



Article

Severity of Vibration at Operating Station of a Tractor with and Without Seeder Fertilizer Coupling Under Different Operating Conditions

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Abstract

The mechanization of the agricultural sector exposes operators to vibrations generated by tractors, terrain inclination, and attached implements. Prolonged exposure to such vibrations can lead to health problems, including visual disturbances, fatigue, spinal injuries, and low back pain. In this context, the present study aimed to assess the severity of mechanical vibrations in an agricultural tractor with four-wheel drive, both as a standalone unit and as part of a mechanized assembly comprising the same tractor coupled to a fertilizer seeder during sowing operations. Vibrations were monitored at four data collection points: the front and rear axles, the cab floor, and the operator's seat. Root mean square (RMS) acceleration values were compared with the limits established by ISO 2631-1, and the comfort levels at the operator's seat were classified as "uncomfortable" and "very uncomfortable." Vibration transmissibility between the rear axle and the cab floor (T2) was found to exceed 1, indicating amplification of vibrations. Overall, the operator's seat attenuated the vibration severity transmitted to the operator. Forward speed significantly influenced vibration severity, with higher speeds associated with increased RMS accelerations. Slope also affected vibration levels, with slope D2 (the sloped area) presenting higher mean RMS acceleration values. Notably, the tractor operating with the seeder fertilizer exhibited attenuated vibration levels compared to the tractor alone.

Keywords: mechanical vibrations; health and comfort; seeder fertilizer

1. Introduction

The pursuit of increased productive efficiency in the agricultural sector drives the demand for new technologies. Consequently, the use of agricultural machinery has become indispensable to the current production model [1], which seeks to maximize the output of agricultural products. The adoption of agricultural mechanization services enhances productive efficiency in rural areas [2]; rather than replacing labor, it complements the workforce and increases sectoral productivity [3]. It is estimated that the Brazilian agro-industrial sector was responsible for about 49% of all national exports in 2024, totaling US\$164.4 billion [4]. In this context, agricultural mechanization is essential for intensifying production and thereby enhancing competitiveness in the global market.

To further the advancement of the rural sector, it is necessary to employ equipment capable of achieving this objective. In this regard, agricultural mechanization is fundamentally supported by the use of tractors, which serve as sources of power and traction



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when coupled with other machinery, such as seeders [5,6]. However, agricultural tractor operators are exposed to vibrations generated by the engine, soil conditions, high temperatures [7], terrain inclination, and the operation of attached implements. Vibrations arising from ground irregularities are transmitted to the tractor cab, as many of these machines lack suspension systems between axles and frames, restricting damping capacity to the tires alone [8]. During engine operation, the resulting vibrations propagate through the machine structure and are transmitted to the operator [9] via contact surfaces, including the seat and cab floor.

Exposure for long periods to vibrations generated by agricultural machinery can cause damage to the health of operators. The transmission of mechanical vibrations through the driver's body may lead to injuries, fatigue, visual disturbances, reduced concentration, and irritability [10]. In their study, Author et al. [11] concluded that while agricultural mechanization—specifically the use of self-propelled machinery—entails lower muscular demands compared to other activities, it exposes tractor operators to whole-body vibration. Further research indicates that whole-body vibration (WBV) is associated with degenerative musculoskeletal disorders (MSDs), particularly spinal injuries, intervertebral disc degeneration, and low back pain [12–14]. Therefore, promoting working conditions that are comfortable and safe helps with the productive effectiveness of operators [15].

While mechanical vibrations in agricultural machinery cannot be entirely eliminated, they can be mitigated through various techniques aimed at reducing health risks to operators and preserving the mechanical integrity of equipment. In this context, the cabin of agricultural machinery must attenuate the frequency and amplitude of vibrations generated to avoid spinal injuries [10]. Ref. [16] investigated the implementation of a self-leveling system in a tractor cab to reduce vibrations and found that, although the system attenuated vibrations in the direction of travel, irregularities in the terrain, combined with the use of a plow and slope, led to increased vibration in the transverse and vertical directions. An additional strategy for mitigating vibrations involves managing the relationship between operating speed and traction force during activities [17], as increases in working speed have been shown to amplify vertical vibration within the tractor cabin [18]. An additional factor that can contribute to the generation of vibrations in the operator's space is the use of implements. Ref. [19] reported that the use of a blade plow system has greater amplitude of vibration in the transverse direction when compared to the horizontal and vertical directions; therefore, the application of these elements must also be studied to minimize generated vibrations. These considerations highlight the importance of addressing the working conditions to which operators are subjected, particularly with regard to safety and comfort [20].

Due to the seriousness of the subject, this study was developed to evaluate the severity of mechanical vibrations of an agricultural tractor with four-wheel drive, both as a standalone unit and as part of a mechanized assembly comprising the same tractor coupled to a fertilizer seeder during sowing operations. A comparative analysis was conducted between the tractor operating alone and the full mechanized assembly. Data were collected at four specific points: the front and rear axles of the tractor, the cabin floor, and the operator's seat. These measurements enabled the assessment of vibration transmissibility from the axles to the cabin floor and from the floor to the seat. The objective was to determine whether the vibration severity to which the operator is exposed complies with the acceptable limits established by current standards for human-machine interaction.

2. Materials and Methods

The experiment was conducted in the city of São Vicente de Minas/MG, Brazil, which is located at latitude 21°42' S, longitude 44°26' W, has an average altitude of 972 m, and has

a CWb climate according to the Köppen classification. The soil of the experimental area is clayey tending to sandy clay. The experimental area consisted of a field maintained under no-till farming conditions.

The vibration data of the tractor operation and, subsequently, of the operation of a mechanized set composed of the tractor coupled to the seeder fertilizer were collected. The mechanized set used in this experiment is presented in Figure 1, which was composed of a John Deere 6180J four-wheel drive tractor (John Deere, Horizontina, RS, Brazil) and a Massey Ferguson MF 629 seeder fertilizer (Massey Ferguson, Ibirubá, RS, Brazil). It is important to emphasize that the Massey Ferguson MF 629 seeder fertilizer was not loaded during the experiment.

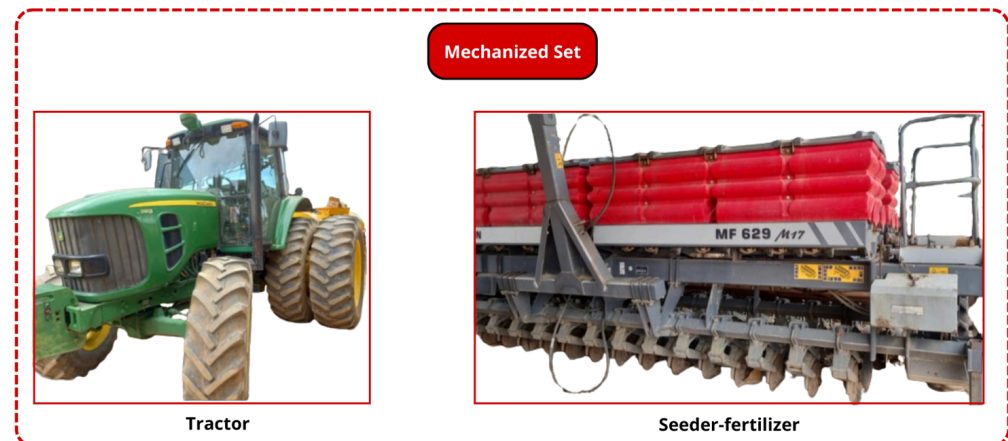


Figure 1. Mechanized set used in experiment in order to determine vibration severity along the machine.

The mechanical vibration collecting points were the operator's seat, the floor of the operating cabin, and the front and rear axles of a John Deere 6180J four-wheel drive tractor. During the experiment, the tractor was configured with front tires 19.9–28 and rear tires 20.8–38 DUAL, with an insufflation pressure of 20 psi in the front and rear tires. The tractor was configured with a front ballast of 300 kg. Additionally, ballast was applied to the tires. The front tires were filled with 70% water, while the rear tires (configured as dual wheels) were each filled with 40% water.

Uniaxial accelerometers were employed to collect vibration severity data along the X-, Y-, and Z-axes (corresponding to the longitudinal, transverse, and vertical directions, respectively), with three accelerometers used at each monitoring point. All accelerometers were accompanied by calibration certificates provided by the manufacturers, from which the sensitivity values of each transducer were obtained. These sensitivity values were used to configure the data acquisition system employed in this study. The accelerometers were positioned in accordance with the guidelines established in [21] for the evaluation of whole-body vibration (WBV). In Figure 2 is illustrates the collection points considered in this work.

The positioning of the accelerometers followed the ISO 2631 standard [21] (Figure 3), which guides the methodologies for the measurement of mechanical vibrations. The reference is given by the operator's working position. It is important to note that the operator presented excellent health conditions and had a body mass of 100 kg. The seat of the John Deere 6180J four-wheel drive tractor was kept in its original factory configuration, with no design modifications; only basic adjustments were made to accommodate the operator's mass and stature.

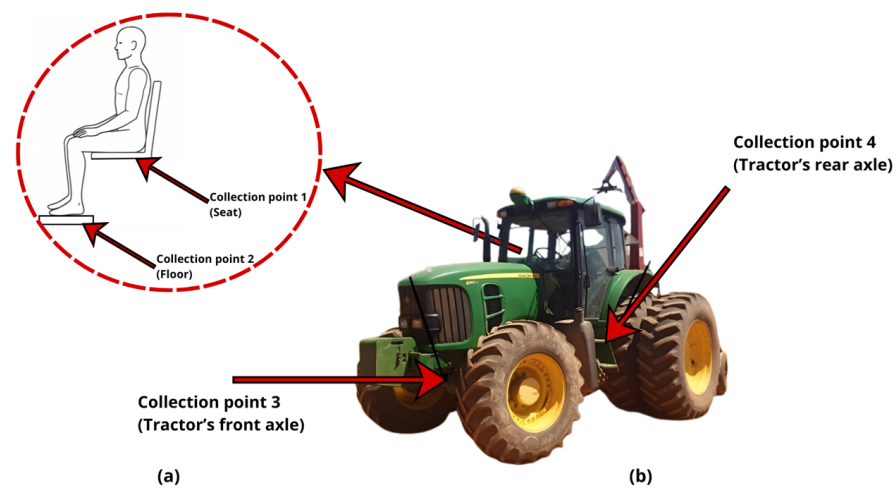


Figure 2. Collection points of the acceleration on x-, y-, and z-axes (longitudinal, transverse, and vertical) in the cabin (a) and outside the cabin (b).

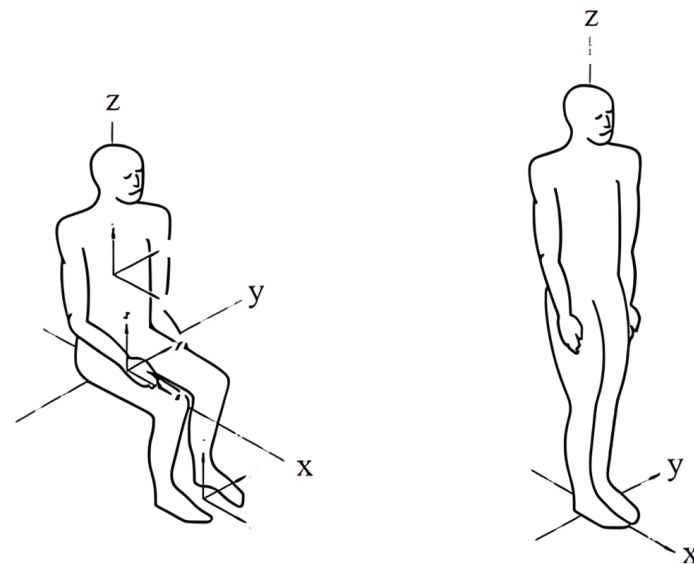


Figure 3. Coordinate system [21].

A National Instruments (NI) data acquisition system, with 3 modules with 4 inputs each, a microcomputer with LabView software, 2016 version, the necessary cabling to interconnect them, and MATLAB software, R2017b version, for signal processing were used. NI 9234 modules, with a 50 ppm sampling rate accuracy, resolution of 12.5 ns, and frequency measurement range from 0 to 20 MHz, were used. The NI 9234 is a 4-channel module equipped with built-in features, including automatic anti-aliasing filters that adjust to the selected sampling rate. The transducers were high-sensitivity PCB industrial accelerometers. Since the mass of these accelerometers is insignificant compared to the mass of the tractor, they were considered to not interfere with the dynamics of the system. A direct current transformer for an alternating current fed by a battery powered the instrumentation used.

In terms of the frequency domain, the Nyquist sampling theorem was used for faithful reconstruction of a signal, establishing that the sampling frequency should be at least twice as high as the highest frequency of the signal, which in mathematical terms is $f_s \geq 2f_c$, where f_s is the sampling frequency and f_c the highest frequency of the signal [22]. Given that the frequencies of interest in this study extend up to 80 Hz, the sampling rate was required to be at least 160 Hz. In the experiment, a sampling rate five times the maximum frequency of interest was adopted, resulting in a sampling rate of 400 Hz.

2.1. Signal Analysis

The frequency spectra of the dynamic behavior and the average root mean square (RMS) of the accelerations were determined from the data, and the transmissibility of vibration from the axles to the operator station floor and from the operator station floor to the operator's seat were determined from these averages. The amplitudes at the characteristic frequencies of the system during operation were determined from the frequency spectrum. The RMS values were exposed in the time domain.

The signal path was given by the data captured by the accelerometers through the modules and the processing of the data by LabView software. These data were collected in the time domain; therefore, Fast Fourier Transform (FFT) in MATLAB software was used to perform transformation to the frequency domain to extract the acceleration peaks. A low-pass filter with a Hamming window was used, and amplitudes below 0.1 m s^{-2} were not considered. From the signal, the frequency spectrum of the system was generated, which showed the characteristic frequencies through the amplitude peaks that highlighted the highest concentration of energy at certain points of the spectrum.

The average RMS values of the accelerations were obtained according to [23]. The RMS value is a measure of both the central data tendency and the dispersion of the vibration. This statistical technique transmits the magnitude of the vibration that acts at the data collection points and is calculated according to Equation 1. The RMS value is related to the energy of the oscillatory movement and its potential to cause damage. It is of great importance in the evaluation of the vibration severity because it considers the history of the wave over time.

$$a_{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^N a_i^2} \quad (1)$$

where

- a_{RMS} is the RMS acceleration in m s^{-2} ;
- N is the number of occurrences of acceleration;
- a is the acceleration data in m s^{-2} .

According to [21], the acceleration signal can be summed to a total value weighted from orthogonal coordinates. Equation (2) determines this value.

$$a_v = (k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2)^{\frac{1}{2}} \quad (2)$$

where

- a_{wx} , a_{wy} and a_{wz} are the effective values of the weighted accelerations relative to the orthogonal axes x, y, and z, respectively, in m s^{-2} ;
- k_x , k_y and k_z are multiplicative factors.

In [21], the weighted mean that measures the effects of periodic vibration in seated people exposed to WBV in terms of health includes the following values for the multiplicative factors: $k_x = 1.4$, $k_y = 1.4$ and $k_z = 1$.

The objective in mechanical systems subjected to vibration is to minimize the vibrational load transmitted to the base [24], which in the case of agricultural machinery prevents strong vibration from reaching the operating cabin and, consequently, the operator. In this context, the vibration transmissibilities between the front and rear axles and the floor (T_1 and T_2 , respectively) and between the floor and the seat (T_3) were measured according to

Equations (3)–(5). The purpose of measuring transmissibility is to observe whether the accelerations that affect the operator are attenuated by the cabin or the seat.

$$T_1 = \frac{RMS_{floor}}{RMS_{front-axle}} \quad (3)$$

$$T_2 = \frac{RMS_{floor}}{RMS_{rear-axle}} \quad (4)$$

$$T_3 = \frac{RMS_{seat}}{RMS_{floor}} \quad (5)$$

where

- T_1, T_2 and T_3 are the vibration transmissibilities;
- RMS_{seat} is the RMS acceleration in the operator's seat in $m\ s^{-2}$;
- RMS_{floor} is the RMS acceleration in the floor of the operator's cabin in $m\ s^{-2}$;
- $RMS_{front-axle}$ is the RMS acceleration found in the front axle in $m\ s^{-2}$;
- $RMS_{rear-axle}$ is the RMS acceleration found in the rear axle in $m\ s^{-2}$.

2.2. Variables Evaluated During Field Operations

To analyze the effect of the tractor's forward speed and slope on the severity of vibration transmitted to the operator, these variables were considered in the execution of the experiment, in addition to the "machinery" variable, which distinguishes the tractor from the mechanized set.

Grain sowing operations are typically conducted at a speed of $6\ km\ h^{-1}$ [25,26]. Therefore, the speeds selected for the experiment were 5, 6, and $7\ km\ h^{-1}$, which corresponded to S1, S2, and S3, respectively. The slope of the experimental area was also taken into account. Figure 4 presents the area where the experiments were carried out.



Figure 4. The experimental area, in which the dashed line indicates the boundary between the two evaluated slopes (D1 and D2).

In Figure 4, D1 indicates a flat area, and D2 indicates an area with a slope of approximately 7.5° . Table 1 shows the experimental design, in which paths of 200 m were made. The distance was measured using the application Strava. The postprocessing of the

data was performed in the software MATLAB, and the time factor was used to divide the distance of 200 m into four equal parts, representing 4 replicates of 50 m each, for each treatment considered.

Table 1. Variations in the paths, where “S” represents the speed, “D” represents the slope, “T” represents the path with the tractor without coupling, and “TS” represents the path of the tractor coupled to the seeder fertilizer.

Mechanized Assembly	Slope	Speed
T (Tractor)	D1	S1
		S2
		S3
	D2	S1
		S2
		S3
TS (Tractor + Seeder)	D1	S1
		S2
		S3
	D2	S1
		S2
		S3

2.3. Statistical Analysis of the Data

The following response variables were evaluated: vibration severity and vibration transmissibility at the operating station. For this purpose, an experiment was conducted according to a completely randomized design in a $2 \times 3 \times 2$ factorial scheme with 4 replicates. The factors evaluated were slope (D1 and D2), speed (S1, S2, and S3), and machinery (the tractor operating alone and the tractor coupled to a seeder fertilizer).

The data were initially subjected to normality tests. Those meeting the normality assumptions were subsequently analyzed using analysis of variance (ANOVA) at a 5% probability level. Means of the qualitative factors were studied using the Tukey test at 5% probability. Means of the quantitative factors were studied through regression analysis, in which the models were selected based on the coefficient of determination, significance of the coefficients, and analysis of lack of fit. All statistical analyses were performed using the R software environment.

3. Results

The frequency spectra shown in Figures 4 and 5 represent the deconvolution of the speed and slope, respectively, and include all repetitions considered for each scenario. Acceleration peaks were observed within frequency ranges of 10–20 Hz, 20–30 Hz, and 40–50 Hz.

The frequencies associated with the acceleration peaks increased with forward speed. As shown in Figure 5, at speed S1, the acceleration peaks across repetitions occurred between 13 and 15 Hz; at speed S2, between 15 and 17 Hz; and at speed S3, between 17 and 19 Hz.

In the deconvolution of the slope (Figure 6), the acceleration peaks within the 10–20 Hz range were concentrated between 15 and 17 Hz for slope D1 and between 16 and 19 Hz for slope D2. In the 40–50 Hz frequency range, the acceleration peaks are concentrated at 46 Hz for slope D1 and at 48 Hz for slope D2.

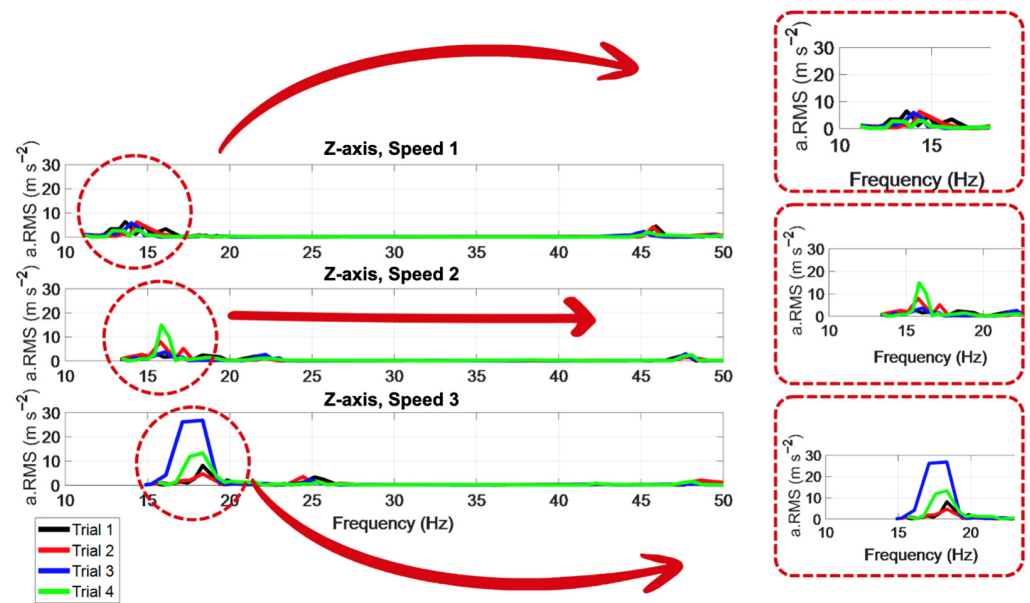


Figure 5. Frequency spectra of the speed in the operator's seat (z-axis) and detail of highest peaks between 10 and 20 Hz.

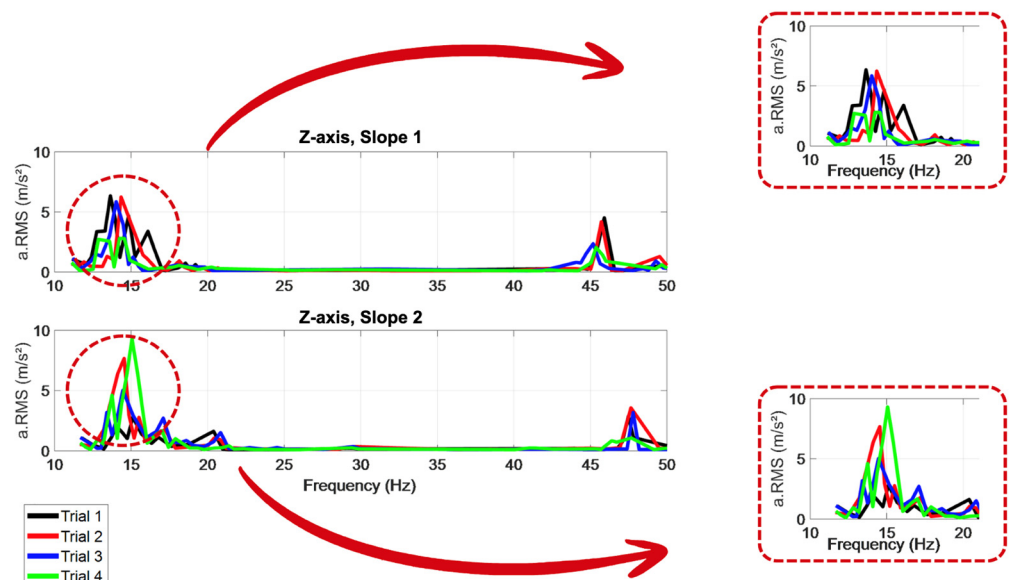


Figure 6. Frequency spectra for the speed in the operator's seat (z-axis) and detail of highest peaks between 10 and 20 Hz.

Analysis of variance was performed to examine the effect of the interactions among the factors studied at each data collection point and at the aforementioned transmissibilities. Table 2 shows that there are significant differences between the results found for the vibration severity of the tractor operating alone and those recorded for the tractor coupled to the seeder fertilizer.

The slope (D) and speed (S) factors, when analyzed separately, revealed significant differences at most data collection points, as well as in the transmissibility calculations. The interactions between D and S and between M and S in the operator's seat are significant. Given the significant interaction between the machinery factor (M), a qualitative variable, and the speed factor (S), a quantitative variable, M, was evaluated using a means comparison test, while S was analyzed via regression analysis.

Table 2. Main results of the analysis of variance of the RMS acceleration determined in the rear axle, front axle, cabin floor, and operator's seat.

Sources of Variation	Front Axle	Rear Axle	Cabin Floor	Operator's Seat
M (Machinery)	F = 293.549 $p = 2 \times 10^{-16} *$	188.199 $p = 2.68 \times 10^{-16} *$	F = 0.117 $p = 0.735$	F = 184.083 $p = 3.80 \times 10^{-16} *$
D (Slope)	F = 53.507 $p = 9.26 \times 10^{-9} *$	F = 9.934 $p = 0.00316 *$	F = 42.255 $p = 1.18 \times 10^{-7} *$	F = 123.813 $p = 1.62 \times 10^{-13} *$
S (Speed)	F = 15.903 $p = 9.59 \times 10^{-6} *$	F = 19.417 $p = 1.55 \times 10^{-6} *$	F = 71.828 $p = 1.23 \times 10^{-13} *$	F = 215.028 $p = 2 \times 10^{-16} *$
D:S	F = 0.211 $p = 0.811$	F = 1.826 $p = 0.17492$	F = 0.395 $p = 0.676$	F = 22.417 $p = 3.71 \times 10^{-7}$
M:D	F = 2.368 $p = 0.132$	F = 54.833 $p = 7.01 \times 10^{-9} *$	F = 0.820 $p = 0.371$	F = 0.097 $p = 0.7568$
M:S	F = 42.174 $p = 2.25 \times 10^{-10} *$	F = 13.886 $p = 2.97 \times 10^{-5} *$	F = 0.747 $p = 0.480$	F = 4.395 $p = 0.0192 *$

* Significant at the 5% probability level.

The results of the means comparison test (Table 3) indicate that, at all speed levels, significant differences exist between the vibration severity of the tractor operating alone and that of the mechanized set comprising the tractor coupled to the seeder fertilizer. Additionally, the vibration severity is higher for the operation of the tractor without coupling.

Table 3. Results of the analysis of the machinery factor at each level of the travel speed factor.

Speed (km h ⁻¹)	Machinery	Floor (m s ⁻²)
5	Tractor (T)	1.02 a
	Tractor–Seeder (TS)	0.87 b
6	Tractor (T)	1.20 a
	Tractor–Seeder (TS)	1.04 b
7	Tractor (T)	1.40 a
	Tractor–Seeder (TS)	1.16 b

Different letters at each speed indicate a significant difference according to the Tukey test at 5% probability.

For the range of RMS averages recorded for the tractor operating alone (1.02 to 1.40 m s⁻²), ISO 2631-1 [21] classifies the vibration levels as “uncomfortable”. The same classification is given for the interval of the tractor operating coupled to the seeder fertilizer (values between 0.88 and 1.36 m s⁻²). According to European Directive 2002/44/EC, the exposure action limit based on the average vibration value for the tractor without the implement corresponds to 7 h and 36 min. In contrast, considering the average value found for the tractor operating coupled to the seeder fertilizer, the exposure limit is 8 h and 13 min.

The regression analyses for both the tractor operating alone (Figure 7a) and the tractor coupled to the seeder fertilizer (Figure 7b) show an increase in the RMS acceleration levels with increasing forward speed. Furthermore, the regression analysis shows that the RMS acceleration values are higher for the tractor not coupled to the seeder fertilizer (1.02–1.40 m s⁻²) than for the tractor operating coupled to the seeder fertilizer (0.88–1.36 m s⁻²).

For the data collected at the operator's seat, Equations (6) and (7) represent the linear models that best fit the tractor operating scenarios without coupling and with coupling, respectively. These models are graphically represented in Figure 7, with coefficients of determination (R²) of 0.69 and 0.63.

$$RMS_T = 0.05 + 0.19S \quad (6)$$

$$RMS_{TS} = 0.14 + 0.15S \quad (7)$$

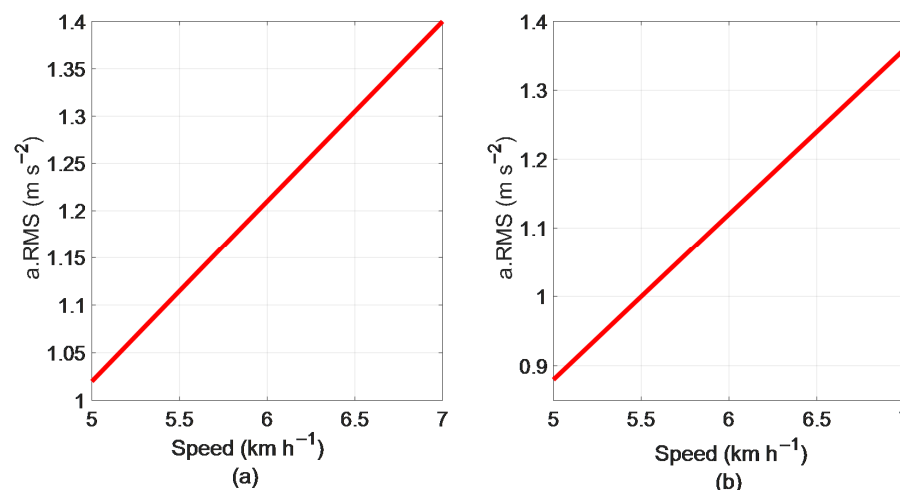


Figure 7. Regression analysis of the speed factor for the operation of the tractor without (a) and with (b) coupling of the seeder fertilizer, as written in Equations (5) and (6), respectively.

An analysis was also conducted using a means comparison test for the slope factor. Table 4 shows that there are differences between the slopes for speeds of 5 and 7 km h⁻¹ in terms of vibration severity for the operation of the tractor coupled to the seeder fertilizer. The highest mean values were observed for slope D2, and vibration severity increased with increasing forward speed.

Table 4. Results of the analysis of the slope factor at each level of the travel speed factor.

Speed (km h ⁻¹)	Slope	Floor (m s ⁻²)
5	D1	0.88 b
	D2	1.00 a
6	D1	1.09 a
	D2	1.14 a
7	D1	1.15 b
	D2	1.42 a

Different letters at each speed indicate a significant difference according to the Tukey test at 5% probability.

The quadratic model provided the best fit for the relationship between speed and slope for both D1 (Figure 8a) and D2 (Figure 8b). Equations (8) and (9), with coefficients of determination of 0.54 and 0.70, describe the models obtained for slopes D1 and D2, respectively.

$$RMS_{D1} = 2.31 + 1.00S - 0.07S^2 \quad (8)$$

$$RMS_{D2} = 2.34 + 0.61S + 0.07S^2 \quad (9)$$

An increase in forward speed resulted in higher vibration severity for both slopes D1 and D2. For the D1 slope, the highest average RMS value is 1.15 m s⁻², at a speed of 7 km h⁻¹. According to the comfort criteria established by ISO 2631-1 [21], this value is classified as “uncomfortable.” For slope D2, the highest mean RMS value was 1.50 m s⁻², also at 7 km h⁻¹, which falls into the “very uncomfortable” category according to the same standard. Based on European Directive 2002/44/EC, the permissible exposure time corresponding to the average vibration value for slope D1 is 9 h, whereas for slope D2 it is reduced to 7 h and 36 min.

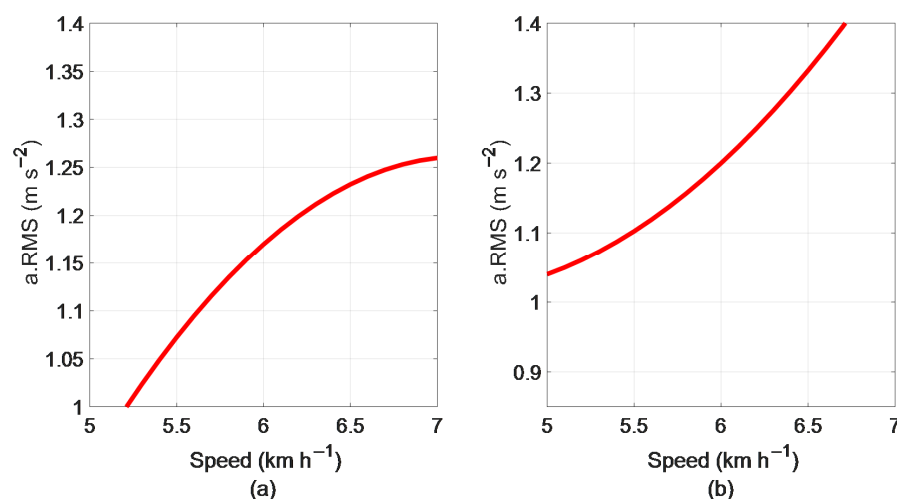


Figure 8. Regression analysis of the speed factor for slopes D1 (a) and D2 (b), as written in Equations (7) and (8), respectively.

From the results of the analysis of variance for the vibration transmissibility (Table 5), the relationships between the machinery, slope, and speed factors were analyzed.

Table 5. Main results of the analysis of variance of the RMS accelerations for the transmissibilities.

Sources of Variation	T ₁	T ₂	T ₃
M	F = 215.349 $p = 2 \times 10^{-16} *$	F = 48.085 $p = 3.02 \times 10^{-8} *$	F = 93.311 $p = 8.86 \times 10^{-12}$
D	F = 5.252 $p = 0.027549 *$	F = 46.145 $p = 4.69 \times 10^{-8} *$	F = 3.308 $p = 0.0768$
S	F = 21.902 $p = 4.71 \times 10^{-7} *$	F = 20.497 $p = 9.16 \times 10^{-7} *$	F = 56.271 $p = 4.37 \times 10^{-12} *$
D:S	F = 0.116 $p = 0.890733$	F = 0.186 $p = 0.83078$	F = 13.766 $p = 3.19 \times 10^{-5} *$
M:D	F = 16.462 $p = 0.000238 *$	F = 35.863 $p = 5.90 \times 10^{-7} *$	F = 0.145 $p = 0.7056$
M:S	F = 43.092 $p = 1.69 \times 10^{-10} *$	F = 7.013 $p = 0.00256 *$	F = 1.355 $p = 0.2702$

* Significant at the 5% probability level.

The analysis of vibration transmissibility in relation to the speed and machinery factors revealed that transmissibility values for T₁ and T₃ remained below 1, whereas those for T₂ were predominantly above 1. Table 6 shows that there are some differences between the RMS acceleration values for the tractor coupled to the seeder fertilizer and the tractor operating alone. Specifically, for the T₃ transmissibility, the coupling of the seeder fertilizer to the tractor resulted in a significant reduction in RMS acceleration levels across all forward speeds evaluated.

Table 6. Results of the analysis of the machinery factor for each transmissibility evaluated.

Speed (km h ⁻¹)	Machinery	T ₁	T ₂	T ₃
5	Tractor	0.89 a	1.25 a	0.81 a
	Tractor-Seeder	0.56 b	0.96 b	0.71 b
6	Tractor	0.94 a	1.35 a	0.76 a
	Tractor-Seeder	0.71 b	1.22 a	0.69 b
7	Tractor	0.75 a	1.21 a	0.90 a
	Tractor-Seeder	0.72 a	1.13 a	0.79 b

Different letters at each speed indicate a significant difference according to the Tukey test at 5% probability.

For the interaction between the speed and slope (Table 7), significant differences in mean RMS acceleration were observed when the fertilizer seeder was coupled to the tractor only under specific conditions: at speeds of 6 and 7 km h⁻¹ for T₂ transmissibility and at a speed of 7 km h⁻¹ for T₃ transmissibility.

Table 7. Interaction between slope (D) and speed (S) factors for T₁, T₂ and T₃ transmissibilities.

Speed (km h ⁻¹)	Slope	T ₁	T ₂	T ₃
5	D1	0.75 a	1.02 a	0.76 a
	D2	0.71 a	1.19 a	0.77 a
6	D1	0.84 a	1.21 b	0.75 a
	D2	0.81 a	1.37 a	0.70 a
7	D1	0.75 a	1.10 b	0.80 b
	D2	0.72 a	1.24 a	0.88 a

Different letters at each speed indicate a significant difference according to the Tukey test at 5% probability.

4. Discussion

The use of an implement coupled to the tractor resulted in reduced acceleration levels. This finding is consistent with the results reported by [27], which corroborate the observations of the present study—particularly those summarized in Table 2. In their evaluation of vibration severity in a 197 hp tractor operating with and without a fertilizer spreader, the authors also recorded higher acceleration values when the tractor was used without the implement.

Ref. [28] conducted a study using the same ballast setting and the same scarification depth in a scarifier coupled to an 85 hp tractor. They found mean acceleration values of 5.5 m s⁻² for a speed of 3.5 km h⁻¹ and acceleration values of 6.5 m s⁻² for a speed of 4.5 km h⁻¹ at the measurement point, which was the operator's seat. In the present study, lower acceleration values were observed at all forward speeds of 5, 6, and 7 km h⁻¹.

Ref. [29] conducted an experiment evaluating the severity of vibration of a tractor operating coupled to a mowing implement both on paved roads and on rural roads. On rural roads, higher vibration severity values were observed for both moving and non-moving mowing conditions compared to paved surfaces. However, there were no significant differences in vibration based on whether the mower deck was active or not.

The results for the regression analysis for the tractor, both with and without the fertilizer seeder, are consistent with the findings of [30], in which the authors varied the forward speed of a 20 hp tractor and found mean RMS acceleration values of 0.31 m s⁻² for the speed of 4 km h⁻¹, of 0.39 m s⁻² for the speed of 5 km h⁻¹ and 0.44 m s⁻² for the speed of 6 km h⁻¹ at a collection point at the center of gravity of the tractor. Furthermore, the regression analysis revealed that RMS acceleration was higher for the tractor operating without the seeder, which aligns with the observations of [25]. From these results, it can be inferred that coupling to the seeder fertilizer contributes to the attenuation of the vibration levels. In contrast, a study evaluating an operator's exposure to whole-body vibration (WBV) while working with a tractor coupled to a timber trailer [29] reported unacceptable WBV levels, which may compromise operator health and work safety during a typical workday. These findings underscore the need for increased attention to WBV, given that the operator plays a fundamental role in the agricultural production process.

Refs. [31,32] investigated whole-body vibration in tractors under different conditions. As a result, they found that vibrations were greater on the rough track. These findings indicate that ground conditions can influence the RMS value. In the present study, higher accelerations were found when the slope increased, as can be observed in the results by [31,32].

Ref. [33] analyzed vibration severity as a function of tractor forward speed, tire inflation pressure, and tire type (diagonal or radial). The study concluded that, for both

diagonal and radial tires, forward speed significantly influenced vibration severity. The authors observed that tractor tires can absorb impacts at lower forward speeds; however, as the speed increases, the wheels are not able to perform this attenuation, and the vibration severity may even increase. Therefore, the higher RMS acceleration observed at increased speeds in the present study may be explained by the capacity of tires to absorb impacts only at lower speeds.

Ref. [34] evaluated the frequency ranges that affect the vibration transmissibility from evaluations inside and outside of the cabin of an 85 cv tractor coupled to a scarifier and considering different levels of ballast. The authors observed amplification in the range from 0 to 15 Hz for the all-metal ballast (AMB), from 0 to 19 Hz for the part-metal ballast (PMB), and from 71 to 76 Hz for the all-liquid ballast (ALB). The mass/power ratios for AMB, PMB, and ALB were 67.36, 58.56 and 66.72 kg k W⁻¹, respectively. Similarly, Ref. [31] evaluated the vibration severity between the cabin floor and the operator's seat for a tractor coupled to a grass mowing implement. Transmissibility values between 1 and 2 in the frequency range between 2 and 4 Hz were found. The findings of the present study are consistent with those reported by [31,34], as an increase in transmissibility associated with a higher speed and steeper slope was also observed.

The fact that the T₂ transmissibility values exceeded 1 in all scenarios—indicating higher RMS acceleration at the cab floor than at the rear axle—can be attributed to the positioning of the rear axle relative to the operator's station. Additionally, the use of double wheels should be considered, as they provide a large contact area between the tires and the surface. This configuration may contribute to mitigating external impacts at the rear axle.

5. Conclusions

Under the conditions in which the study was conducted, the following conclusions can be drawn:

- Significant differences in vibration severity were observed between the tractor operating alone and the tractor coupled to the fertilizer seeder, with the mechanized assembly attenuating the vibration levels. This finding was consistent across all data collection points.
- The slope factor influenced the vibration severity levels, and slope D2 (slope area) presented a higher average RMS acceleration.
- Forward speed had a substantial effect on vibration severity in both operational configurations (tractor alone and mechanized set) and on both slopes. Higher speeds were associated with increased mean RMS accelerations at the operator's seat.
- Overall, the operator's seat reduced the vibration severity transmitted to the operator, effectively fulfilling its intended role of damping impacts arising from terrain irregularities, tractor motion, and vibration-generating machine components.

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Abbreviations

The following abbreviations are used in this manuscript:

RMS	Root Mean Square
WBV	Whole-Body Vibrations
MSD	Degenerative Musculoskeletal Disorders
NI	National Instruments
FFT	Fast Fourier Transform
AMB	All-Metal Ballast
PMB	Part-Metal Ballast
ALB	All-Liquid Ballast

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