

## Article

# Whole Body Vibrations during Fully Mechanised Logging

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**Abstract:** This paper seeks to answer the question of whether the magnitude of vibrations affecting the whole body of the harvester operator (WBV) that are generated by the harvester boom is affected by the size of the processed trunk volume, to specify closer, the magnitude of WBVs generated during forest logging, and to localise these WBVs in individual partial operations. For these purposes, the production process, i.e., forest logging, was divided into six partial operations (Searching; Felling; Processing; Unproductive time; Machine movement; Stationary position). WBVs were scanned in the respective partial operations according to standard ISO 2631-1:1997 and the European Directive 2002/44/EC, and then the values were mutually compared. Volumes of processed trunks were recorded, which were then assigned to the given WBV during the respective operations. Research results did not demonstrate a correlation between the size of the transmitted vibrations and the volumes of cut trunks in the partial work operations of Felling and Processing. Neither a difference was found between the individual partial operations with two exceptions: Searching and Felling/Processing and Unproductive time. The research further showed that the average WBV of three partial operations did not meet the daily limit of  $0.50 \text{ m/s}^2$  permitted by European Directive 2002/44/EC, within a range from 12.20% to 27.02%.

**Keywords:** whole body vibration (WBV); single grip harvester; CTL technology; correlation; trunk volume; forest logging



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## 1. Introduction

The share of assortment logging method (cut to length—CTL) in the total annual cut is currently increasing in Europe, and in some countries, the method is used as the only one [1,2]. In comparison with southern and south-eastern Europe, the largest share of CTL technology is found in the countries of northern, central and western Europe [3,4]. One of the reasons is the species composition. Coniferous tree species are more suitable for the CTL technology and are dominant in northern, central and western Europe [5,6]. The expansion of this method lies in the use of harvesters. These machines are very powerful and can perform consecutive tasks such as felling, measuring and processing the felled tree trunk. Due to the semi-automation of the production process, productivity rates increased, operating costs reduced, and the modern design of these machines provided comfort and safety to their operators [7,8], thus increasing their use worldwide [9,10]. At present, these machines are also used in deciduous stands [11,12], in which the WBV rate has not yet been determined.

In spite of these considerable advantages, there are still worries that the machine operators may work in unfavourable ergonomic conditions. One of these unfavourable conditions is the exposure of operators to whole body vibrations during work operations [13,14]. WBV can be understood as a transmission of mechanical energy existing in machines onto the sitting or standing operator's body [15]. The exposure of operators to high WBV levels during the working day is one of the most significant ergonomic factors, which cannot only cause discomfort but also represent a danger to health and safety if combined with repetitive movements and incorrect body posture for a long period of

time [16–18]. The harvester provides some comfort for the operator during logging, which increases work productivity. However, if the operator's comfort is inadequate, occupational accidents and disease may increase [19,20]. Adverse health consequences to operators of forest machines caused by exposure to vibrations were pointed out already in several studies [21–25]. These negative consequences rank with the main problems of mechanised logging because they become exacerbated with repeated movements of the hands and arms if the harvester operator's body posture is not neutral [15,26].

Long-term exposure to WBV can be connected with an increased risk of numerous diseases affecting the back, digestive, circulatory and nervous systems [27,28], and sexual and urinary systems [29,30]. The exposure to WBVs at work clearly relates also to the increased risk of lumbar pains, the pain of the sciatic nerve and disorders of lumbar intervertebral discs [15,29,31,32] as well as musculoskeletal symptoms in the area of the neck and shoulders [14,33,34]. WBV can also cause the loss of tenderness in the limbs as well as skeletal and gastrointestinal disorders [15]. Some symptoms of disorders may also appear in the form of fatigue, insomnia and tremor [35]. Apart from health effects, exposure to vibrations may impair the performance of operators, particularly in activities with high demands on accuracy that are characteristic of the operation of forest machines [36] as well as harvesters.

Limits and preventive recommendations concerning the exposure to WBVs are established in international standards serving as a reference for national legislations, the major standard being ISO 2631-1:1997 [37]. In Europe, minimum requirements for health protection and safety of persons exposed to risks of vibrations are defined in European Directive 2002/44/EC [38] which aims to prevent workers from the exposure to extensive vibrations by setting limits for their daily exposure and by defining preventive measures against the effects of vibrations. The Directive stipulates that the daily limit of exposure value standardised to the reference time of eight hours is  $1.15 \text{ m/s}^2$  or—as chosen by the specific member state—the vibration dose value (VDV) amounts to  $21 \text{ m/s}^{1.75}$ . Further, the daily value of exposure triggering the action, standardised per eight hours of the reference time, is  $0.5 \text{ m/s}^2$  or the vibration dose value is  $9.1 \text{ m/s}^{1.75}$ , according to the choice of the concerned member country [38].

One of the main causes of vibrations generated in the working harvester is the machine travel on the ground surface because soil characteristics significantly affect the level of WBV in the machine cab. The machine movement on the partly elastic, deformable soil surface significantly modifies the natural profile. The soil profile's capacity to absorb energy causes dynamic excitation of the machine [39]. Thus, the most important terrain factors which contribute to the exposure of the harvester operator to WBVs are terrain roughness and soil bearing capacity [34]. Other causes, including the machine design (seat, cab, engine, boom), working techniques [40] and requirements for high operating speeds increase the level of vibrations [41–43]. One of the important causes of WBV are movements of the hydraulic boom equipped with the harvester head that is generated during various work operations and is transmitted to the machine cabin and further onto the driver's seat [16]. A question should be asked whether the magnitude of WBV generated by boom movements can be affected by the volume of the processed trunk.

The issue of WBV in forestry is addressed by a number of authors across different types of machines, such as harvesters [17,44–46], harvesters and forwarders [17,47–51] and other machines [18,52,53]. However, the problem of the precise localization of the WBV in the individual sub-operations during harvesting, by the harvester, was addressed by none of them. Therefore, the aim of this research is to specify the size of WBVs that arise during logging and to more precisely localise the given WBVs in their individual sub-operations. It is assumed that the highest WBV will occur during the machine movement. However, the question remains whether the size of the WBV will be affected by the size of the processed trunk volume.

## 2. Materials and Methods

### 2.1. Research Site and Machine

This research was conducted in the Czech Republic, with the forest company Lesy města Brna a. s., Forest District of Deblín (49.3157978 N, 16.2991733 E). The terrain had

a slope of  $0^\circ$  without obstacles and the subsoil was cambisol with a rock share of about 30%. The measured forest stand was aged 33 years. Stem volumes of cut trees ranged from  $0.1429 \text{ m}^3$  to  $0.8803 \text{ m}^3$ ; the average stem volume was  $0.4045 \text{ m}^3$ . The total number of measured Norway spruce trees (*Picea abies* (L.) H. Karst.) was 189. Throughout the measurement activities, the harvester was operated by the same person.

The subject of research was a large wheeled harvester 1270E (Figure 1) made by Deere & Company, which is known under the trademark of John Deere. The machine is equipped with the hydraulic, parallel, automatically levelling boom of 11.7 m in reach, located on the front part of the articulated machine frame. This part of the frame is also attached to a swivel cab with the suspended pneumatic seat. The cab is able to balance its tilt in all directions up to  $17^\circ$ , which is less than the maximum possible angle of boom levelling, which is possible only forward and backward within a range from  $-15^\circ$  to  $+28^\circ$ . On the rear part of the frame, there is a combustion engine with an output of 170 kW at 1900 rpm, which receives fuel from the fuel tank of 435 L in volume, situated next to the engine. The front part of the harvester frame is fitted with bogie axles with 710/45 R26.5 tyres. A fixed axle with 710/55 R34 tyres is mounted onto the rear harvester frame part. The machine was further equipped with the harvester head H414 from the same manufacturer, the weight of which was 1 100 kg. The total weight of the machine with the equipment was 18,400 kg. Machine parameters are presented in Table 1.



Figure 1. Machine 1270E.

Table 1. Basic parameters claimed by manufacturer.

Basic machine parameters	Weight [kg]	18,400
	Length (without boom) [mm]	7550
	Width [mm]	2900
	Wheelbase [mm]	4050
	Ground clearance [mm]	650
	Engine power [kW] (1900 rpm)	170
Hydraulic boom	Lifting torque [kNm]	197
	Slewing torque [kNm]	50
	Reach [m]	12
	Tilting [ $^\circ$ ]	$-15/+28$
	Slewing angle [ $^\circ$ ]	220
Cab	Tilting [ $^\circ$ ]	$\pm 17$
	Side tilting [ $^\circ$ ]	$\pm 17$
	Rotating angle [ $^\circ$ ]	160

## 2.2. Measuring Vibrations

The WBV of the harvester operator was measured using the Datalogger CEM accelerometer model DT-178 A with a range of 18 G and resolution of 0.00625 G. It recorded the acceleration of vibrations in three basic axes ( $x, y, z$ ) and total shock in G ( $m/s^2$ ). All records were provided with the time information [54]. The range of time collection was set to 1. Records were stored in the internal memory of the instrument with the capacity of up to 85,000 records of data [54]. The data were then exported to the PC using USB 2.0 where they were evaluated in the programme Vibration Datalogger 1.0. The accelerometer was attached to the harvester seat in order to take records of WBVs on the main interface between the human body and the source of vibrations [37]. The time for measuring vibrations was in order to ensure the required statistical accuracy and typical vibrations for the assessed position [37]. In accordance with standard ISO 2631-1, a quantity for the expression of the magnitude of vibrations is acceleration.

Vibrations were measured conforming to standard ISO 2631-1 [37] which defines the method of measuring whole body vibrations. It also defines axes  $x, y$  and  $z$  as the horizontal, transverse and vertical axes. For each axis, effective values of root-mean-square (RMS) acceleration  $a_w$  and frequency weighted acceleration  $a_w(t)$  have to be evaluated according to [37] as follows:

$$a_w = \left[ \frac{1}{T} \int_0^T a_w^2(t) dt \right]^{\frac{1}{2}}$$

where:

$a_w$ —weighted acceleration as a function of time [ $m/s^2$ ];

$T$ —total time of measuring [s].

On the operator's seat, one can experience a combination of vibrations in more than one direction. According to [37], a total value of vibrations from weighted effective values of acceleration determined from vibrations in orthogonal coordinates can be calculated from the following equation:

$$a_w = \left( k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2 \right)$$

where:

$a_{wx}, a_{wy}, a_{wz}$ —weighted effective values of acceleration in the direction of orthogonal axes  $x, y, z$ ;

$k_x, k_y, k_z$ —multiplication factors.

The weighted effective value of accelerated vibrations was determined for each axis ( $x, y, z$ ) from translation vibrations on the surface, which supports the person. The vibrations were assessed with respect to the highest frequency weighted acceleration, determined on any axis of the seat cushion. In the case of our measurements, it was a sitting person in which the following frequency weighting was used with the  $k$  multiplication factors:

axis  $x$ :  $k = 1.4$ ,

axis  $y$ :  $k = 1.4$ ,

axis  $z$ :  $k = 1.0$ .

Assessment of the level of exposure to vibrations is based on the calculation of daily exposure A (8) expressed as equivalent continual acceleration for eight hours calculated as the highest effective value or the highest vibration dose value (VDV) of frequency-loaded accelerations determined on three orthogonal axes ( $1.4a_{wx}, 1.4a_{wy}, 1a_{wz}$  for a sitting or standing person) [37].

In the European Union, permissible vibrations are stipulated by the Directive of the European Parliament and of the Council 2002/44/EC [38] of 25 June 2002, on the minimum requirements for occupational health and safety for the exposure of employees to risks associated with physical agents (vibrations).

### 2.3. Operations

To achieve the goal of the research, i.e., to assess the magnitude of the WBV affecting the operator during harvesting operations, the production process was split into the following operations:

**Searching**—The operation starts with the initial movement of a hydraulic boom toward a tree selected for felling and ends with the activation of the harvester head cutting mechanism by which the trunk was seized.

**Felling**—The beginning of the operation was considered the activation of the harvester head cutting mechanism in order to fell the selected trunk, and the end of the operation was considered to be the fall of the felled tree crown onto the ground and the start of harvester head feeding mechanism.

**Processing**—A part of the production process when the feeding mechanism of the harvester head is activated by which the trunk processing begins (delimiting, trunk cross-cutting and stocking of assortments). The end of the operation is considered the positioning of the harvester head into a vertical position, and the start of machine travel (turning of machine wheels).

**Unproductive time**—The unproductive time included activities outside the other partial operations, such as working with the deck of assortments, slash carpet, and other non-production operations during which the combustion engine was running at working speed.

**Machine movement**—This operation was recorded when the machine moved from a working position to another one, i.e., when a rotation of wheels was recorded during the machine displacement.

**Stationary position**—This operation was included in the production process with the machine standing still on the spot, the engine not running at working speed (thanks to the ECO function of the harvester manufacturer), and with none of the above partial operations taking place (logging).

In order to be able to assign the measured data to the respective partial production process operations (harvesting operations), a video record had to be taken that would help to define the operations and hence to assign the individual WBV to them. For this purpose, the action camera Vega 6 was used, with automated image stabilisation, made by Niceboy. The camera was installed in the machine cab so that it corresponded to the driver's view. Video recording quality was set up to 1440 p (1920 × 1440) at 60 fps, which means that 60 images were taken per second in quality 1440 pixels.

### 2.4. Statistical Analyses

Data obtained from the vibrometer recorded during the harvester working process were divided into the respective partial operations that were then mutually compared in software STATISTICA 12 by TIBCO. Prior to the comparison, they were subjected to the Shapiro–Wilk normality test. In the test, the  $p$ -value was set up to 0.05, i.e., if a situation occurred when the test result exceeded this value, then the data corresponding to the Student's distribution, and the following test was one-way ANOVA with a  $p$ -value of 0.05. Data from the individual operations then mutually differed if the result of the given statistical test exceeded the set-up  $p$ -value. If the result of the Shapiro–Wilk test was lower than the  $p$ -value set up therein, the data already did not correspond to the mentioned division, and a non-parametric test had to be chosen—in this case, the Kruskal–Wallis test whose  $p$ -value was set to 0.05 again. If the test result exceeded this value, the data did not mutually differ.

In addition, descriptive statistics were performed for the individual operations and their data, and a box chart was plotted to better illustrate the data. One of the research goals was to prove whether a dependence exists between the trunk volume and the magnitude of vibrations in the operations of Felling and Processing. For this purpose, data on volumes of all processed trunks were taken from the harvester computer, which was assigned to WBV records from the operations of Felling and Processing thanks to the video record taken. The data were checked for homoscedasticity using a scatterplot with the mean and

standard deviation shown. Subsequently, a correlation was used to prove dependence, whose result was then used in testing the significance of the correlation coefficient ( $R$ ). In order to prove the above-mentioned dependence, the test criterion (a result of the test) had to be higher than the critical value, which equals a quantile of the Student's distribution at a probability of 0.05.

### 3. Results

Figure 2 shows the distribution of recorded WBVs affecting the machine operator during the respective partial operations of the harvester working process. It can be clearly seen that no extreme WBV values were recorded during the field survey, which is documented by a very low difference between the mean and the median of all sets that ranged from 0.002273 to 0.004336  $\text{m/s}^2$ . The highest vibrations (0.790000  $\text{m/s}^2$ ) were recorded during the operation of Machine movement (see Table 2). The lowest WBV value (0.310000  $\text{m/s}^2$ ) was recorded during the operation Stationary position. During this operation, the machine operator was exposed to the lowest overall effect of WBV within the whole working process, which is documented by the distribution of 75% of data values which were considerably lower if compared with the other partial operations. Another interesting phenomenon was the WBV concentration in the partial operation of Processing in which 100% of data ranged from 0.370000 to 0.740000  $\text{m/s}^2$  (Table 2), which was considerably more than in the other operations. For example, 100% of values recorded in the Felling operation corresponded only to 75% of values in Processing.

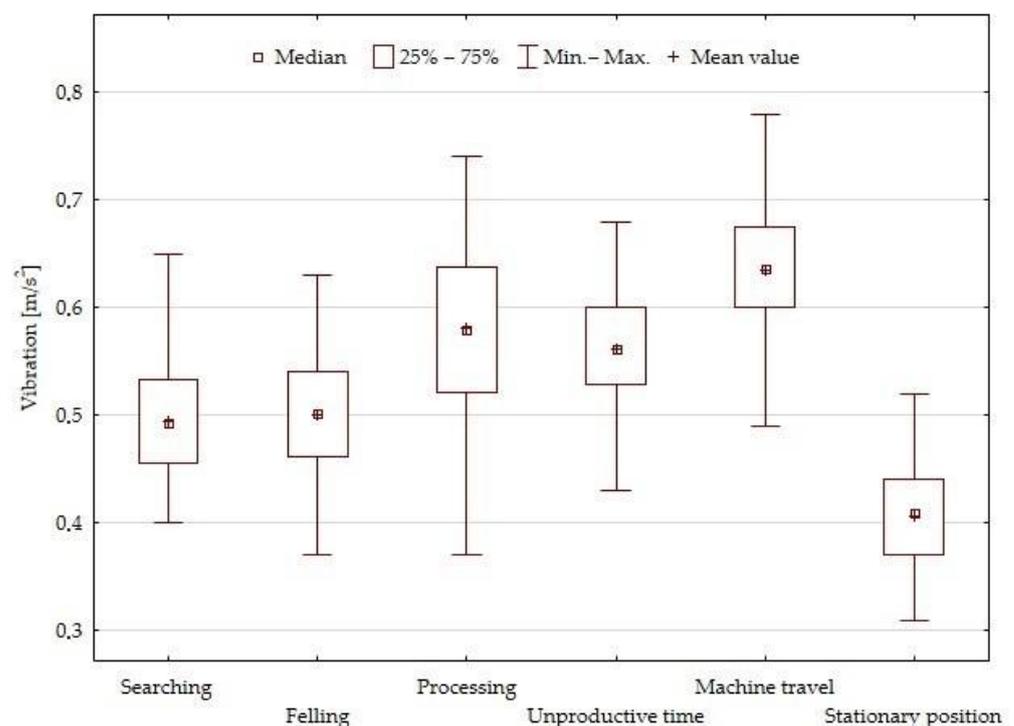


Figure 2. Distribution of vibration data in the respective operations.

It was found that during the Searching operation, the harvester operator was exposed to an average WBV of 0.494776  $\text{m/s}^2$ . Compared with this, the average WBV during the Felling operation amounted to 0.501128  $\text{m/s}^2$ . However, the difference of 0.006352  $\text{m/s}^2$  between the two operations was nearly negligible as confirmed by the result of the statistical test (Table 3), which was higher than the  $p$ -value (0.05); hence, the two operations did not mutually differ. The highest WBV in the working process affecting the operator was recorded during the operation of Machine movement (0.790000  $\text{m/s}^2$ ). However, the average WBV was 0.580880  $\text{m/s}^2$ , which was 0.086104  $\text{m/s}^2$  more compared with the

operation Searching. This relatively considerable difference confirms the result of the statistical test (Table 3) which demonstrated a difference between the operations.

**Table 2.** Basic evaluation.

Operation	Mean Value [m/s <sup>2</sup> ]	Median [m/s <sup>2</sup> ]	Mode [m/s <sup>2</sup> ]	Frequency of Mode	Min. [m/s <sup>2</sup> ]	Max. [m/s <sup>2</sup> ]	Standard Deviation [m/s <sup>2</sup> ]
Searching	0.494776	0.492502	0.490000	17	0.400000	0.660000	0.046603
Felling	0.501128	0.501413	0.490000	16	0.370000	0.630000	0.047500
Processing	0.580880	0.580000	0.590000	48	0.370000	0.740000	0.068829
Unproductive time	0.561005	0.561621	0.590000	17	0.430000	0.680000	0.055880
Machine travel	0.635119	0.636466	0.590000	23	0.430000	0.790000	0.054416
Stationary position	0.405689	0.410025	0.420000	4	0.310000	0.520000	0.046156

**Table 3.** Results of the statistical comparison of operations.

Operation	Searching	Felling	Processing	Unproductive Time	Machine Travel	Stationary Position
Searching	-	1.000000	0.000000	0.000000	0.00	0.00
Felling	1.000000	-	0.000000	0.000000	0.00	0.00
Processing	0.000000	0.000000	-	0.064674	0.00	0.00
Unproductive time	0.000000	0.000000	0.064674	-	0.00	0.00
Machine movement	0.000000	0.000000	0.000000	0.000000	-	0.00
Stationary position	0.000000	0.000000	0.000000	0.000000	0.00	-

<0.05 = operations differ

The working process should also include the operation of Unproductive time during which the harvester operator was exposed to an average WBV of 0.561005 m/s<sup>2</sup> (Table 2). The difference of 0.066229 m/s<sup>2</sup> between the Searching and the Unproductive time can be considered considerable, which is corresponded to the result of the conducted statistical analysis that demonstrated a difference between the compared data files. Another partial operation that was compared with the Searching was the Machine movement. The average WBV affecting the machine operator during this operation amounted to 0.635119 m/s<sup>2</sup>, which was 0.140344 m/s<sup>2</sup> more than compared with the Searching. The difference indicates that the WBV of given operations differed, which was also confirmed by the result of the statistical test (Table 3), which did not exceed the set-up *p*-value (0.05). In the last partial operation of the Stationary position, the average WBV affecting the operator was only 0.405689 m/s<sup>2</sup>, which means that the difference between the Searching and this operation was 0.089087 m/s<sup>2</sup>. The statistical processing of the compared data and its results demonstrated that the WBV values during the Searching and Stationary position were different.

Another partial operation of the working process to be compared with the other ones was that of Felling. Results of statistical tests from this comparison are presented in Table 3. This operation and generated WBVs are apparently different from the WBVs of the other operations with the exception of Searching at which—as mentioned above—nearly identical values were reached, and a minimum difference (only 0.006352 m/s<sup>2</sup>) was in the magnitude of average WBVs. When the Felling was compared with the Processing, the difference was already 0.079752 m/s<sup>2</sup> in favour of Felling. Compared with the Unproductive time, the recorded difference amounted to 0.059877 m/s<sup>2</sup>, again in favour of Felling. During the Machine travel, WBV reached values higher on average by 0.133991 m/s<sup>2</sup>. By contrast, WBVs recorded during the Stationary position were, on average, by 0.095439 m/s<sup>2</sup> lower.

The comparison of Processing with the other partial operations did not reveal a difference only in the comparison with the Unproductive time (see Table 3). The difference between the WBV of these operations was only 0.019876 m/s<sup>2</sup>, in favour of the Unproductive time. In the comparison of Machine travel and Processing, an increase in WBV by

0.054239 m/s<sup>2</sup> was recorded in the first-mentioned operation. By contrast, considerably lower WBVs were recorded in the Stationary position. The WBV difference between the Processing and Stationary position was 0.175191 m/s<sup>2</sup>.

Another partial operation compared with the other operations was Unproductive time. Statistical results of the comparison are presented in Table 3. A difference from the other partial operations was not demonstrated only in the already mentioned comparison with the Processing. During the Unproductive time, the machines generated an average WBV of 0.561005 m/s<sup>2</sup>, which is 0.074115 m/s<sup>2</sup> less than in travelling machines (Machine travel) and by 0.155316 m/s<sup>2</sup> more than in the Stationary position, the WBV of which differed from all partial operations (see Table 3) and particularly from WBVs in the Machine travel. Specifically, in the Stationary position, the average WBVs were 0.229430 m/s<sup>2</sup> lower than in the Machine travel, with the average difference being the highest between the two operations recorded during the measurements.

It can be summarised that as compared with average values, the daily limit for WBV affecting the machine operator set up, pursuant to [38], was exceeded in the operations of Processing, Unproductive time and Machine travel. Specifically, the average WBV exceeded the daily limit for Processing, Unproductive time and Machine travel by 16.18%, 12.20% and 27.02%, respectively.

A partial goal of the research was to determine the correlation between the trunk volume and magnitude of WBVs affecting the machine operator during the operations of Felling and Processing. The total number of processed spruce trunks was 189; a minimum trunk volume was 0.1429 m<sup>3</sup> and a maximum trunk volume was 0.8803 m<sup>3</sup>. The volume of the average trunk was 0.4045 m<sup>3</sup>, and the volume of the most frequently processed trunk was 0.4130 m<sup>3</sup>. Results of statistical tests did not demonstrate a correlation between the trunk volume and the magnitude of WBVs affecting the machine operator during the two operations because the test criterion in the given statistical analysis did not exceed the critical value. Specifically, the test criterion in the Felling was  $-0.889663904$ , while the critical value was 1.96274896. In the other compared operation of Processing, the test criterion was 1.256748, while the critical value was 1.960669.

#### 4. Discussion

The average exposure to WBV transmitted onto the harvester operator through his seat during all work operations within the measurements was 0.560366 m/s<sup>2</sup>, which is 0.010366 m/s<sup>2</sup> more than reported in the research conducted by [44] who took measurements on different machines made by different manufacturers. The authors in [17] assessed the exposure of the operator in seven models of harvester, and concluded that an average acceleration was 0.30 m/s<sup>2</sup>. It should be noted, however, that the authors worked with several machines of different designs and with different tree species, the trunk volume of which ranged from 0.13 to 0.64 m<sup>3</sup>. Although the influence of WBV transmitted onto the operator's seat by the volume of processed trunks can be considered theoretically problematic, the results of this research refuted the consideration.

The authors in [47] made a comparative analysis between harvesters and tractor-and-trailer units and detected vibration levels transmitted onto their operators from 0.27 and 0.70 m/s<sup>2</sup> in logging eucalyptus. The exposure to vibrations affecting the whole operator's body during the logging with harvesters and tractor-and-trailer units was a subject of several other studies [17,48–51] which stated a vibration transmission rate between 0.10 and 2.0 m/s<sup>2</sup>. Other research [18,52,53] demonstrated that during the operation of forest machines, their operators are exposed to high levels of vibrations that are harmful during the whole work shift.

In our research, the highest average WBV values and at the same time, the highest total WBVs were recorded during the Machine travel. The finding is in concordance with the research results of [51], who measured vibrations in the wheeled harvester made by Silvatec A/S. The highest vibrations were reached during the machine travel and in the studies of authors [34,45], who adds that in addition to the machine travel, the main source of WBV is

the turning of the machine. The authors in [55] inform that the exposure to vibrations onto the driver's whole body in the terrain is approximately linearly proportional to the machine travel speed, and [56] mention that vibrations during the machine travel are also affected by the smoothness of travel. This phenomenon results from difficult work conditions, such as steep terrains, the occurrence of rocks or large dimensions of trees requiring higher performance of engines and drive sub-systems [34].

Apart from travel speed and smoothness, the magnitude of WBV can be also affected by the style of driving, machine design and geometry, and/or by the selected seat suspension, power transmission onto wheels or the distribution of machine weight [57]. Some studies on harvesters demonstrated, for example, a frequency weighted acceleration on the seat from 0.1 to 0.6 m/s<sup>2</sup> during the production process, i.e., logging [45,46]. According to [58], the system of seat suspension reduces vibrations by 15–36% in different working conditions. Seat material quality is an important factor [53]. The magnitude of vibrations can be affected also by the adjustment of the backrest [59]. Using swing axles instead of bogie axles in order to reduce vibrations still remains a question. This was dealt with by [60] who indicates lower vibrations in the swing axles thanks to the system of hydraulic suspension. The information opens a way to further research together with the development of new designs of machines and axles.

The lowest vibrations were recorded in the Stationary position. In this partial operation, the harvester operator was exposed to the lowest total magnitude of vibrations in the whole production process. This was given by the fact that during this partial operation, the harvester was standing on the spot and was not moving. The boom did not move either and the combustion engine was idling.

Causes of WBV can be reduced in many ways and alternatives. For example, the seat padding of the operator's seat [53] can be made of materials absorbing vibrations in the horizontal direction [22]. The position of the seat is an important factor that may cause harm to the operator [61]. Correct seat selection is a factor potentially affecting WBV [57]. Moreover, the reduced machine travel speed [62,63], and choice of harvester undercarriage as tracked harvesters exhibit markedly higher levels of WBV than harvesters that have tyres [18]. Likewise, a change of pressure in tyres, as higher pressure in tyres increases exposure to WBV [64]. Last, but not least, regular training of operators and work technology reorganisation can assist [55], as the rate of exposure to vibrations can be also affected by the operators' experience [24]. Reduced WBV should improve the working environment in forestry. Moreover, the reduction in vibrations can reduce machine wear and damage to the soil [65].

It should be pointed out that WBV represents a very specific issue with many variable factors. This is why the research results measured by us cannot be compared with the results of other authors, but only proportionally. The machines differ in types, age, weight, engine output and design as well as in both standard and optional equipment, which affects exposure to vibrations directly or indirectly [34,66]. A general instruction says that exposure to vibrations at work should be minimised [15].

## 5. Conclusions

In our research, the magnitude of WBV differed in all the compared partial operations, with two exceptions. The first of them was the comparison of Searching and Felling operations, and the second one was the comparison of Processing and Unproductive time operations. In these two cases, the magnitude of WBV was statistically evaluated as identical. The highest values of WBV were reached during the Machine movement (0.790000 m/s<sup>2</sup>) and the lowest WBV values were recorded during the Stationary position (0.310000 m/s<sup>2</sup>). Correlation between the magnitude of WBV and the volume of the trunk during its felling and processing was not proven by the research.

It was found that according to European Directive 2002/44/EC, the average WBV of three partial operations (Processing, Unproductive time and Machine movement) did not

meet the stipulated daily limit of 0.50 m/s<sup>2</sup>. The average WBV exceeded the daily limit by 16.18% (Processing), 12.20% (Unproductive time) and 27.02% (Machine movement).

It is concluded that the future creation of new harvesters or their individual parts should pay increased attention to the reduction in WBV during the processing of the trunk, during the Unproductive time (smooth boom movements) and during Machine movement on the terrain.

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