Whole-body vibration: Measurement of horizontal and vertical transmissibility of an agricultural tractor seat

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Effects of the operative characteristics of an agricultural tractor on seat vibration transmissibility

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Short form of the title: Seat transmissibility of a tractor

Abstract

The seats may significantly reduce the solicitations levels transmitted to the driver, but the European Directive requires only tests on the damping capacity along the vertical direction, whereas nothing is required for the longitudinal and transversal directions.

Field tests were carried out using a 93 kW tractor to verify the vibrational comfort values given by seat with pneumatic suspension. The tests were executed with the tractor running on different surfaces, at two forward speed and tire pressures other than with different tractor masse). The accelerations were always measured on both the seat and the cabin platform and the calculations were done using the ISO 2631 standard. The vibration total values and the transmissibility along the 3 perpendicular axes were calculated.

Despite different boundary conditions (surface, tire pressure, forward speed tractor mass distribution), along the Z axis the transmissibility was constantly around 0.7, to confirm that the seat worked well to damp the vertical solicitations. Different were the situations for the X and the Y axes. Excluding the asphalt, on the other crossed surfaces high transmissibility values were observed (never less than 1), especially along the X axis, with peaks over 2.

Keywords: agricultural tractor, WBV, seat transmissibilty

Introduction

The agricultural works engage the farmers for many hours per day almost throughout all the year: during the busiest days the farmers use the tractor for up to 12-14 hours per day [1]. As a consequence, as other machine drivers, they are exposed to physical risks (noise, whole body and hand arm vibration): in particular, during field operations and on/off road transportation they are exposed to whole body vibration (WBV) which may cause biomechanical problems to the back [2,3,4]. The WBV analysis in agriculture is more complex than in the industrial sector, because it depends on many changing factors during the field work. For example, it is strictly connected to the surface type and condition, other than the machine configuration, the performed task and the operator behaviour: in fact, all these aspects contribute to produce low-frequency vibration, which may become severe for the operator's health [5,6,7].

The high number of combination produced by the surface, the machine configuration (for example the tire pressure, the presence of ballasts and of implements), the forward speed and the operator behavior cause high ranges of unpredictable accelerations which cannot be a priori standardized. This is the problem which arises to foresee the WBV exposure levels of the operator in the agricultural work: to solve this question efforts were addressed by some Authors [8,9] using an artificial track (ISO 5008:1979, [10]) and comparing the acceleration results with the same obtained during field works: unfortunately only little resemblances were observed.

The dispositive which should minimize the vibration solicitations coming from the tractor platform is the seat: the damping effect is obtained positioning elastic deformable elements (the seat suspension systems) between the tractor and the driver's body. Usually these elements are metallic or air springs, with one hydraulic shock absorber: all these elements may be adjustable to adapt to operator's mass.

Many studies have been carried out to analyse the vibration transmitted to the tractor driver's seat [11,12,6,13]. To justify the severity of transmitted vibration, these studies were developed using the standard ISO 2631-1:1997 [14], which locates a frequency interval between 0.5 and 80 Hz (useful in order to safeguard human health) and weighting filters to consider the different human body sensibility to the vibrating stimulus frequencies. This standard, however, only defines the whole body vibration measurements with a method to calculate the vibration exposure, without giving indications how to measure machines vibration in the real workplace [9]. The EN 1032:2003+A1:2008 [15] and the ISO/TR 25398:2006 [16] standards tried to solve this not simple problem (for example, these standards do not describe the surface characteristics and use statistical methods to obtain vibration values at the driver seat place).

Nevertheless, the damping capacities of the seats are verified using the Directive 78/764/EEC [17] that requests laboratory tests, using special vibrating benches [18,19,20]. The Directive requires furthermore to verify only the seat behavior along the vertical axis (Z) and nothing is required for the other two directions X and Y (longitudinal and transversal).Many researchers obtained in their studies that the seat damping effect was operative along the vertical axis [21,22], while it did not appear along the longitudinal and transversal directions [23,24,25].

It was moreover studied that the vibration along the X and Y axis may be very harmful for the human body [26,27]. In the ISO 2631-1 formula itself [14], which calculates the vibration total exposure, the acceleration measured along the X and Y axis are multiplied by a 1.4 factor, to enhance the higher sensibility of the human body to the mechanical solicitations along these directions.

In a complex panorama like this, aim of this study was to use a common agricultural tractor equipped with a widespread pneumatic seat in different field conditions (crossed surfaces, tire pressure, forward speed, modified tractor mass with ballast and implements), to analyze the acceleration values (vertical, longitudinal and transversal) on the platform and on the seat of the machine. The presence of the same skilled operator (which usually executed agricultural operations) and the accomplishment of all the field tests in the same period of the year and in the same climatic conditions, permitted to really compare the results, without the influence of further exogenous parameters. Three set of in field tests were performed: in the first set the unladen tractor crossed four different typical agricultural surfaces (asphalt, grass, harrowed clay, unmetalled farm road) at the same speed (2.78 m/s) with the tire pressures set alternatively at two different values (90 and 160 kPa). In the second experiment, the tractor (always unladen) crossed the same agricultural surfaces at two different speed (2.78 and 5.56 m/s) with the tire pressure at 160 kPa. Finally, the same surfaces were travelled at the speed of 2.78 m/s and the tire pressure at 160 kPa by the tractor differently equipped (unladen, with ballast and then with implement).

2. Materials and methods

2.1 Tractor and seat characteristics

To verify the vibrational comfort values given by the seat, tests have been carried out using a 4WD tractor defined as a Category A, class II tractor by the Directive 78/764/EEC [17] (Table 1).

Table 1 here

In Table 2 there are the main characteristics of the seat, equipped with pneumatic suspension and hydraulic dumper.

Table 2 here

2.2 Surfaces characteristic

The field test tracks were present at the IMAMOTER experimental field site located at Candiolo (Torino, Italy; GPS: E 7.55902, N 44.95578).

The asphalt track was a conglomerate bituminous rectilinear plane of 1000 m length without asperity, the grass surface was 1400 m long, the harrowed clay track (1200 m long) was flat and homogeneous, the unmetalled farm road (2000 m long) was a non-uniform surface with random potholes of different depth (2-3 cm maximum).

2.3 Operative conditions

The same forward speed of 2.78 m/s was maintained during the first and the third tests, considering that it is possible to perform different operations at this speed on all the tested surfaces. In the second test, a speed of 5.56 m/s was monitored, to analyse the seat transmissibility with an higher tractor velocity.

The tractor forward speed was monitored by a radar (model Dj CMS 200, www.dickey-john.eu).

The same skilled operator (70 kg mass and 180 cm tall) performed all the field tests, which were all conducted in the month of June, with an average of 25 °C and a air humidity of 50%.

Three sets of field test were planned. Tires were new of factory.

In the first group of tests, the tire pressures were set at two different values (90 and 160 kPa) for all the unladen tractor passages at 2.78 m/s on the different surfaces. In the second experiment the tractor (unladen and with the tire pressure at 160 kPa) crossed the four surfaces at two different forward speed (2.78 and 5.56 m/s).

The third set of tests was performed at the same tire pressure of 160 kPa, but the tractor had different settings (Table 3): unladen (without any ballast), with ballast and with ballast plus one implement (an harrow tines of 600 kg mass).

Table 3 here

Three repetitions were carried out for each field test, for a total of 84 races and 168 measures.

2.4 Instruments

Accelerations were measured along the three mutually perpendicular directions (X, longitudinal; Y transverse; Z, vertical), both on the surface of the operator's seat and on the vehicle cab floor, close to the seat mounting (Figure 1).

Figure 1 here

A semi-rigid disc, incorporating three mutually-perpendicular piezoelectric accelerometers (ICP®, Integrate Current Preamplifier, from PCB, type 356B41 with sensitivity of 100mV/g, frequency range ±5 % from 0.5 to 1000 Hz), was positioned on the seat cushion of the driver under his ischial tuberosities (below the SIP - Seat Index Point), to measure the vibration on the driver's seat. A second three mutually-perpendicular piezoelectric accelerometer (ICP®, Integrate Current Preamplifier, from PCB, type 356A02 with sensitivity of 10mV/g, frequency range ±5 % from 1 to 5000 Hz) was positioned on the cab floor close to the seat mounting, using a magnetic mounting base. The output signals from the accelerometers were processed in real time through an eight channels NI (National Instruments) 9402 (cut-off frequency 1 Hz, - 1dB). The Sound and Vibration Assistant software (National Instruments) was used to post-process the data. All the measurement chain was previously calibrated. The acquisition time during each test was always more than 10 minutes.

2.5 Vibration total value, transmissibility and frequency analysis

Accelerations along the three perpendicular axes (a_x, a_y, a_z) were simultaneously measured. These measures were carried out both at the seat pan and on the cab floor. The accelerations were frequency weighted using the weighting curves W_k and W_d respectively, obtaining the root mean square (r.m.s.) accelerations values a_{wx}, a_{wy} and a_{wz} along the individual axes, as described in the ISO 2631-1 standard. The vibration total value a_v (m/s^2) of r.m.s. weighted acceleration was calculated as follows (Eq. 1):

$$a_v = (1.4^2\, a^2_{wx} + 1.4^2\, a^2_{wy} + a^2_{wz})^{1/2} \qquad \text{(Eq. 1)}$$

The a_{wx}, and a_{wy} components were multiplied by a factor of 1.4, as specified in ISO 2631-1.
The transmissibility T_i along each axis (i =X,Y,Z Eq. 2) was then calculated, as the ratio between the acceleration measured on the seat and the corresponding acceleration obtained on the cab floor of the tractor, in the frequency range 0.5-80 Hz (as requested by the ISO 2631-1).

$$T_i = \frac{a_{wiS}}{a_{wiF}} \qquad \text{(Eq. 2)}$$

where:
a_{wiS} is the r.m.s. weighted acceleration on the surface of the operator's seat along the i axis
a_{wiF} is the r.m.s. weighted acceleration on the vehicle cab floor along the i axis
Three repetitions were carried out (for each X, Y and Z axis) for each field test.
The transmissibility (seat/platform) is a good indicator of the damping properties of the seat. In theory, this value should always be less than the unit.
To appreciate the vibration energy distribution along the three axes on the seat and the platform, the frequency analysis was performed.

2.6 Statistic calculation

To better understand the possible influence of the tire pressure, the track type, the forward speed, the ballast and the implement over the measured vibration, data were elaborated using the SPSS 22 software, also to verify differences among tracks and tractor settings and velocity, using the GRAPH command and the GLM (General Linear Model), ANOVA procedure.

3. Results

3.1 Field tests at different tire pressures and at the same forward speed (2.78 m/s) on different transit surfaces

In the first set of field tests, the crossed surface was the parameter more influencing the vibration total values both on the seat and on the platform. Concerning the tire pressures, a trend in an increment of the averages of the vibration total values was observed at the higher pressure level.

The averaged vibration total values, a_v, measured on the seat and on the platform were quite similar (as values) (Figure 2) and higher data were usually obtained with the tires pressure at 160 kPa. On the asphalt the registered acceleration were always lower than 0.5 ms^{-2} (except the value corresponding to the tire pressure at 160 kPa on the platform). The highest vibration total values were found on the harrowed clay and on the grass with the tire pressures at 160 kPa, while on the unmetalled farm road the values ranged around 1 ms^{-2}.

Along the crossed surfaces, the acceleration a_v obtained on the seat and on the platform were statistically different among them. The surface always influenced the vibration total values on both the platform and the seat, while concerning the tire pressures, it influenced the acceleration on the platform, not on the seat (Table 4). The post-hoc analysis (based on the Tukey test) revealed similarities of the vibration data obtained on the grass and on the unmetalled farm road surfaces on both the seat and the platform.

Figure 2 here

Table 4 here

The transmissibility along the Z axis was always less than 1 (approximatively around 0.75), save for the asphalt, whereas it was lower (around 0.5, Figure 3).

Along the X and Y axis on the asphalt the transmissibility was around 1, while for the other surfaces it was possible to notice that the ratio along the Y axis was more concentrated around 1.2-1.3 and normally lower than 1.5, whereas along the longitudinal X direction the ratio was variable in a wider range (between 1.2 and 1.8).

Figure 3 here

3.2 Field tests with the same tire pressures (160 kPa) and with different forward speed (2.78 and 5.56 m/s)

The forward speed detected different vibration total values almost for all the surfaces, except for the grass (Figure 4). On both the platform and the seat, acceleration higher than 2 ms^{-2} were reached at the speed of 5.56 m/s.

Figure 4 here

The surfaces alike the speed statistically influenced the accelerations over the platform and the seat (Table 5).

Table 5 here

High transmissibility values, with the majority of data between 1.3 and 2.4, were present along the X axis (sometimes more than 2, Figure 5): here, the highest values were determined by the forward speed at 5.56 m/s, especially on the harrowed clay and on the unmetalled farm road. At this velocity it is interesting to notice the high spread of the values on the asphalt, with a maximum equal to 1.9. On the asphalt, the same happened along the Y axis, with a maximum equal to 2.25. Nevertheless along the transversal axis in the other combination (surface and speed) the transmissibility was here more concentrated around 1.5. As usual, the Z axis presented its own story, with a transmissibility around 0.6, regardless of the crossed surface.

Figure 5 here

3.3 Field tests with the same tire pressures (160 kPa), the same forward speed (2.78 m/s) with/without ballast and implements on different transit surfaces

The presence of the ballast first and of the implement later, produced lower vibration total values both on the seat and on the platform (Figure 6): as it was easy predictable, the lowest acceleration data were obtained by the double presence of ballast plus implement. On the asphalt, for example, the average acceleration over the platform decreased from 0.53 to 0.44 (ballast) and to 0.36 (ballast plus implement): the same decreasing trend was present on all the remaining surfaces, with the exception of the unmetalled farm road, where the presence of the ballast alone did not seem to influence the accelerations.

The range (max-min) of the measured acceleration in Figure 6 evidence an higher data variability when the ballast was not present in the machine and for the unmetalled farm road. Acceleration obtained on the seat were lower than the same data obtained on the platform, except for the unmetalled farm road.

Figure 6 here

The surface, the presence of the ballast and of the implement all influenced the measured accelerations both on the platform and on the seat (Table 6).

Table 6 here

The analysis of the transmissibility along the three axis (Figure 7) highlighted the same shape previously evidenced in the other figures related to the transmissibility: on the asphalt the registered values were in the average lower for all the axis (about 1 along X and Y and about 0.5 along Z).

The X axis had more spreadable and higher values than the others axis Y and Z. The presence of the ballast or/and of the implement produced lower values along the X axis. The same fact was not so evident observing the Y axis where, on the contrary, on the asphalt higher values were observed when the ballast and the implement were installed: when the machine was unloaded higher transmissibility values were detected, corresponding to higher transversal solicitations for the driver (it must be however observed that in most cases this higher values only ranged from 1 to 1.25).

Along the Z axis, the transmissibility was always the same (around 0.7, except on the asphalt where it was slightly lower), regardless of the presence of ballast and implement.

Figure 7 here

3.4. Frequency analysis and acceleration amplitude

In Figure 8 are reported the frequency spectra in one-third octave bands obtained on both the platform and the seat of the tractor crossing the grass at 2.78 m/s without and with the implement (raised from the ground). Along the X and Y axes the acceleration values measured on the seat were higher than the same obtained on the platform (first 4 graphs in Figure 8), especially when the machine was without the implement. In the last 2 graphs of Figure 8 it is instead noticeable how the accelerations on the seat were lower than the same values obtained of the platform, to confirm that the seat was correctly working as it dumped the vertical solicitations along the Z axis.

Figure 8 here

Along the longitudinal X axis the vibration energy was between 1.25 and 5 Hz (Figure 8) both with and without the presence of the implement.

Analysing the energy distribution along the transversal Y axis, a remarkable signal amplification on the seat compared to the platform was present, due to the higher seat position. The energy peak was at 1.25 Hz. Because of the frequency cut (-1dB at 1 Hz) caused by the instruments, the signal amplitudes were not guaranteed. On the contrary, their ratio was correct and it demonstrated that along the transversal direction an acceleration amplification was present on the seat.

In the vertical (Z) axis two peak acceleration were recorded: the first between 2 and 5 Hz, the second around 12.5 Hz. The largest acceleration response (0.7 ms^{-2}) occurred at 2.5 Hz, with the tractor without the implement. The 2.5 Hz is the oscillating main frequency of category A class 2 wheeled tractor (ISO 5007: 2003) [28].

5. Discussion

Considering that the tests were carried out in field and not in standardized situations as in laboratory (albeit maintaining the same operator and in the same climatic conditions), the different groups of results are quite interesting.

On the platform an higher tire pressures caused higher vibration total values on all the surfaces (especially on the asphalt and on the grass): different were the results on the seat where on the harrowed clay and on the unmetalled farm road the accelerations were quite similar.

Concerning the forward speed, an higher forward speed caused higher acceleration values both on the platform and on the seat, across all the travelled surfaces: a greater data variability was also obtained at 5.56 m/s.

The accelerations increased proportionately as the tractor forward speed increased but did not always increase by increasing tires inflation pressure: the same results were obtained by Cuong et al. [29] on the front and rear axle and the tractor body of their tested machine.

The absence of both the ballast and the implement produced higher accelerations, especially on the grass and on the harrowed clay. Higher data ranges were present on the unmetalled farm road, also in presence of the ballast and of the implement. Considering that the tractor is used in field with ballast and implements, the lower vibration total values generated in these cases on the seat are positive, also if hygienistic considerations should be taken into account. Also Metha et al. [30] found that in presence of an implement (other than a lower forward speed) the acceleration values measured on the seat decreased. The crossed surfaces highly influenced the measured acceleration values, as it was also observed by Marsili et al. [31].

Despite different boundary conditions (surface, tire pressure, forward speed tractor mass distribution), along the Z axis the transmissibility was constantly around 0.7, to confirm that the seat worked well to damp the vertical solicitations in all the working conditions.

Different results were obtained along the longitudinal and the transversal axes. Here, on the asphalt the transmissibility, with the unique exception of the forward speed at 5.56 m/s, was almost always around 1. On the other crossed surfaces, instead, high ranges of transmissibility were observed (with values never less than 1): especially along the X axis, peaks over 2 were revealed. At this point, considering the acceleration transmissibility along the driver seat of an agricultural tractor, it seems that an amplification problem exists, especially along the longitudinal and transversal directions, and especially in an unladen machine which crosses surfaces different from the asphalt.

In these conditions and along the longitudinal (X) and transversal (Y) axes, the seat acceleration levels often increase of more than 1.5 than the same recorded values upon the cab floor (seat and floor a_v were simultaneously measured). From this figure the seat effectiveness installed on the tested tractor would appear questionable. These results are not however surprising, since all the machine lateral (roll) and longitudinal (pitch) movements start from its centre of gravity and the operator's seat surface is positioned higher than the cab floor which, in turn, is positioned higher that the centre of gravity. The seat height and the track width of the wheels determine the magnitude of the roll velocity and acceleration which cause acceleration in the Y direction to the operator. The fact that the seat height influences the magnitude of the roll velocity and that consequently the acceleration increases along the Y direction was evidenced also by Langer et al., 2015 [32].

In the sixties and in the seventies many studied [33,34,35,36,37] were carried out to the operators' exposure at the WBV and many of them agreed to the necessity of an intervention to mitigate the problem: after more than 40 years few things changed. The major changes have been in the development of seats with air spring or with electronic control of vertical seat movement [38,39] which may effectively minimize the vertical solicitations, less the longitudinal and the transversal. The reason of this implementation is in the international standard, addressed to the seat effectiveness for off-road vehicles (Directive 78/764/EEC [17], ISO 7096 [40], ISO 5008 [10]), which require to the seat manufacturers to not exceed the acceleration values only for the vertical axis. Nowadays do not exist standards referring to devices to lower the longitudinal and transversal accelerations. Some manufacturers install on their seats devices which should be able to mitigate these accelerations (especially along the longitudinal axis X), but they are not standardized and therefore it is not possible to validate their efficiency. These devices are usually formed by metallic springs and shock absorbers [41] both non-adjustable and therefore not suitable to the different operator's mass [23,24]. Concerning the Y direction there are very few devices to attenuate the transversal solicitations, because of the proximity of the seat to the lateral control panels of the tractor: these panels heavily restrict the available room, hindering the lateral movement of the seat [6,23].

If the discomfort caused by low-frequency lateral oscillation is a common problem in land transport [42] a fortiori the physical damages occurred to agricultural tractor drivers must be considered.

Conclusion

The objective of the work was to analyse the dynamic response of a pneumatic seat installed on an agricultural tractor, when the machine crossed different working surfaces, at different tire pressures (90 and 160 kPa), at different forward speed (2.78 and 5.56 m/s) and with or without ballast and implement.

The field tests permitted to have a wide range of conditions to be analysed: concerning both the vibration total values and the transmissibility data along the three directions, the forward speed and the crossed surface were the main discriminatory parameters which influenced all the results. The presence of the ballast and of the implement significantly reduced the acceleration data and especially the longitudinal transmissibility (more than the transversal), but not relevant differences were noticed along the vertical axis.

Until today the suspension seat development has been concentrated upon the vertical (Z) axis performance, because the existing standards require only to verify the vertical damping.
Modern seat suspensions undoubtedly serve to improve operator ride comfort, but they are most likely to attenuate the Z axis vibrations: moreover their effectiveness is limited to circumstances when the input acceleration (cab floor) frequency is greater than the natural frequency of the seat suspension system.
When the solicitation frequency is very low, under 2 Hz, the seat suspension system may work bad and may amplify the solicitations coming from the platform (as visible in Figure 8).
Concerning the solicitations damping along the longitudinal and the transversal axes, the issue should be addressed by the ISO working group. They should propose effective tests to validate new devices for damping the seat lateral solicitations. It should be a strong stimulus for the manufacturers and a progress for the agricultural operator comfort.

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FIGURE LEGENDS

Figure 1. Accelerometer position on the cab floor of the tractor, near the seat anchorage (left), and over the seat (right).

Figure 2. Box whisker graph of the vibration total values on the platform and on the seat with the tractor crossing all the surfaces at the same forward speed of 2.78 m/s with tire pressures at 90 and 160 kPa.

Figure 3. Box whisker graph of the transmissibility data along the three directions (T_x, T_y, T_z). Tractor is crossing all the surfaces, with tire pressures at 90 and 160 kPa.

Figure 4. Box whisker graph of the vibration total values on the platform and on the seat (tractor crossing all the surfaces, at the forward speed of 2.78 and 5.56 m/s with tire pressures at 160 kPa).

Figure 5. Box whisker graph of the transmissibility data along the three directions (T_x, T_y, T_z). Tractor is crossing all the surfaces, at the forward speed of 2.78 and 5.56 m/s with tire pressures at 160 kPa.

Figure 6. Vibration total values (average, minimum and maximum) on the platform (left) and on the seat (right) obtained in the examined surfaces and machine configuration (without ballast, with ballast and with ballast and implement).

Figure 7. Box whisker graph of the transmissibility along the three directions (T_x, T_y, T_z) with the absence/presence of the ballast and of the implement.

Figure 8. Overall acceleration values and frequency bands along the X, Y and Z direction, measured on the seat and on the platform of the tractor running on the grass at 2.78 m/s with the implement (left) and without the implement (right).

FIGURES

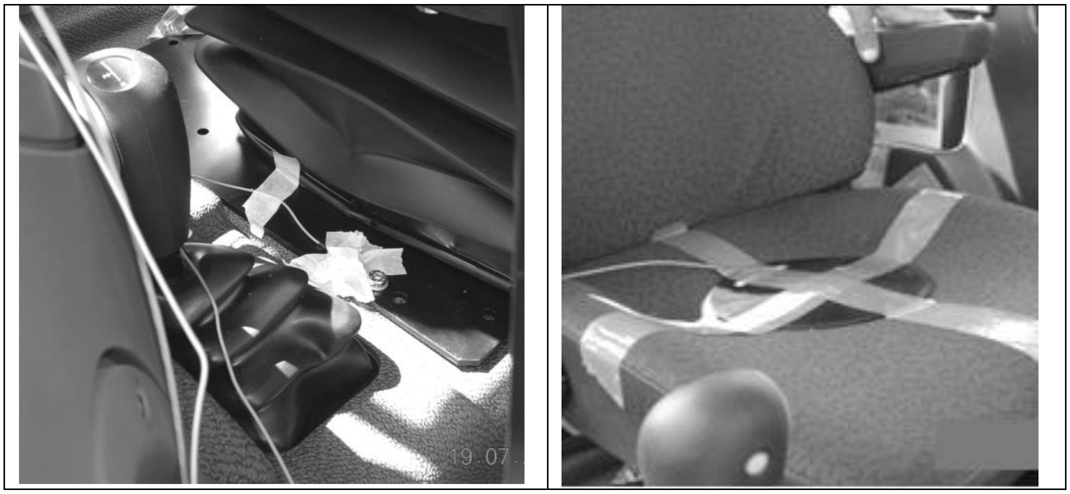


Figure 1. Accelerometer position on the cab floor of the tractor, near the seat anchorage (left), and over the seat (right).

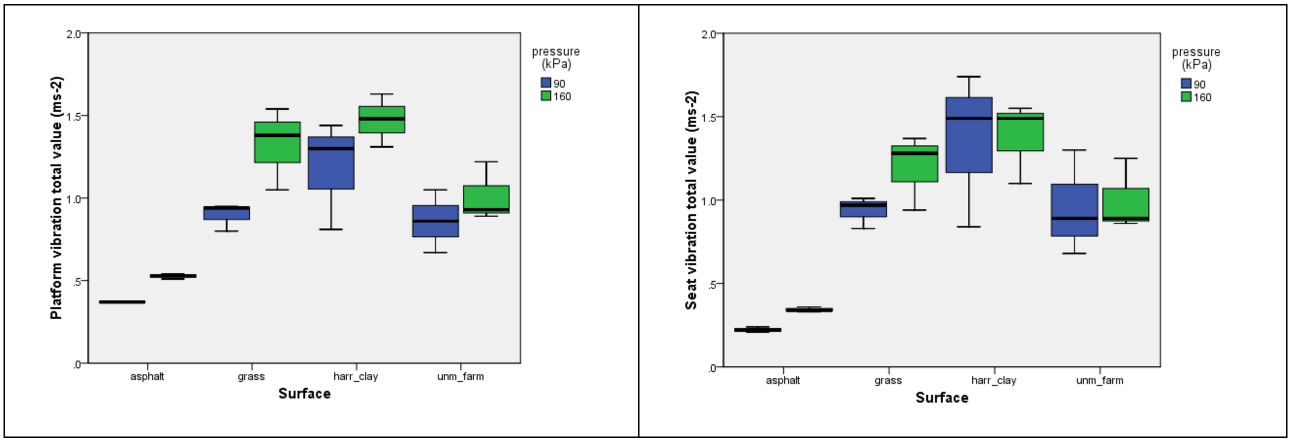


Figure 2. Box whisker graph of the vibration total values on the platform and on the seat with the tractor crossing all the surfaces at the same forward speed of 2.78 m/s with tire pressures at 90 and 160 kPa.

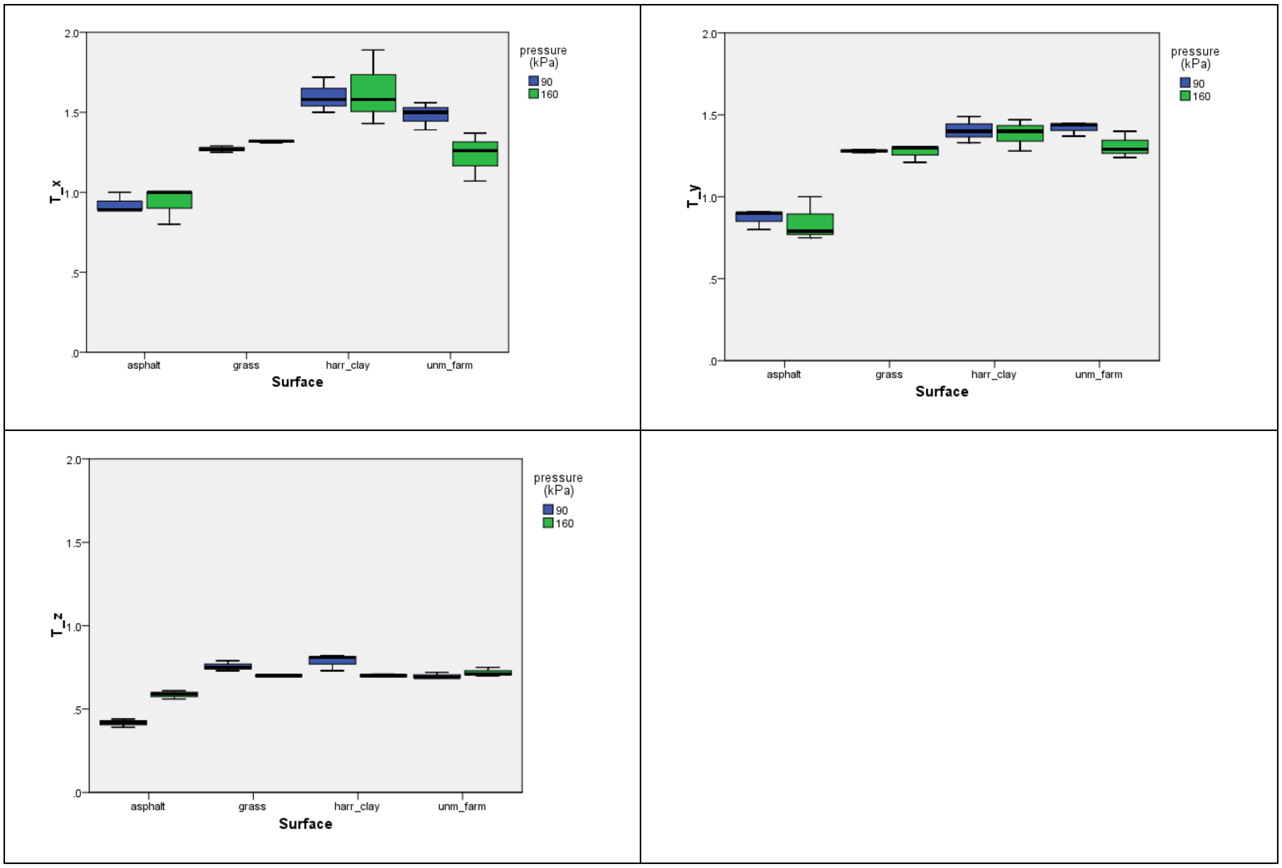


Figure 3. Box whisker graph of the transmissibility data along the three directions (T_x, T_y, T_z). Tractor is crossing all the surfaces, with tire pressures at 90 and 160 kPa.

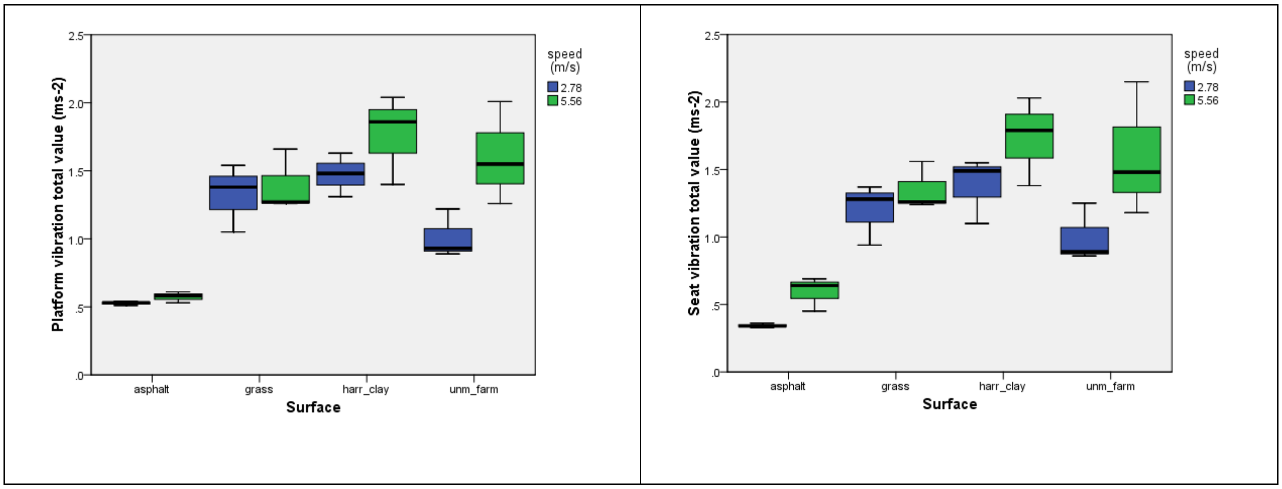


Figure 4. Box whisker graph of the vibration total values on the platform and on the seat (tractor crossing all the surfaces, at the forward speed of 2.78 and 5.56 m/s with tire pressures at 160 kPa).

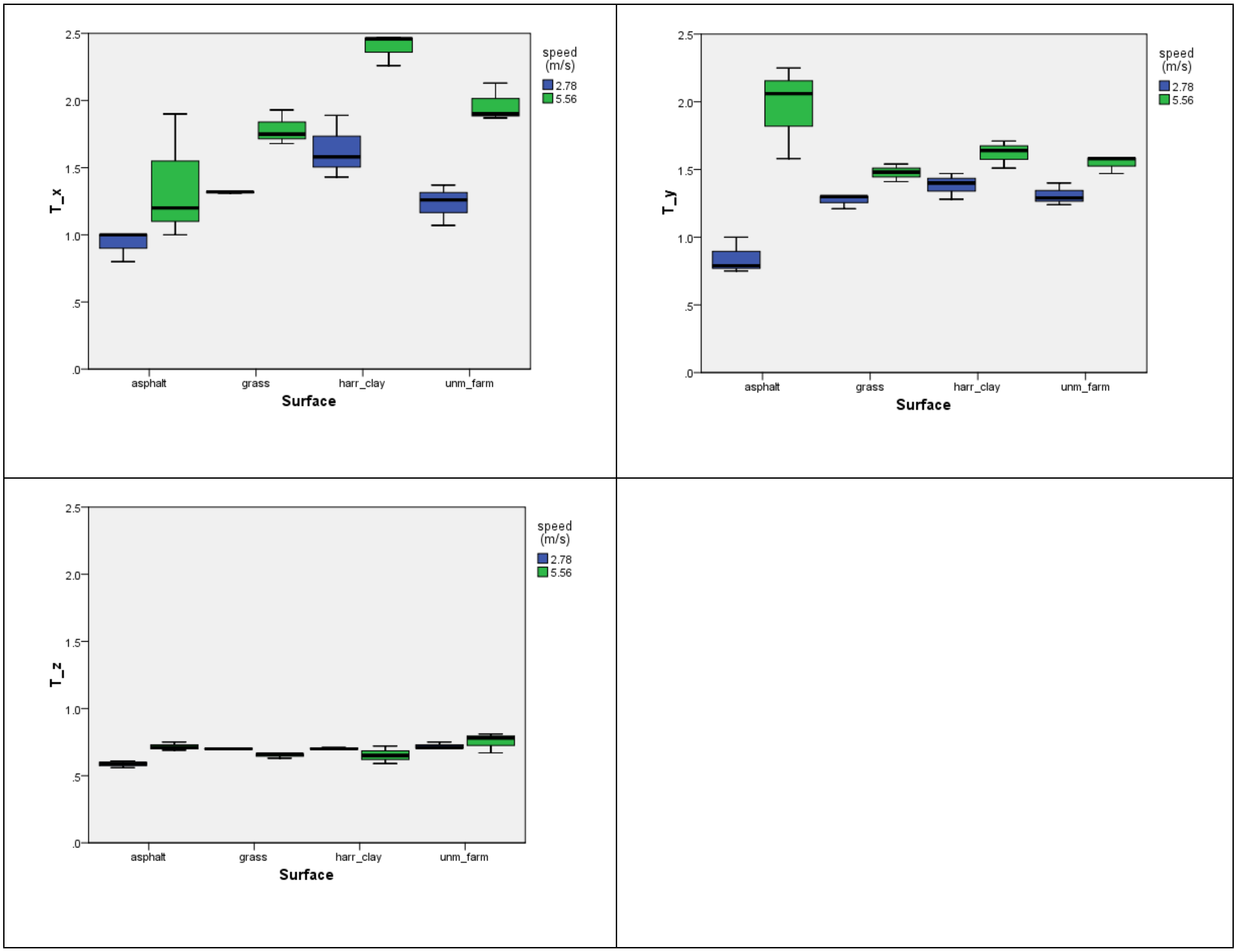
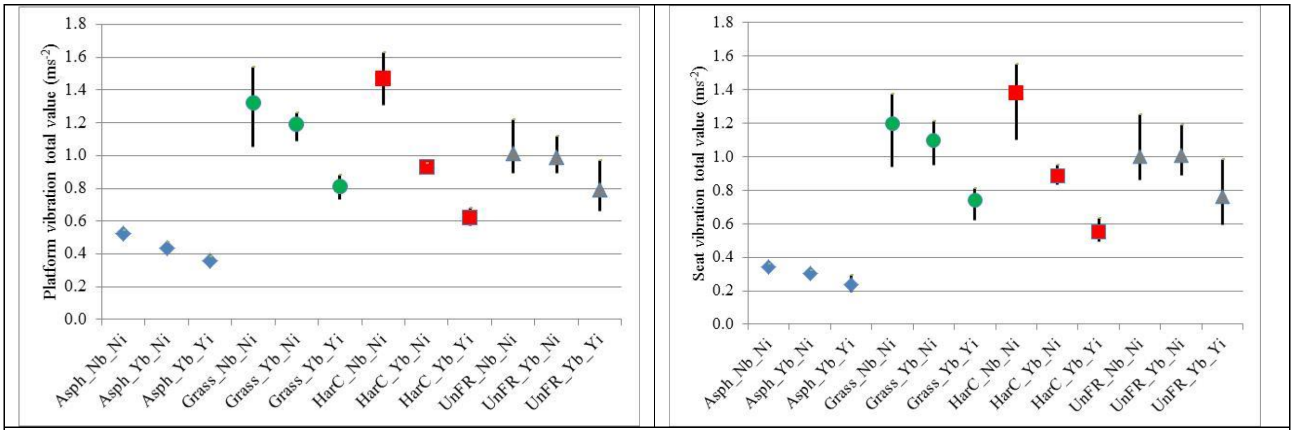


Figure 5. Box whisker graph of the transmissibility data along the three directions (T_x, T_y, T_z). Tractor is crossing all the surfaces, at the forward speed of 2.78 and 5.56 m/s with tire pressures at 160 kPa.



Legend: Asph=Asphalt; HarC=Harrowed clay; UnFR=Unmetalled farm road; Nb=No ballast; Ni=No implement; Yb=Yes ballast; Yi=Yes implement

Figure 6. Vibration total values (average, minimum and maximum) on the platform (left) and on the seat (right) obtained in the examined surfaces and machine configuration (without ballast, with ballast and with ballast and implement).

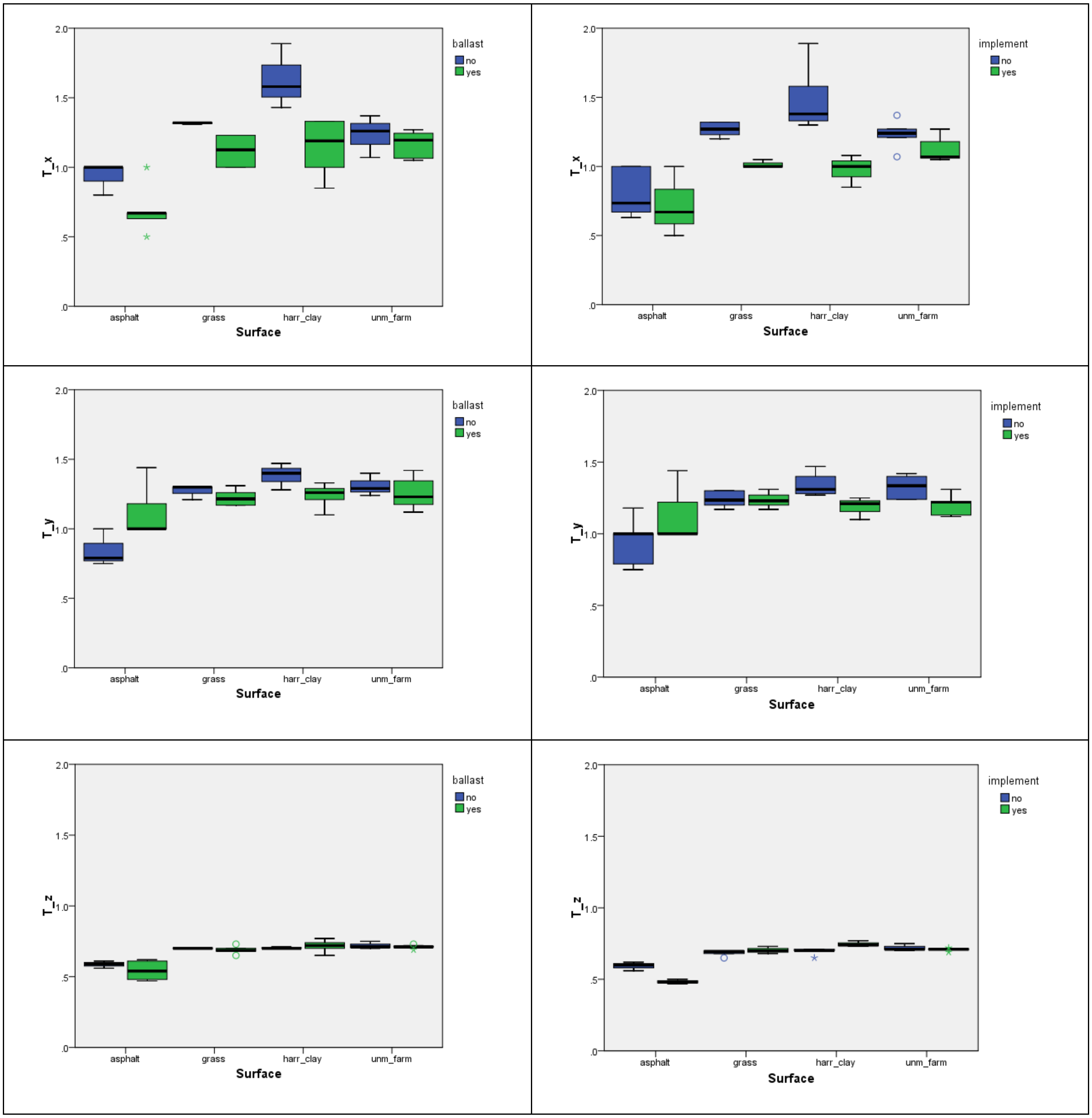


Figure 7. Box whisker graph of the transmissibility along the three directions (T_x, T_y, T_z) with the absence/presence of the ballast and of the implement.

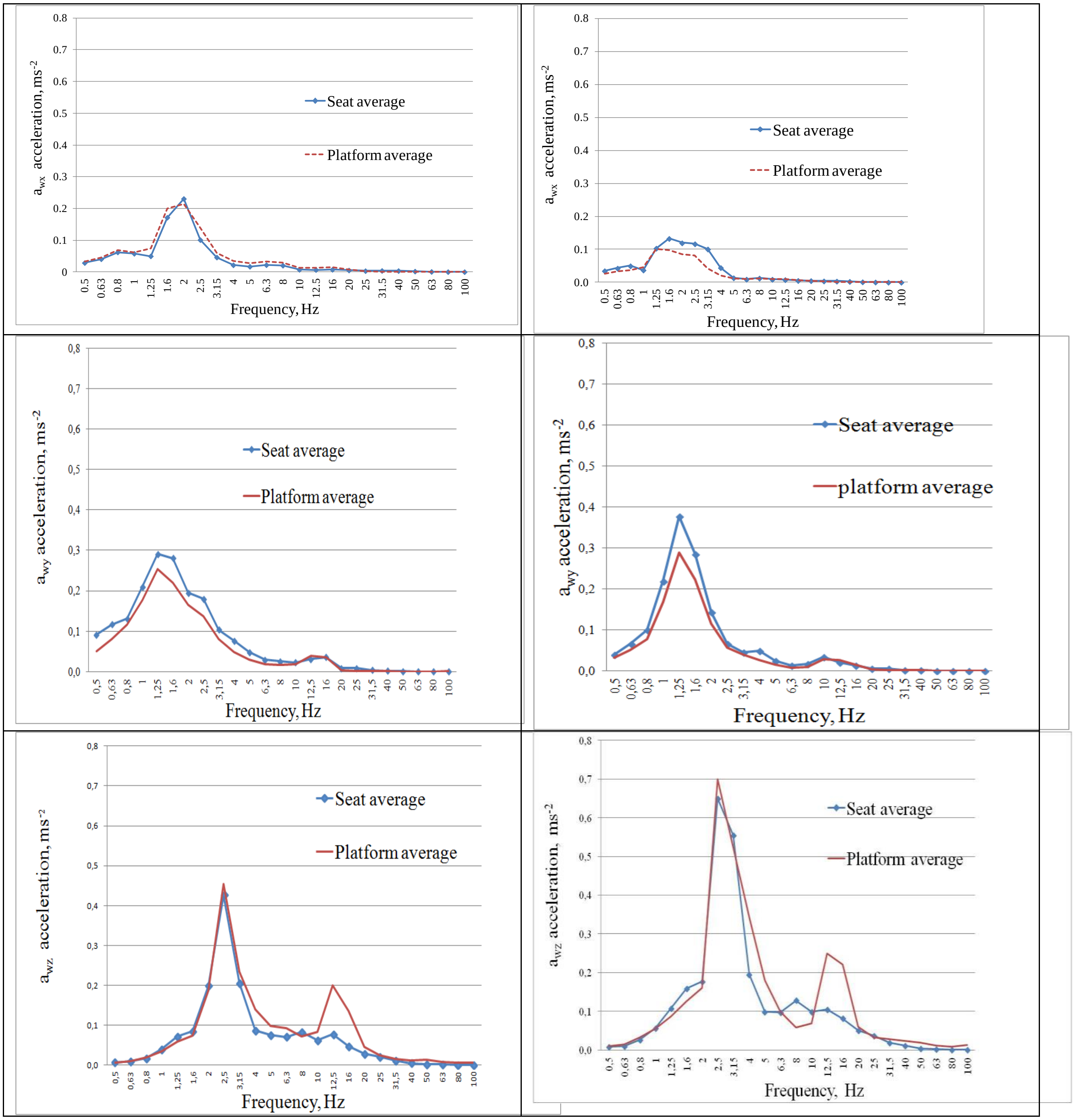


Figure 8. Overall acceleration values and frequency bands along the X, Y and Z direction, measured on the seat and on the platform of the tractor running on the grass at 2.78 m/s with the implement (left) and without the implement (right).

TABLES

Table 1. Tractor features.

Item	Measure unit	Value
Tractor power	kW	93
Displacement	cm^3	6720
Cylinders	n	6
Wheel base	mm	2661
Track width front	mm	1407
Track width rear	mm	1426
Unladen mass	kg	3770
Cab suspension		silent-blocks
Axles suspension		Any
Front tires	320/70 R 24	
Rear tires	480/70 R 30	

Table 2. Seat characteristics.

Suspension type	Pneumatic
Dumper type	Hydraulic
Category (78/764 EEC standard)	II and III
Fore-aft isolator	No
Lateral suspension	No

Table 3. Mass distribution of the tractor under investigation in the second set of field tests.

	front kg	%	rear kg	%	Total kg
Unladen	1530	40	2220	60	3770
Laden	2160	47	2440	53	4560
Laden plus implement	1660	32	3510	68	5160

Table 4. Univariate GLM analysis of the vibration total values measured on the seat and on the platform of the tractor with different tire pressures ($p<0.05$).

	Platform			Seat		
	F	Sig.	Observed Power[b]	F	Sig.	Observed Power[b]
Corrected Model	12.52	0.00	1.00	9.26	0.00	1.00
Intercept	641.84	0.00	1.00	339.58	0.00	1.00
surface	24.62	0.00	1.00	20.91	0.00	1.00
tire_pressure	11.57	0.00	0.89	1.24	0.28	0.18
surface * tire_pressure	0.74	0.54	0.17	0.28	0.84	0.09

b. Computed using alpha = .05

Table 5. Univariate GLM analysis of the vibration total values measured on the seat and on the platform of the tractor running at different forward speed ($p<0.05$).

	Platform			Seat		
	F	Sig.	Observed Power[b]	F	Sig.	Observed Power[b]
Corrected Model	12.02	0.00	1.00	9.93	0.00	1.00
Intercept	659.31	0.00	1.00	452.71	0.00	1.00
surface	23.87	0.00	1.00	19.06	0.00	1.00
speed	7.13	0.02	0.71	9.93	0.01	0.84
surface * speed	1.80	0.19	0.38	0.79	0.52	0.18

b. Computed using alpha = .05

Table 6. Univariate GLM analysis of the vibration total values measured on the seat and on the platform of the tractor with different masses ($p<0.05$).

	Platform			Seat		
	F	Sig.	Observed Power[b]	F	Sig.	Observed Power[b]
Corrected Model	24.40	0.00	1.00	17.77	0.00	1.00
Intercept	1739.39	0.00	1.00	928.74	0.00	1.00
surface	47.75	0.00	1.00	39.62	0.00	1.00
ballast	15.45	0.00	0.97	6.42	0.02	0.68
implement	24.24	0.00	1.00	17.08	0.00	0.98
surface * ballast	5.46	0.00	0.90	3.38	0.03	0.70
surface * implement	1.70	0.19	0.39	1.12	0.36	0.27

b. Computed using alpha = .05