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The whole-body vibration in operation of wheeled and tracked harvester IN *PINUS* thinning

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ABSTRACT

Technological advances available in wood harvesting machines have provided productivity improvements and more comfort in forestry operations. However, operators may be exposed to whole-body vibration which can lead to a wide variety of health disorders and industry losses. This research aimed to evaluate the exposure of workers to whole-body vibration in thinning harvesting operations comparing two models of harvesters (tracked and wheeled) working in *Pinus taeda* stands submitted to the first commercial thinning. Whole-body vibration was determined by the three orthogonal axes (X, Y, and Z) using a 3-Axis integrator vibration meter, and the data were analyzed according to the criteria established by the ISO 2631–1:1997 and the European Directive, 2002/44/EC, concerning the resulting acceleration from normalized exposure A (8) and value of the resulting vibration dose value (VDV). The acceleration and vibration levels obtained by the tracked harvester presented mean values of A (8) of 0.6 m/s^2 and VDV 11.2 $m/s^{1.75}$, while by the wheeled harvester, mean values were A (8) of 0.4 m/s^2 and VDV 9.3 $m/s^{1.75}$, respectively. It was possible to verify the expressive vibration from the tracked harvester analysis, the operators were exposed to the whole-body vibration above the limits recommended by the regulating norms.

1. Introduction

In Brazil, planted forests have grown significantly in the last decades, with the intensification of mechanization caused by the market opening to import high technology machines (Moreira et al., 2004). As a result, the forestry sector has imported modern machines with a high technology available to forestry companies, providing improvements in productivity, cost reduction, and greater comfort and safety for operators in the execution of forestry operations (Machado, 2014).

The wood harvesting operations in planted forests can be performed by the clearcut or thinning, and the mechanized systems can differentiate as to the system of wood harvesting or cut and wood extraction machines. The cutting stage is characterized by tree cutting, wood processing operations, and harvester models equipped with wheels or tracks.

However, despite the significant technological evolution available in the current wood harvesting machines, which has provided gains in terms of productivity, there are still questions as to whether operators are working under favorable ergonomic conditions in the workplace. Among the ergonomic factors is the exposure to whole-body vibration caused by bumps that occur during the execution of the operations and that may suffer variations with the use of different types of rolling stock of the machine (tracked and wheeled).

Exposure to whole-body vibration (WBV) can be associated with a wide variety of diseases, which affect the functioning of the body, such as the vertebral column, reproductive organs, digestive, circulatory, and nervous system (Griffin, 1990; Pope et al., 2002). Several studies have pointed to the negative health consequences of forest machine operators caused by exposure to vibration (Oh et al., 2004; Jack and Oliver, 2008, Almeida et al., 2014; Häggström et al., 2016). In addition to health effects, exposure to vibration can compromise operator performance mainly in activities with a high demand for accuracy, characteristic of forest machine operations (Conway et al., 2006), and the fact that operators remain seated in static or with few movements in the workstations for long periods.

Whole-body vibration has also brought great concern to mechanized

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Fig. 1. Location of the study area.

forest operations, and its adverse effects are intensified by performing repetitive movements of the upper limbs and also of the entire body (Burström et al., 2014). Rehn et al. (2009) attribute a high prevalence of pain in the cervical region in forest machine operators to the vibrations caused by shocks or bumps during the work.

Due to most of the ergonomic problems are related to the whole body vibration in the operations with forest machines, several studies have been developed, with emphasis on the evaluation of damping systems in forest machines (Gellerstedt, 1998; Sherwin et al., 2004; Gerasimov and Sokolov, 2009), and alternative systems of wood harvesting (Cation et al., 2008).

However, despite the many studies carried out in forestry machines proving the damage caused by exposure to vibration, there is no comparative research between tracked and wheeled machines. Considering that, the thinning operation requires constant operator attention and frequent postural change, these occupational factors can further compromise workers' health.

To assign exposure limits to vibration levels, the European Directive (2002) limits the standard daily exposure to a reference period of 8 h, with A (8) being 1.15 m/s^2 or the VDV raised to the fourth power value of 21 $m/s^{1.75}$, stipulating that measures should be taken to reduce the impact of full-body vibration if the values of A (8) and VDV exceed 0.5 m/s^2 and 21 $m/s^{1.75}$, respectively.

The limits and precautionary recommendations regarding exposure to whole-body vibrations are set out in international standards that serve as a reference for national legislation, the main standards being: ISO 2631-1: 1997 (whole-body vibrations - WBV); ISO 5349–1 (vibration of hands); and European Directive, 2002/44/EC.

The objective of this research was to evaluate the exposure of operators to the whole-body vibration in tracked and wheeled harvesters' operation in the execution of *Pinus taeda* thinning, aiming to contribute with improvements in working procedures, greater comfort, and operators' health.

2. Material and methods

This research was carried out in a forest company located in the southern region of Brazil, in planted forests of *Pinus taeda* submitted to the first commercial thinning at the age of 10 years, with an average individual tree volume of 0.289 m^3 and density of 1600 trees per hectare. The ground was characterized as flat to corrugated, with slope varying from 0 to 15° (Fig. 1).

In this research, two harvester models were evaluated, tracked harvester, and wheeled harvester. The technical specifications are described in Table 1. The studied operators had the same level of experience and similar biotype, with body mass varying between 86 and 93 kg, and height between 1.76 and 1.82 m.

The study was approved by a Brazilian Research Ethics Committee under the opinion nº. 2,645,278, and the participating operators signed the Free and Informed Consent Term (TCLE), as determined by the National Health Council of the Ministry of Health (BRASIL, 2013).

To obtain a significant number of samples, a pilot study of forest cutting operations with both machines was carried out, based on their parameters according to the equation proposed by Conaw (1977), assumpting the minimum sampling frequency with 95% of confidence (Equation (1)).

$$n \geq \frac{t^2 \, x \, s^2}{e^2} \quad [1]$$

where: n = number of samples; matched value at 95% probability (Student t distribution); s = standard deviation; and e = Permissible error.

The minimum number of samples required for the study are presented in Table 2. Measurements were performed for 24 days during the day shift, and data were recorded for 30 min per sample performed to cover an acceptable number of samples operating cycles.

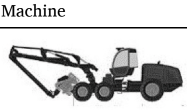
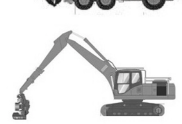
The data collection involved two operators (one for each machine

Table 2
Number of samples required and collected, with 95% of confidence level.

Harvester model	S	T	E	DOF	n	Sampling collected
Tracked	0.098	2.447	5%	6	23	24
Wheeled	0.082	2.571	5%	5	18	24

Were: n = number of samples required; s = standard deviation; t = tabulated value at 95% probability (Student t distribution); e = Allowable error; and DOF = Degrees of Freedom

Table 1
Wheeled and tracked harvester technical specifications.

Machine	Power (HP)	Weight (kg)	Width (mm)	Height (mm)	Crane reach (m)	Hour meter (h)	Seat
	255	20.700	2.990	3.930	10	12.000	Fixed foam with air damper
	115	13.980	2.600	3.110	10	13.000	Fixed foam with air damper

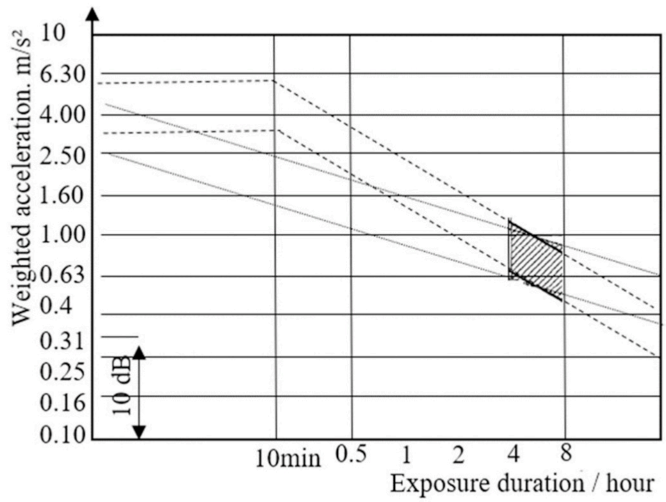


Fig. 2. Health guidance caution zones.
Source: ISO (1997), Annex B.

Table 3
Propositions of action levels and exposure limits from European Community Directive, 2002)/44.

Directive, 2002/44/EC - Exposure limits and action levels	
Parameter	Whole-body vibration
Action Level (NA)	0.5 m/s^2 A (8) ([a]) or 9.1 $m/s^{1.75}$ VDV([b])
Exposure Limit	1.15/s^2 A (8) ([a]) or 21.0 $m/s^{1.75}$ VDV ([b])

model), working in the machines during measurements with traffic across the field.

For the evaluation of whole-body exposure, the standard ISO 2631–1: 1997 (ISO, 1997) was adopted, which establishes a coordinate system originating from the point of contact between the vibratory source and the human body. The method used for the measurements was the weighted acceleration, expressed in m/s^2. The total value in the orthogonal coordinates was calculated using Equation (2), where a_{wx}, a_{wy} and a_{wz} were the weighted accelerations of the orthogonal axes, x, y and z, respectively and k_x, k_y and k_z are multiplier factors, where $k_x = 1.4$, $k_y = 1.4$ and $k_z = 1.0$ (ISO, 1997).

$$a_v = \sqrt{k_x^2.a_{wx}^2 + k_y^2.a_{wy}^2 + k_z^2.a_{wz}^2} \quad [2]$$

From the results obtained, vibration exposure levels were evaluated according to the chart in Annex B of the ISO 2631–1: 1997 (Fig. 2), with emphasis on exposures in the range of 4–8 h for sitting people.

The graph shown in Fig. 2 indicates, in the hatched region, precautions regarding potential health risks, with the region above indicating health risks and for the region below the health effects were not clearly documented or observed.

European Community Directive, 2002/44 has also been used as a reference for occupational vibration exposure assessments, which proposes action levels and exposure limits, as shown in Table 3.

The assessment of whole-body vibration exposure (WBV) is based on the determination of daily exposure A (8) expressed by the equivalent acceleration over a standard 8-h period obtained from the largest portion of the effective values, or the portion vibration dose value (VDV), the frequency-weighted accelerations determined along the three orthogonal axes (1.4 awx, 1.4 awy, 1 awz for sitting or standing workers), as per chapters 5, 6 and 7 and Annexes A and B from ISO 2631–1: 1997. The VDV, parameter to be used according to ISO 2631–1 when there are significant peaks or shocks.

The sample rate of the setup of the measurements was 80 Hz, for the measurements were used a Bruel and Kjaer triaxial vibration meter model type 4447, complying with ISO 8041, ISO 2631, ISO 5349 and ISO 10819, which provides the sum of each axis in an integrated manner and the total sum of acceleration. The accelerometer was fixed to the harvester seat by a seat pad device with a triaxial accelerometer attached to the operator's waist (Fig. 3).

To comparatively evaluate the occupational exposure to vibration in both machines, the measurements were submitted to the test t of comparison of means, aiming to prove statistically if the results were significantly different. The random vibrations were 3 DFs broadband random frequency exposures between 0.5 and 20 Hz with r.m.s. Amplitudes between 0.2 and 2.0 m/s^2 on all three translational axes.

3. Results

The vibration levels in which the operator was exposed at the work station of the tracked harvester were above the acceptable level for the work. The acceleration result A (8) presented an average value above the action level (0.6 m/s^2), demonstrating that the tracked machine provided vibration levels above the maximum limit recommended for the job.

Table 4 shows the levels of instantaneous acceleration in each orthogonal axis, the maximum levels of vibration achieved, as well as the dominant frequency in which they occurred. When analyzed in terms of frequency, it can be seen, in Fig. 4, that the levels of vibration

Fig. 3. Vibration meter and seat positioning.

Table 4
Whole-body vibration levels on the different orthogonal axes and maximum permissible exposure level for the operating cycles of thacked and wheeled harvesters.

Tracked Harvester													
Vibration exposures	operating cycles (seg)	x-axis				y-axis				z-axis			
		r.m.s (m/s^2)	Peak (m/s^2)	CF	DF (Hz)	r.m.s (m/s^2)	Peak (m/s^2)	CF	DF (Hz)	r.m.s (m/s^2)	Peak (m/s^2)	CF	DF (Hz)
1–24	31.4–39.5	0.22–0.35	2.16–4.27	6.79–12.08	1–1.6	0.11–0.23	1.38–3.45	6.61–14.18	1–1.6	0.16–0.32	3.27–9.17	10.17–31.79	0.24–3.15
Average	36.8	0.29	3.11	9.03	1.44	0.19	2.34	10.08	1.31	0.24	5.78	18.04	2.24
PD	1.29	0.04	0.44	1.52	0.23	0.03	0.53	2.11	0.23	0.04	1.59	5.57	0.54
CV (%)	3.5	12.3	14.1	16.9	15.8	15.8	22.8	20.9	17.3	15.5	27.4	30.9	24.1
Wheeled Harvester													
Vibration exposures	operating cycles (seg)	x-axis				y-axis				z-axis			
		r.m.s (m/s^2)	Peak (m/s^2)	CF	DF (Hz)	r.m.s (m/s^2)	Peak (m/s^2)	CF	DF (Hz)	r.m.s (m/s^2)	Peak (m/s^2)	CF	DF (Hz)
1–24	26.2–25.9	26.1–35.9	0.16–0.22	1.47–4.83	6.07–15.78	1.0–2.0	0.15–0.28	2.72–4.66	7.27–14.73	1.0–2.0	0.13–0.21	1.71–7.77	9.16–29.91
Average	31.2	0.19	2.39	9.40	1.30	0.21	3.52	11.67	1.40	0.16	3.33	14.50	1.82
PD	2.15	0.01	0.74	1.87	0.31	0.03	0.61	1.65	0.25	0.02	1.73	5.73	0.40
CV(%)	6.9	7.6	31.0	19.9	23.6	14.2	17.3	14.1	18.1	12.0	51.9	39.5	22.0

r.m.s = root mean square; CF = crest factor; DF = dominant frequency.

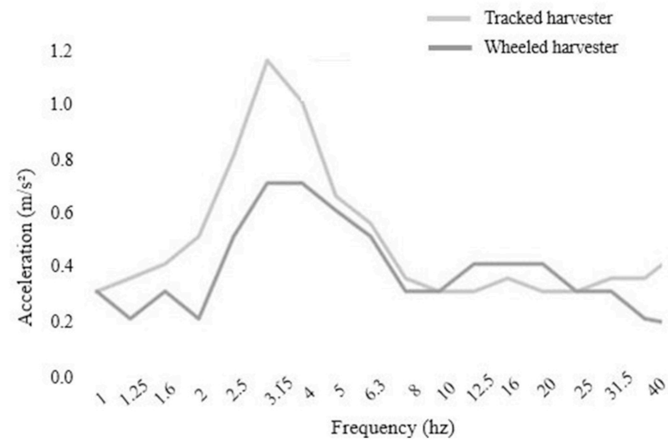


Fig. 4. Resultant WBV exposure in the frequency domain.

were represented in greater intensity in the ranges between 2 and 5 Hz in both machines, with this frequency range being harmful to the spine.

The results showed that the tracked harvester showed mean levels of instantaneous acceleration significantly higher in the x and z axes, and close values in the y-axis.

However, it is noted that the wheeled machine achieved greater efficiency in terms of attenuation of vibration levels, with better-operating conditions being evidenced. The average acceleration A (8) and daily VDV results are shown in Fig. 5.

It is observed that the average time of the operational cycles is higher for the tracked harvester, therefore, it was identified that in addition to the wheeled harvester obtaining greater operational performance, the conditions of comfort and safety, in terms of occupational exposure to vibration, are superior.

The results for VDV indicated values above the action level, with 11.2 and 9.3 $m/s^{1.75}$ values, to tracked and wheeled harvesters, respectively, indicating, therefore, the need for adopting preventive measures in both workstations.

Fig. 6 illustrate the results of the acceleration resulting from the mean exposure, representing the vibration levels on each orthogonal axis during the workday.

Statistical analyzes by the *t*-test ($p < 0.05$) showed that the acceleration A (8) and vibration dose value (VDV) values were statistically different between the tracked and wheeled harvesters, thus this result indicates higher vibration levels for the tracked harvester.

4. Discussion

Observing the results the dominant frequency ranges in which vibrations occurred were below 2 Hz for the x and y axes of both machines, however, when compared to vertical vibrations, it was observed that the wheeled harvester remained in the dominant frequency ranges below 2 Hz, but the tracked harvester indicated a dominant frequency between 2 and 4 Hz. Thus, occupational exposure to vibration in the tracked harvester can be more harmful to operators, as this frequency range generates greater damage to the spine.

Another result to be considered is the crest factor, which is the relationship between the maximum instantaneous peak value and the weighted acceleration r.m.s. Measured in the same direction. Comparing to vertical accelerations, higher peak values and crest factor were observed in the tracked harvester, indicating greater machine limitation in resisting vertical acceleration peaks.

Tracked harvester has less capacity to attenuate the occupational vibrations that are characteristic of this type of operation, which can provide greater occupational problems to the operator, especially in vertical accelerations. With that, it is concluded that the use of machines with purpose-built characteristics in the harvest of the wood can be

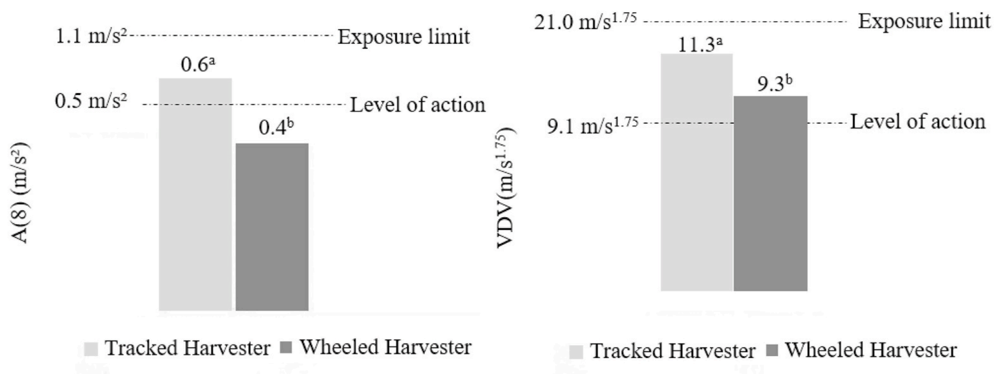


Fig. 5. Resultant of normalized exposure A (8) and vibration dose value (VDV).

considered a fundamental factor for the reduction of occupational exposure to vibration.

Significant differences were identified between the levels of exposure to the workstation vibration for the two evaluated forest harvesters' machines. The difference between the machines can be attributed mainly to their design characteristics.

The wheeled harvester has a feature of greater adaptability, as it has independent suspension to unstable ground conditions, minimizing the effects caused by ripples and obstacles. The studied tracked harvester was adapted from construction operations and therefore are not designed for traffic in unstable ground conditions such as in the field.

The wheeled forest machines have a smaller size, with rigid wheels and therefore have greater sensitivity to ripples generating greater impact by obstacles. In the uneven field, it absorbs impacts of the operation due to the impact transmitted by tracked machines, that have no independent suspension, it was observed that in thinning operation, which needs greater displacement of the machine the performance may be affected.

The adapted tracked machines were constructed for lower displacement without damping system ends transmitting greater vibration intensity to the operator at X and Z angles rather than Y (lateral). Already the forest wheeled harvester machine built for forest operations better absorbs the impacts. It is also worth noting that the vibration peaks were generated mainly during the machine's traffic, with greater intensity for the tracked harvester.

It is important to emphasize that the VDV uses a more sensitive method of analysis about the exposure to vibration, raised to the fourth power value, and it is indicated for the analysis of vibration peaks. This measure allows obtaining the vibration peaks, which in most cases are related to the shocks or bumps by old stumps from other harvested trees, exposing the operator at the work station to grater vibration during the execution of the wood cutting operation in the stands subject to thinning.

Due that tree cutting and wood processing occurs in extremely small spaces inside the forest stand in thinning operations, it was still possible to verify the occurrence of the machinery crane contacting with the trees. This operation also contributed to the occurrence of bumps that often becomes consequently, on the vibration peaks observed in this study. Another factor that may have contributed to the vibration peaks was the traffic of the machine which, due to the irregularities and presence of branches on the ground, contributed to the occurrence of bumps in the workstations.

It should be noted that the design of the machines was important for the difference in vibration levels, as it was observed during the operation that the wheeled harvester better attenuated the impacts suffered, and may be related to the leveling system, cab cushioning and kind of rolled. Another aspect relates to the weight of the machines, as the wheeled harvester had a higher weight and, therefore, the machine tended to be more stable on the ground and with less impact caused by the operation. On the other hand, the tracked harvester presented lower weight and, therefore, tended to attenuate with a smaller magnitude the reaction forces generated by the operation, resulting in a higher level of vibration exposure to the operator.

Analyzing the design of the machines, it was concluded that the adapted machines were not designed to work in a parked way and with small movements, when subjected to the wood harvesting operations with the need of displacements between the trees to proceed to the cut and wood processing, wear of the physical components of the machine are worn out more quickly. In this way, the wheeled harvester has better withstand the operating conditions, providing greater comfort to operators in terms of exposure to whole-body vibration.

Another aspect to be highlighted concerns the seat of the wheeled

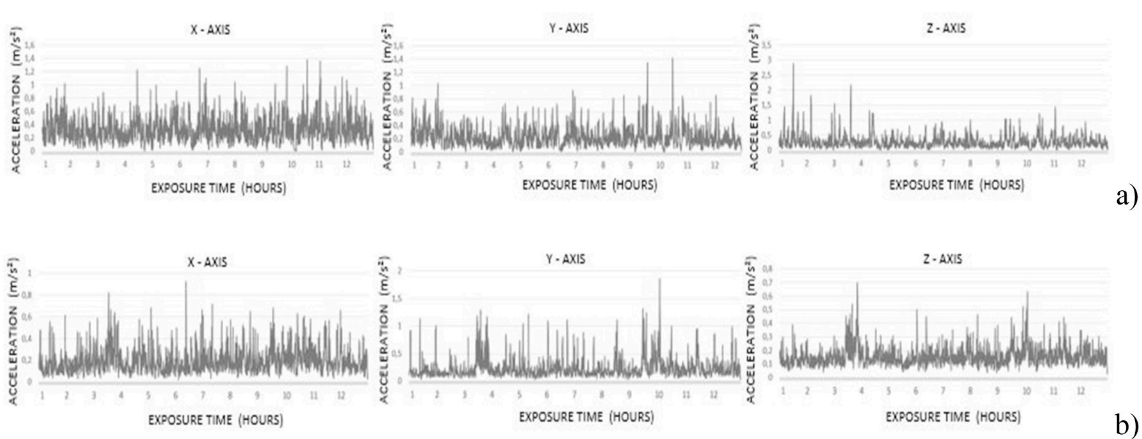


Fig. 6. Behavior of the resulting acceleration by orthogonal axis in the tracked (a) and the wheeled (b) harvesters.

harvester because the machines adopt pneumatic damping systems in the seats, which may have contributed to higher levels of vibration exposed to the operator of the tracked harvester. This observation was confirmed by the operators, who pointed out greater discomfort in the workstation of the tracked harvester.

According to the results, it was observed the need to adopt preventive measures to reduce the levels of vibration in the workplace. Among these measures, the use of a machine with rolling stock of wheels would be the measure that would bring the best results in terms of attenuation of the vibration dose value (VDV), since the values of vibration peak were more accentuated during the machine displacement, being that wheels allow better cushioning the impacts suffered by the machine during the field displacements.

Another strategy for the reduction of vibration exposure levels is associated with the design of the machine, with improvements of materials with greater capacity of absorption of impacts, as well as damping systems of the machine and the seat designed for the forest operation. Moreover, it is recommended to adopt periodic machine maintenance, with lubrication of mechanical components to reduce friction and, consequently, machine vibration.

Gerasimov and Sokolov (2014) evaluated the operators' exposure to vibration in seven models of harvesters and found average levels of average acceleration equivalent to 0.3 m/s^2, indicating compliance with the values established in the standards considered. However, the authors worked with the assessment of several types of machines and species harvested with average individual tree volumes varying from 0.13 to 0.64 m^3, so these factors may have influenced in lower levels of vibration on the study.

Marzano et al. (2017) performed a comparative analysis between the harvesters and forwarders, verifying vibration levels between 0.27 and 0.70 m/s^2 in eucalyptus wood harvesting. The results identified by the authors are in agreement with the acceleration levels found in our study, demonstrating that wood harvesting operations performed by harvesters present vibration levels close to the action level (0.5 m/s^2).

5. Conclusions

The vibration levels obtained at the workstations in both harvester models were following the maximum limits advised by ISO 2631–1:1997 and European Directive 002/44/CE Norm. However, it is recommended to adopt some preventive measures to reduce the vibration to below the proposed level of action.

The tracked harvester presented bigger acceleration levels then the wheeled machine, attributed to the wheelset type of the machine weight, poor seat conservation, and worse machine design.

The vibration peaks identified during the thinning were caused by the contact of the harvesters with the trees and during the traffic over the stand that contained irregularities and obstacles on the ground. The wheeled machine allowed the attenuation of vibration levels compared to the tracked one.

CRediT authorship contribution statement

Alysson Braun Martins: Conceptualization, Methodology, Writing - original draft, preparation. **Eduardo da Silva Lopes:** Supervision, Responsible for supervision and types of equipment uses and accuracy. Laboratory and research team chief. **Nilton César Fiedler:** Methodology, method and equipment corrections. **Felipe Martins de Oliveira:** Data curation, Project administration, Writing - original draft, Assistance in data collection, project development and writing. **Millana Bürger Pagnussat:** Writing - original draft, Calculation and writing revisions plus language corrections.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ergon.2020.103006.

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