alone mode. The Tuckey test has been carried out not only considering all 3 terms, but also on each single term and on the cross of various couple of terms.

3 Results and discussion

For the several test conditions surveyed, the values of the frequency-weighted acceleration $1.4 a_{wx}$, $1.4 a_{wy}$, a_{wz} and a_{wsum} are given, in subsequent tables and graphs.

Figs. 2 to 5 show the performance of the tractor alone compared with those of the tractor and slurry tank combination, in order to highlight the behaviour modification introduced by the towed implement.

On a general view, the levels are progressively high by increasing the travelling speed and passing from the field to the rough track, both with the front axle suspension working or locked. In particular, the travelling on rough track at 4.44 m s^{-1} evidenced a critical situation in all the axes, and consequently also for the RMS value. Curiously, the suspension system reveals its benefit in a more effective mode when the tractor is travelling alone. In other words, the coupling with a towed implement seems to reduce the levels decrease assured by the suspension working.

As expected, in all the axes the slurry tank causes a worsening of the comfort condition. In particular, in the X-axis a strong statistical significance was found in the conditions 1, 3, 5 and 7 (suspension working) both on the field and on the rough track and at the different speed values. The soil unevenness causes a continuous dynamic stress of the slurry tank to the tractor through the hitch, in terms of fast generation of push-pull forces, resulting in back-front vibrations of the tractor body.

On the contrary, on the Y-axis the levels did not evidenced significant differences, apart in the field at low speed, both with the suspension working and locked. In this case, the rough surface causes wide lateral oscillations at low frequency that are fully taken into account due to the typical weighing of the horizontal axis provided by ISO 2631.

The Z-axis did not provided a clear trend; the statistical significance is quite strong only in conditions no. 1 (travelling at low speed on the field with the suspension working) and no. 8 (rough track, 4.44 m s^{-1} and suspension locked).

The RMS values do not highlight a strong statistical significance, except at low speed in the field and at the opposite condition, i.e. at high speed on rough track.

Considering the requirements of the standards actually in force, the towing of an implement is certainly worsening the levels, in particular on X- (back-front) and Z- (vertical) axes.

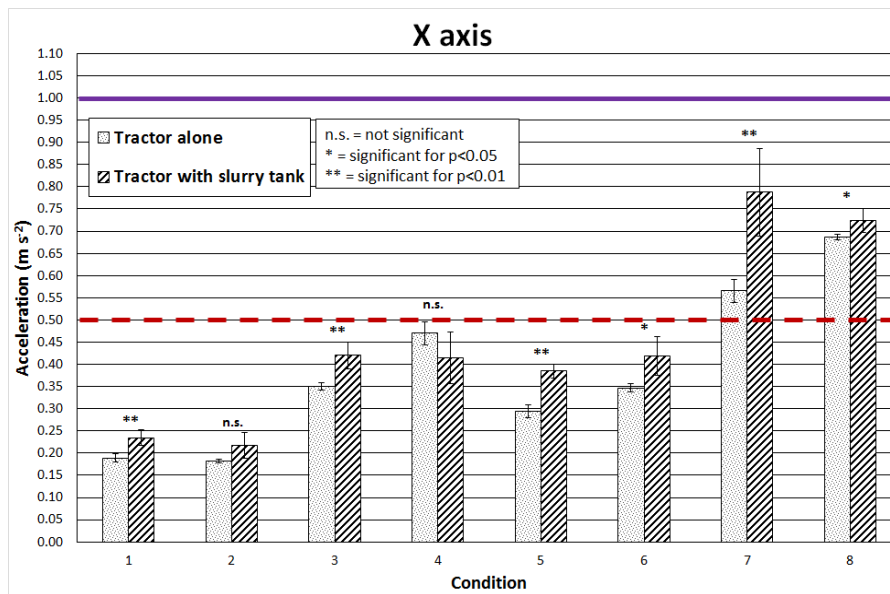


Fig. 2: Acceleration values on X-axis (longitudinal) for the tractor alone and coupled with the slurry tank. (test conditions are shown in tab. 3. Broken line: action value; solid line: limit value)

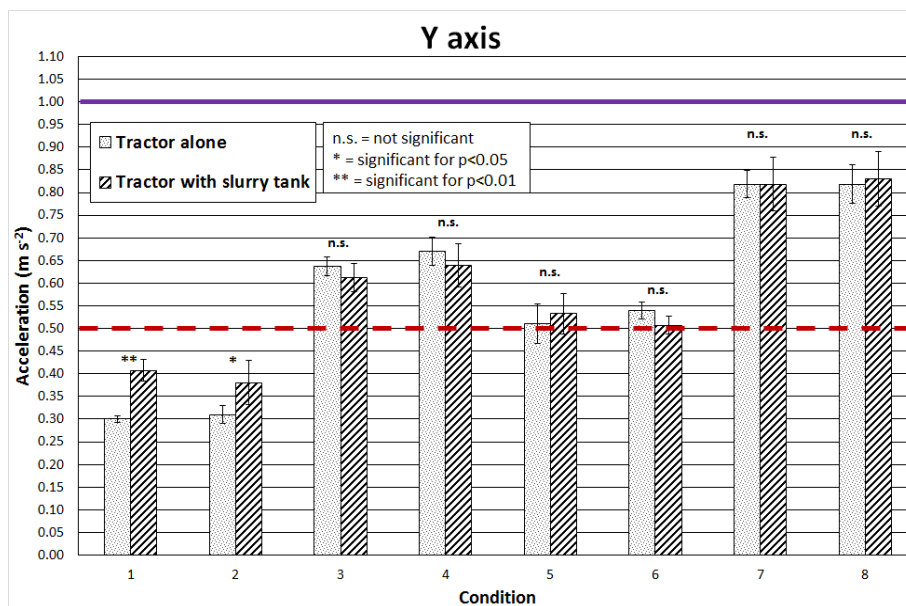


Fig. 3: Acceleration values on Y-axis (transversal) for the tractor alone and coupled with the slurry tank. (test conditions are shown in tab. 3. Broken line: action value; solid line: limit value)

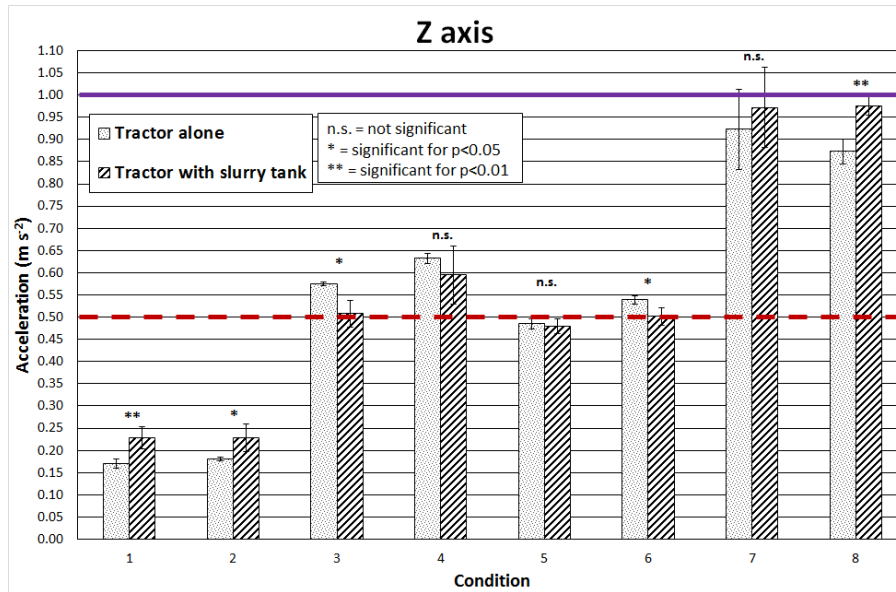


Fig. 4: Acceleration values on Z-axis (vertical) for the tractor alone and coupled with the slurry tank. (test conditions are shown in tab. 3. Broken line: action value; solid line: limit value)

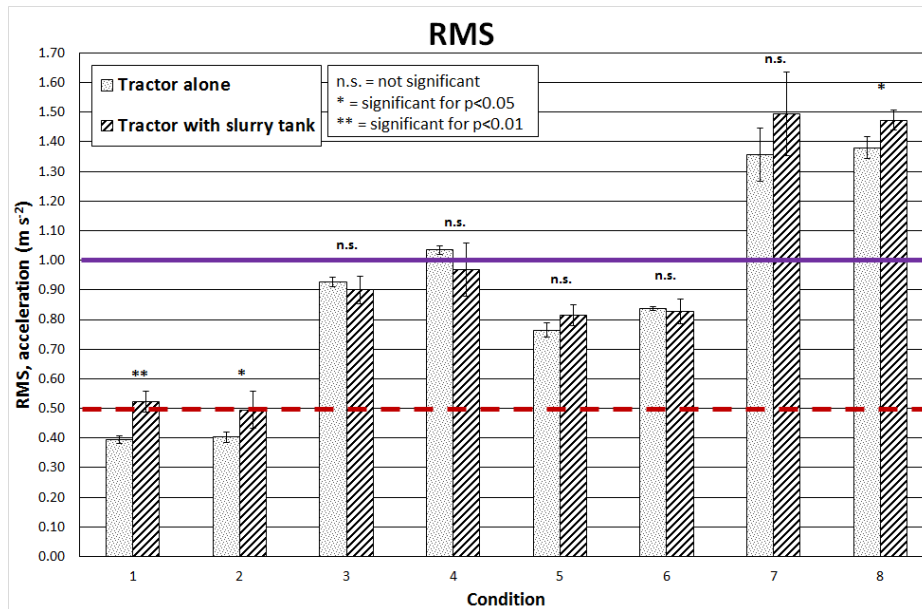


Fig. 5: Overall acceleration values for the tractor alone and coupled with the slurry tank. (test conditions are shown in tab. 3. Broken line: action value; solid line: limit value)

At the travelling speed of 2.22 m s⁻¹ the tractor was tested in all the conditions provided; for this reason, the data collected at this speed were statistically analysed in a detailed mode, through the ANOVA variance and the Tuckey test, in order to stress the significance of the results (tab. 4 and fig. 6).

In the investigated conditions, the suspension system generally reduced the vibration levels at the driver's seat, but a sufficient significance is obtained only in the field, for X-axis with the tractor alone e for Z-axis with the combination tractor and slurry tank (getting in this last case a remarkable reduction, of 14.6%).

Axis		Tractor alone				Tractor with slurry tank			
		Field		Rough track		Field		Rough track	
		Susp on	Susp off	Susp on	Susp off	Susp on	Susp off	Susp on	Susp off
X	means	0.351 ^{bc}	0.470 ^a	0.294 ^c	0.346 ^{bc}	0.420 ^{ab}	0.415 ^{ab}	0.385 ^{ab}	0.420 ^{ab}
	s.d.	0.009	0.026	0.015	0.009	0.030	0.057	0.016	0.044
Y	means	0.637 ^a	0.670 ^a	0.511 ^c	0.540 ^{bc}	0.613 ^{ab}	0.639 ^a	0.533 ^{bc}	0.507 ^c
	s.d.	0.020	0.031	0.043	0.019	0.031	0.047	0.045	0.020
Z	means	0.574 ^{abc}	0.632 ^a	0.485 ^d	0.539 ^{bcd}	0.508 ^{cd}	0.595 ^{ab}	0.480 ^d	0.501 ^{cd}
	s.d.	0.005	0.011	0.011	0.009	0.031	0.065	0.017	0.020
RMS	means	0.926 ^{abc}	1.035 ^a	0.764 ^d	0.838 ^{cd}	0.900 ^{bc}	0.968 ^{ab}	0.814 ^{cd}	0.828 ^{cd}
	s.d.	0.016	0.015	0.025	0.006	0.047	0.089	0.036	0.042

(Superscript letters a,b,c,d indicate significant differences at $P < 0.05$ among three factors for the same axis. For the same axis, means that share a letter are not significantly different)

Tab. 4: Vibration levels (m s⁻²) of the tests carried out at 2.22 m s⁻¹ in different working conditions, and relevant statistical analysis

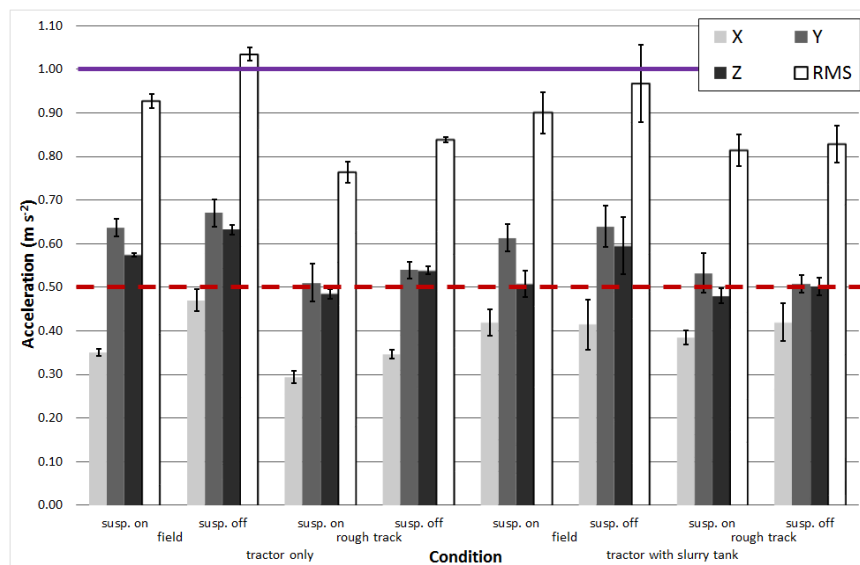


Fig. 6: Results at 2.22 m s⁻¹ in different working conditions, compared with the EC 2002/44 limits. (broken line: action value; solid line: limit value)

The 2002/44 EC Directive establishes two limits for the operator's exposure evaluation. The lowest is fixed to 0.5 m s^{-2} and is called "*action value*": if exceeded, the employer shall establish and implement a programme of technical and/or organisational measures intended to reduce to a minimum exposure to mechanical vibration and the attendant risks.

If, despite the measures taken by the employer to comply with this Directive, the highest limit ("*limit value*", 1.0 m s^{-2}) is exceeded, the employer shall take immediate action to reduce exposure below the exposure limit value. He shall identify the reason(s) why the exposure limit value has been exceeded, and shall amend the protection and prevention measures accordingly in order to prevent it being exceeded again.

The situation highlighted in this survey does not appear dramatically critical, but some warnings have to be underlined. Taking into account the single axes values, the Y- and Z-axes evidenced a general overcoming of the action value, but they remained within the limit value. On the rough track at the max travelling speed (4.44 m s^{-1}) the levels recorded for both the tractor alone and with the slurry tank were often close to the limit value (1.0 m s^{-2}).

Of course, the situation is worsening if the provided limits are compared to the RMS overall values. Not only the tractor coupled to the slurry tank overcame the limit value on the rough track at the max travelling speed, but the level of 1.0 m s^{-1} was exceeded also at 2.22 m s^{-1} in the field, with the suspension system locked. Table 5 shows the situation by assembling the data for each testing condition, analysing firstly the single means and then the interactions among two different means. For the X and Z axes the vibration values of the tractor with the slurry tank are lower than those of the tractor alone, respectively of 11 and 6.5%. This apparently is an unexpected result, but it could be explained taking into account the possible creation of dangerous resonance produced when the tractor is travelling alone.

Ascertained that for the same travelling speed the levels recorded in the field are always higher than those obtained of the rough track, the suspension system is efficient in reducing the levels by 12.3% in the X-axis, 9.7% in the Z-axis and by 7.2% for the RMS. Only for the Y-axis no significant differences were found; this is an expected behaviour, because the suspension is designed to reduce the vibration in the back-front and vertical directions, but not in the lateral direction.

The comparison of couples of means revealed what follows:

- the surface and the tractor coupling comparison did not evidenced a statistical significance, as well as that between the tractor coupling and the suspension system on or off;
- on the contrary, the differences are significant by comparing the suspension condition and the surface of the test, especially for the X and Z axes.

The overall RMS values confirm what specified.

Condition	No. of tests	X	Y	Z	RMS
Tractor alone	12	0.410 ^a	0.589 ^a	0.558 ^a	0.891 ^a
Tractor with slurry tank	12	0.365 ^b	0.573 ^a	0.522 ^b	0.877 ^a
Field	12	0.414 ^a	0.640 ^a	0.577 ^a	0.957 ^a
Rough track	12	0.361 ^b	0.523 ^b	0.501 ^b	0.811 ^b
Susp. off	12	0.413 ^a	0.589 ^a	0.567 ^a	0.917 ^a
Susp. on	12	0.362 ^b	0.573 ^a	0.512 ^b	0.851 ^b
Tractor alone, field	6	0.410 ^a	0.653 ^a	0.603 ^a	0.981 ^a
Tractor with slurry tank, field	6	0.417 ^a	0.626 ^a	0.551 ^b	0.934 ^a
Tractor alone, rough track	6	0.320 ^b	0.525 ^b	0.512 ^{bc}	0.801 ^b
Tractor with slurry tank, rough track	6	0.402 ^a	0.520 ^b	0.490 ^c	0.821 ^b
Tractor only, susp. off	6	0.408 ^a	0.605 ^a	0.585 ^a	0.936 ^a
With slurry tank, susp. off	6	0.417 ^a	0.574 ^a	0.548 ^{ab}	0.898 ^{ab}
Tractor only, susp. on	6	0.322 ^b	0.573 ^a	0.530 ^{bc}	0.845 ^b
With slurry tank, susp. on	6	0.402 ^a	0.573 ^a	0.494 ^c	0.857 ^b
Field, susp. off	6	0.442 ^a	0.655 ^a	0.614 ^a	1.001 ^a
Field, susp. on	6	0.385 ^b	0.625 ^a	0.541 ^b	0.913 ^b
Rough track, susp. off	6	0.383 ^b	0.523 ^b	0.520 ^{bc}	0.833 ^c
Rough track, susp. on	6	0.339 ^b	0.522 ^b	0.483 ^c	0.789 ^c

(Superscript letters a,b,c,d indicate significant differences at $P < 0.05$ between indicate factor for the same axis. For the same axis, means that share a letter are not significantly different)

Tab. 5: Mean vibration levels (m s^{-2}) obtained by assembling the data for each testing condition, at a travelling speed of 2.22 m s^{-1}

4 Conclusion

Many modern tractor models, both high and medium powered, are equipped with a front axle suspension system, generally hydraulically operated and completed with nitrogen accumulators. Initially fitted for reducing the bouncing when travel-

ling on the road at high speed, the design of this kind of suspension was more recently updated to assure a benefit in other working conditions, such as the execution of field tasks and the travelling on rough track.

The efficiency of the front axle suspension system is good enough for reducing the vibration values of the tractor alone, but the suspension benefit is less evident when the tractor is coupled with a towed implement, especially in the back-front direction.

In respect to the limits provided by the dedicated Standards, the situation does not appear dramatically poor: the action value established by the 2002/44 EC Directive (0.5 m s^{-2}) is frequently exceeded, but the limit value (1.0 m s^{-2}) is generally respected. At a general extent, the operator's ride comfort is guaranteed, except in some working situations when is required a reduction of the normal working time to assure the best efficiency of the driver.

The progressive extension of the suspension devices (seat, cab and front axle) on the agricultural tractors of small power could certainly improve the comfort condition of the operators potentially exposed to high vibration levels, because these tractors are frequently used in specialised cultivations (i.e. in vineyard and orchard), where the typical travelling speed and the rough soil surface could create critical conditions.

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