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Magnitude of WBV Affecting the Tractor with a Timber Trailer Operator During Individual Timber Forwarding Operations

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ABSTRACT

The study deals with measuring operator's whole-body vibrations (WBV) at work with the tractor with a timber trailer. The research was done directly at the workplace during the production stage of timber forwarding. The goal of the research was to find out how the magnitude of machine-generated WBV influencing the operator's body is affected by individual activities and work operations of timber forwarding and whether the magnitudes differ during those operations. For the purpose, the process of timber forwarding was divided into seven partial operations. WBV were recorded in the individual partial operations according to the valid standard ISO 2631-1:ISO 1997. During the measurements, duration times of the respective partial operations were recorded. Research results showed a correlation between the respective work operations and the WBV magnitudes. The operator of the tractor with a timber trailer was exposed to different WBV values during almost the entire process of timber forwarding.

Keywords: whole-body vibrations; tractor with a timber trailer; work safety; forwarder; cut to length technology

INTRODUCTION

The need to use fully mechanized technologies, logging and hauling machines in forestry has been growing in order to increase productivity of timber logging and transport and to eliminate physically demanding work operations. Another reason is to improve work safety (Neruda et al. 2013). Fully mechanized timber logging technology including harvesters and forwarders is commonly used in forestry in many parts of the world (Nurminen et al. 2006) thanks to its high productivity (Dvořák et al. 2008) and work safety (Axelsson 1998).

Forwarding is an operation at which felled timber is situated on the load area between the stanchions. In principle, forwarding machines are classified into two groups: forwarding tractors (forwarders) and tractors with timber trailers (Dariusz et al. 2023). A common feature of these two groups is that they are equipped with hydraulic crane and grapple. Tractors with timber trailers and forwarders bring stems or logs to the roadside landing from where they are further transported, for example to a woodworking plant (Sherwin 2007). A tractor with a timber trailer unit consists of two independent means of which the first one is in most of cases a tractor and the second one is a timber trailer. This combination is advantageous because the two means can be used not only for timber forwarding but also separately for other purposes, for example when the amount of timber felled is reduced (Naskrent et al. 2019). The prime driver of a tractor with a timber trailer unit is usually a general-purpose wheeled tractor with a 4x4 drive and an output of ca. 70 kW (Neruda et al. 2013).

Operators are affected by many factors of the working environment (Bačić et al. 2024). Some of them are given by the environment itself as well as by its technical equipment (Malý et al. 2019). There are numerous dangerous and harmful factors in the working environment, which negatively impact human health (Amiard et al. 2016). A harmful factor is defined as any agent, condition, circumstance or feature of the work system that can cause occupational accident, occupational disease and the like. This is why the factors should be searched and efficiently eliminated (Marek and Skřehot 2009). Vibrations represent a very significant factor of the work environment, which affects the whole body of forwarder operators.

Vibrations are periodical movements whose source are activities of engines, machines and other devices (Menčík 2018). Vibrations can be characterized as movements of an elastic body whose individual points oscillate. Mechanical oscillations are vibrations at which a determining quantity is the mechanical quantity (Rónay and Sláma 1989). Vibrations can be referred to when the oscillation frequency and amplitude can be felt, for example on the human body. Vibrations transmitted onto the body can be whole-body vibrations (WBV) and local vibrations, usually affecting the upper extremities (Bačić et al. 2023). Their distinction depends on the point of their transmission onto the body. Effects of vibrations onto humans may differ from nausea to physical injury. It should be pointed out that some problems may arise even after a short impact of vibrations onto the human body (Bostrand 1992).

Working with the forwarder, operators are exposed particularly to WBV, whose risk depends on their intensity and duration. Vibration rate inside the machine cabin depends, for example, on the vehicle type, terrain condition, operator's experience, driving speed, condition of the machine etc. (Rehn et al. 2005). Long-term exposure to WBV was demonstrated to be a cause of many muscoskeletal symptoms such as lower back pain, shoulder pain etc. (Rehn et al. 2002, Staněk et al. 2023). At higher frequencies, vibrations may cause discomfort, injury, fatigue etc. (Bostrand 1992). Increasing fatigue impairs the operator's working rhythm, attention and speed of thinking, and the operator becomes less productive and more prone to mistakes and accidents (Fiedler et al. 2011). Because of WBV, forest machine operators often complain of back pain, pains in cervical spine, stomach pain, breathing problems and muscle spasms (Bostrand 1992).

As for local vibrations, they occur mainly whilst working with mechanically driven tools such as a chainsaw when the most affected body parts are hands and arms. Although the operators cannot sometimes avoid the work, the risk of damage to human health by vibrations is low exactly because the exposure to them is occasional. However, long-term operation can cause health complications such as loss of sensation in the fingers and hands (Bostrand 1992).

Machine operators perform various work operations with different vibration levels during their shift. Rehn et al. (2002) found that the rate of WBV is lower at loading and unloading timber onto/from the loading area of the machine. It is also lower when the vehicle is loaded as compared with the empty vehicle (Rehn et al. 2002). Rehn et al. (2005) claim that higher WBV were recorded when driving with the empty loading area. It follows from the above that the level of WBV is variable during the shift. Exposure to its impacts should be therefore assessed with respect to the factor of time (Rehn et al. 2005).

Working with the machines, lower WBV can be achieved by choosing a different machine, by modifying drive and minimizing operations in very difficult terrains (Rehn et al. 2005). If this is not possible, WBV have to be reduced, for example by more substantial machine maintenance (Bostrand 1992).

The issue of WBV was studied by many authors on different machine types, e.g. harvesters and forwarders (Gerasimov and Sokolov 2014, Poje et al. 2019, Martins et al. 2020). As far as we know, the issue of WBV affecting operators of tractors with timber trailers at individual forwarding work operations during a day shift has not been researched to date. The goal of this research is therefore to specify the magnitude of WBV generated in individual work operations during timber forwarding and to compare them. It is assumed that the highest WBV will be recorded in the travelling machine. However, a question remains whether the magnitude of WBV is affected, for example, by the load or by the terrain on which the machine is moving.

MATERIALS AND METHODS

Measuring of Vibrations

WBV affecting the operator of tractor with a timber trailer were measured using the Datalogger CEM model DT-178 A. This is an instrument with a range of 18 G and resolution of 0.00625 G. The instrument recorded the acceleration of vibrations in three basic axes (*x*, *y*, *z*) and total shock in G ($m \cdot s^{-2}$) with all records providing information about the event time (CEM 2023). The range of time collection was set to 1 second. During the measurement, the recorded values were stored in the instrument's internal memory which provided for the recording of as many as 85,500 data (CEM 2023). Upon completion of the practical measurements, all measured data were exported into the PC to be evaluated in the Vibration Datalogger 1.0 programme. During the WBV measurements, the accelerometer was fixed on the seat of tractor with a timber trailer according to the relevant standard (ISO 2631-1), i.e. on the main interface between the human body and the source of vibrations (ISO 1997). WBV measurement duration was observed too (ISO 1997) in order to ensure the necessary statistical accuracy and vibrations typical for the evaluated exposure. Pursuant to the standard ISO 2631-1, the quantity for expressing the magnitude of vibrations is acceleration.

As mentioned above, the vibrations were measured according to the valid standard ISO 2631-1 (ISO 1997) which defines the method for measuring vibrations affecting the whole body (in our case of the operator of the tractor with a timber trailer). The standard also defines the x, y and z axes as horizontal, transverse and vertical. Effective values of mean quadratic (RMS) acceleration a_w, and frequency weighted acceleration $a_w(t)$ for each axis have to be evaluated on the seat according to (ISO 1997) (Equation 1):

$$\left[\frac{1}{T}\int_{0}^{T} a_{w}^{2}(t)dt\right]^{\frac{1}{2}}$$

where a_w is weighted acceleration as a function of time in $m \cdot s^{-2}$, and T is total time of measurement in s.

On the seat of the tractor with a timber trailer operator, we are met with a combination of vibrations in more than just one direction. According to the standard (ISO 1997), a cumulative value of vibrations from weighted effective values of acceleration determined from vibrations in orthogonal coordinates is calculated according to the following (Equation 2):

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

where a_{wx}, a_{wy}, a_{wz} are weighted effective values of acceleration in the direction of orthogonal axes *x*, *y*, or *z*, and k_x, k_y, k_z are multiplying factors.

The weighted effective value of accelerated vibrations was determined for each axis (*x*, *y*, *z*) of translation vibrations on the surface which supports the person. Vibrations were evaluated with respect to the greatest frequency weighted acceleration determined in any axis of the seat cushion. In case of this research, parameters of the sitting person used (frequency weighting with the multiplying *k* factors) were as follows: axis *x*: *k*=1.4; axis *y*: *k*=1.4; and axis *z*: *k*=1.

Work Operations

The tractor operator sat on a seat inside the tractor cab during all work operations. The seat on which the operator was sitting had a rotating function. The crane controls were positioned at the back of the cab (behind the seat). WBV affecting the operator of the tractor with a timber trailer were recorded during individual partial work operations. The records of these individual work operations were processed, evaluated and mutually compared. The work operations were as follows:

- Loading – Begins with the movement of the hydraulic crane used by the operator to load timber stems from the ground to the load area of the tractor with a timber trailer. The operation includes also the time of the hydraulic crane movement and ends with putting the hydraulic crane to the default position.
- Drive in the stand – This is an operation when the tractor with a timber trailer moves in the forest stand on the flat terrain where logging residues, stumps, branches or tree tops are left. The operation starts with the machine start in the forest stand and ends with the machine stop.
- Drive with load – The beginning of this work operation was the start of movement of the tractor with a timber trailer along the forest road from the place of timber loading to the place of timber unloading. The forest road length was 1.7 km. The forest road was loamy and unpaved. The tractor with a timber trailer was at all times moving along the same route during this operation. The end of this work operation was the moment when the tractor with a timber trailer stopped at the place of unloading.
- Unloading – This operation started with the movement of the hydraulic crane for the purpose of unloading stems from the load area of the tractor with a timber trailer onto predetermined roadside landing, and involved all the time needed for unloading the stems, including the movement of hydraulic crane. This operation also involved occasional deck levelling with the hydraulic crane of the tractor with a timber trailer. The end of this work operation was considered putting the hydraulic crane into the default position.
- Drive without load – The beginning of this work operation was considered the starting movement of the tractor with a timber trailer along the forest road from the place of timber deck at the roadside to the place of timber loading. The forest road length was 1.7 km. The forest road was loamy and unpaved. The tractor with a timber trailer was at all times moving along the same route during this operation. The end of this work operation was the moment when the tractor with a timber trailer stopped at the place of loading.
- Drive on asphalt – This operation began at the moment when the machine reached a driving speed of about 40 km·h^{-1} and maintained it during the whole operation. The machine was moving along the paved asphalt road without the load. Distance travelled by the tractor with a timber trailer during this operation was 11.7 km. The end of this work operation was the moment when the machine reduced the speed below 40 km·h^{-1} in order to move from the paved asphalt road onto the unpaved forest road.
- Stationary position – This work position involved the tractor with a timber trailer standing motionless on the spot with engine “idling” and none of the above-mentioned work operations being in progress.

Research Site

Research data were collected in the cadastral area of Žďár nad Sázavou (49.5678014 N, 15.9679178 E), in the Czech Republic. The total volume of stems forwarded on the load area of the tractor with a timber trailer during one travel was ca. 7 m^3. The timber species was Norway spruce (*Picea abies* (L.) H. Karst.) and the stems were 4 metres long. During the measurements, the tractor with a timber trailer was operated by one person whose weight was 80 kg, age 24 years and experience as an operator of the tractor with a timber trailer 1.5 years.

Machine

The tractor with a timber trailer consisted of a John Deere 6230 tractor with a timber trailer 10T made by STS Prachatice. The tractor John Deere 6230 has an engine output of 70 kW, 16/16 transmission and its weight is 4.43 tons. The dimensions are 4.29 m (length), 2.28 m (width) and 2.72 m (height). Front tyres are 380/70R24 and rear tyres are 480/70R34. Air pressure in the tyres was according to the manufacturer's instructions. The number of tractor motor-hours at the time of measurement was ca. 17.000 MH. The timber trailer has a load capacity of 10 tons and weight of 2,355 kg. Trailer dimensions are: total length 6.36–7.11 m, load area length 4.25–5.05 m, width 2.21 m, ground clearance 53 cm. Dimension of the wheels are 400/50x22.5. The trailer is equipped with a hydraulically steerable drawbar. The number of trailer motor-hours at the time of measurement was ca. 3,000 MH.

Statistical Analyses

Data recorded by vibrometers during forwarding with the general-purpose wheeled tractor with a timber trailer were divided into the respective partial operations which were mutually compared. For this purpose, a data analysis was performed in the software STATISTICA 14 (TIBCO). The Shapiro-Wilk normality test was used for the correct evaluation of the data. In this test, p-value was set to 0.05; if a situation occurred with the test result exceeding this value, then the data corresponded to the Student’s

Figure 1. Tractor John Deere 6230 with a timber trailer 10T STS Prachatice.

distribution, and the following test was one-factor ANOVA with a p-value of 0.05 again. Vibrations from the respective operations then differed if the result of the statistical test did not exceed the set value. If the result of the Shapiro-Wilk test was lower than the set p-value, then the data did not correspond to the mentioned distribution. In such a case, a non-parametric (Kruskal-Wallis) test was used whose p-value was again set to 0.05. The operations and their data differed when the test result did not exceed the p-value. For a better representation of the data, descriptive statistics and box plots were created for the respective operations and their data.

RESULTS

Figure 2 shows the distribution of vibrations affecting operators of tractors with timber trailers during individual operations. The highest concentration of data (i.e. vibrations) was recorded in the Stationary position. The highest value of vibrations (4.100000 $m \cdot s^{-2}$) (see Table 2) was recorded during the work operation of Drive in the stand. A minimum value of vibrations (0.100000 $m \cdot s^{-2}$) was observed in the same operation. The same value was recorded also in Loading. Figure 2 also shows a considerable dispersion of vibrations in the work operation of Drive with load (standard deviation 0.139860 $m \cdot s^{-2}$) and Drive without load (standard deviation 0.137502 $m \cdot s^{-2}$), whose 25% of values corresponded to 100% of values in Unloading. In the operation Drive with load, the minimum and maximum values were 0.200000 $m \cdot s^{-2}$ and 2.850000 $m \cdot s^{-2}$, respectively, which was the second highest maximum recorded in the measurements. During the operation Drive without load, the operator was affected by vibrations of limit values of 0.110000 $m \cdot s^{-2}$ and 1.360000 $m \cdot s^{-2}$. It can be stated that the highest vibrations affect the machine operator during Drive with the load and the lowest vibrations affect him during Loading and Unloading.

Table 1 shows the results from the statistic comparison of individual partial operations of forwarding with the general-purpose wheeled tractor with a timber trailer. In the comparison of Loading and Drive in the stand, the results of statistical analysis were lower than the p-value (0.05), which indicates that the magnitudes of vibrations in the operations mutually differed. Nevertheless, the difference between mean vibrations was only 0.0462320 $m \cdot s^{-2}$ to the benefit of Loading (0.261534 $m \cdot s^{-2}$). However, the maximum value of vibrations in this operation was 1.870000 $m \cdot s^{-2}$, which was by 2.230000 $m \cdot s^{-2}$ less than in Drive in the stand. Smaller deviations between maximum vibrations were already recorded in the comparison of Loading and Drive with load (0.980000 $m \cdot s^{-2}$ to the disadvantage of Drive with load). A difference between mean vibration magnitudes was 0.214238 $m \cdot s^{-2}$ to the benefit of Loading. The statistical analysis confirmed the diversity of these two operations. A

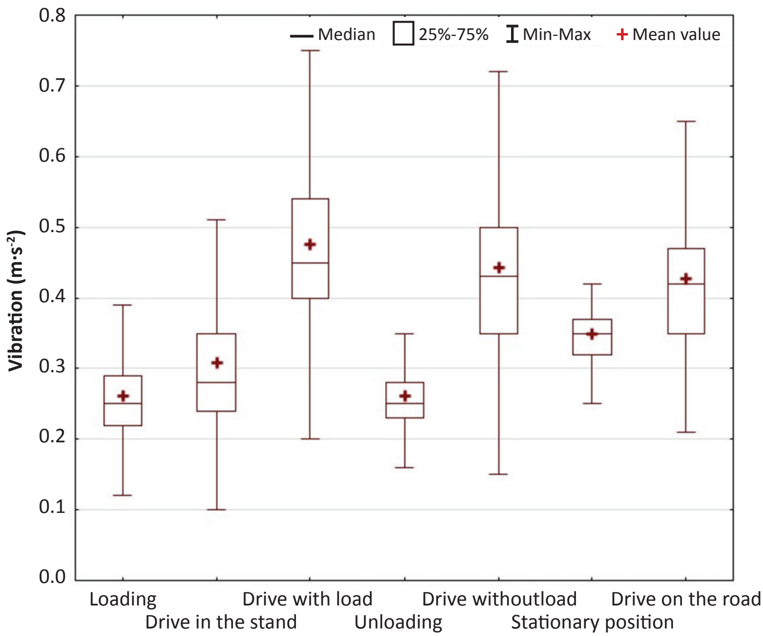

Figure 2. Distribution of vibrations in the respective work operations.

different statistical evaluation (i.e. of the same magnitude of vibrations) between the operations was also recorded between Loading and Unloading, where the p-value of 0.05 was not exceeded. This result was achieved in spite of a very small difference between the intensity of mean vibration which was only 0.000588 $m\cdot s^{-2}$ to the benefit of Loading. The maximum vibration affecting the machine operator in Unloading was by 0.140000 $m\cdot s^{-2}$ higher. The mean vibration value in Loading was also lower compared with Drive without load (by 0.181408 $m\cdot s^{-2}$). Minimum values of vibrations differed only by 0.010000 $m\cdot s^{-2}$ to the benefit of Loading. In spite of that, the operations were statistically evaluated as diverse. The same result was recorded also in the comparison of Loading and Stationary position with a higher mean value of vibrations recorded in the Stationary position (difference was 0.087061 $m\cdot s^{-2}$). The last operation compared with Loading was Drive on the road. Mean vibrations of these operations differed by 0.166634 $m\cdot s^{-2}$.

Furthermore, we compared the work operations of Drive in the stand and Drive with load. Mean vibrations of Drive in the stand were 0.307766 $m\cdot s^{-2}$, which was by 0.168006 m s^{-2} less than those of Drive with load. The most frequently recorded value was however 0.280000 $m\cdot s^{-2}$. Table 1 shows the result of the statistical test, which is lower than 0.05 and the two operations can therefore be considered diverse. The same results were recorded when comparing Drive in the stand and Unloading work operations, with the mean shock being by 0.045644 $m\cdot s^{-2}$ lower in Unloading. A maximum value of vibrations affecting the machine operator in Unloading was 1.730000 $m\cdot s^{-2}$,

Table 1. Results of the statistical comparison of respective work operations.

Operation	Loading	Drive in the stand	Drive with load	Unloading	Drive without load	Stationary position	Drive on the road
Loading		0.000000	0.000000	1.000000	0.000000	0.000000	0.000000
Drive in the stand	0.000000		0.000000	0.000000	0.000000	0.000000	0.000000
Drive with load	0.000000	0.000000		0.000000	0.000000	0.000000	0.000076
Unloading	0.000000	0.000000	0.000000		0.000000	0.000000	0.000000
Drive without load	0.000000	0.000000	0.000000	0.000000		0.002021	1.000000
Stationary position	0.000000	0.000000	0.000000	0.000000	0.002021		0.000590
Drive on the road	0.000000	0.000076	0.000000	0.000000	1.000000	0.000590	

<0.05 = combinations differ

which is by 2.370000 m·s^{-2} less than in Drive in the stand. A higher difference but the same result was recorded when comparing Drive in the stand and Drive without load, where the maximum magnitude of vibrations differed by 2.740000 m·s^{-2}. Minimum vibration values differed, however, only by 0.010000 m·s^{-2} to the benefit of Drive in the stand. The diversity was also corroborated by the result of the statistical test which did not exceed the p-value. According to the test, the operations of Drive in the stand and Stationary position can be considered also mutually diverse, where a difference of 3.610000 m·s^{-2} was recorded when comparing maximum vibration values to the benefit of the latter. A smaller, yet still high difference of 2.960000 m·s^{-2} in the maximum value was recorded when comparing Drive in the stand and Drive on the road, where the mean value of vibrations differed only by 0.120402 m·s^{-2}. The difference of these operations was also confirmed by the results of the statistical analysis.

Other operations compared within the research were Drive with load and Unloading. Mean vibrations affecting the machine operator during the work operation of Drive with load were 0.475772 m·s^{-2} (see Table 2), which was by 0.213650 m·s^{-2} more than in Unloading. The greatest difference of 1.120000 m·s^{-2} in this comparison was recorded at maximum vibrations where higher shocks were observed in Drive with load. This diversity was demonstrated statistically, too. Furthermore, a comparison of Drive with load and Drive without load was made. The recorded mean value of vibrations in Drive without load (0.442942 m·s^{-2}) was by 0.032830 m·s^{-2} lower than in Drive with load. In Drive without load, the operator was most frequently exposed to vibrations of 0.450000 m·s^{-2} and the same situation was recorded also in the other compared operation. Despite these small differences, the two operations differed according to the statistic evaluation. Stationary position was statistically compared with that of Drive with load, too, and the different values of vibrations in the two operations were confirmed. The mean value of vibrations in Stationary position was by 0.127177 m·s^{-2} higher. A similar situation was recorded in maximum vibrations where the difference was 2.360000 m·s^{-2}. A smaller difference of these values was recorded when comparing Drive with load and Drive on the road, which was 1.71000 m·s^{-2} to the benefit of the latter operation. The mean vibration in Drive on the road was by 0.047604 m·s^{-2} smaller than in Drive with load. Despite the small difference, the data of the operations were evaluated as diverse.

Another operation compared with the other ones was Unloading. It was compared with Drive without load, Stationary position and Drive on the road. The mean vibration of Unloading was 0.262122 m·s^{-2} (see Table 2) which was by 0.180820 m·s^{-2} less than in Drive without load. The same result was recorded in comparing values of maximum vibrations affecting the machine operator, with the difference being 1.250000 m·s^{-2}. According to the statistical analysis, the operations were classified as diverse. The analyses demonstrated a difference in the mean values of vibrations also in the work operations of Unloading and Stationary position (0.086476 m·s^{-2} to the benefit of Unloading). Very small different values to the benefit of Unloading were also recorded in minimum (0.140000 m·s^{-2}) and maximum vibrations (0.380000 m·s^{-2}). The operation of Unloading was further compared with Drive on the road. The results of the statistical test showed diversity between the operations despite very small differences in the magnitudes of vibrations, which ranged from 0.100000 m·s^{-2} to 0.166046 m·s^{-2} to the benefit of Unloading.

The last operation compared with the other ones was Drive without load. More precisely, it was compared with the Stationary position where mean vibrations mutually differed by 0.094347 m·s^{-2} to the benefit of the first mentioned operation. Despite the small difference, the data were statistically evaluated as diverse. Drive without load was further compared with Drive on the road. The result of comparing these two operations was, however, opposite than in the previous case, and the vibration values did not differ (larger than the p-value). A difference between the mean values of vibrations was only 0.014774 m s^{-2}. The last operations compared were Stationary position and Drive on the road. In this case, the diversity was already demonstrated statistically. The values of vibrations differed from 0.040000 m·s^{-2} to 0.079573 m·s^{-2}. Larger and smaller vibrations respectively affected the machine operator during Drive on the road and Stationary position.

Table 2. Parameters of respective operations.

Operation	Mean Value (m·s^{-2})	Median (m·s^{-2})	Mode (m·s^{-2})	Frequency of Mode	Min. (m·s^{-2})	Max. (m·s^{-2})	Standard Deviation (m·s^{-2})
Loading	0.261534	0.250000	0.250000	689	0.100000	1.870000	0.072700
Drive in the stand	0.307766	0.280000	0.250000	164	0.100000	4.100000	0.167305
Drive with load	0.475772	0.450000	0.450000	151	0.200000	2.850000	0.139860
Unloading	0.262122	0.250000	0.250000	555	0.110000	1.730000	0.055110
Drive without load	0.442942	0.430000	0.450000	93	0.110000	1.360000	0.137502
Stationary position	0.348595	0.350000	0.350000	18	0.250000	0.490000	0.039693
Drive on the road	0.428168	0.420000	0.350000	84	0.210000	1.140000	0.104225

DISCUSSION

Our research showed that the mean magnitude of WBV affecting the operator of a tractor with a timber trailer during the working day shift is 0.323219 $m \cdot s^{-2}$. This value is by 0.276781 $m \cdot s^{-2}$ lower than the value mentioned by Jankovský et al. (2016), who measured the values not only on forwarders only but also on various types of harvesters. Repeated whole-day measurements of WBV in the cabin of tractor with a timber trailer unit were made by Häggström et al. (2016), who reported the mean value of these vibrations to be 0.3 $m \cdot s^{-2}$ and the maximum value to be 0.38 $m \cdot s^{-2}$. It follows that the mean values recorded in the study by Häggström et al. (2016) were lower than values recorded in our research. It should be pointed out here that the diversity of WBV can be caused by the choice of machines. Jankovský et al. (2016) and Häggström et al. (2016) took the measurements mainly on forwarders, in which the rate of WBV is mitigated by the machine design. Another factor affecting the size of WBV can be the terrain in which the timber is forwarded. In their research conducted in karst areas, Poje et al. (2019) found out that the intensity of WBV is greater during timber forwarding in areas with stones and a thin soil layer. Langer et al. (2012) state that the exposure to vibrations onto the driver's whole-body in the terrain is approximately linearly proportional to the machine travel speed.

According to Marzano et al. (2017), who compared harvesters and forwarders during logging of eucalypt timber, the WBV level was between 0.27 and 0.7 $m \cdot s^{-2}$. The results by these authors are in correlation with the results of our study where the recorded mean value nears the lower limit of 0.27 $m \cdot s^{-2}$, not exceeding the permitted exposure limit of 0.5 $m \cdot s^{-2}$. WBV were measured on several forwarders also by Jack et al. (2010), who found in their research conducted in the north of Ontario that the mean WBV value ranged from 0.36 to 0.57 $m \cdot s^{-2}$ during forwarding. It follows that the mean WBV value recorded in our research is below the lower limit of range recorded by the authors. At the same time, it can be stated that the values are very similar. Tiemessen et al. (2007) claim that the magnitude of WBV can be affected by driving speed, by machine geometry and design, by the distribution of machine weight and by seat suspension in the cabin. According to Ji et al. (2005), WBV affecting the machine operator can be mitigated using a seat with an air cushion.

In our research, the highest values of WBV were recorded in the forwarder travelling with the load. This finding corresponds with the results published by Jack et al. (2010), whose research demonstrated the highest WBV values when travelling with the empty load area. According to Rehn et al. (2005), the operator is exposed to higher WBV when driving with an empty trailer rather than when driving with a loaded machine. This finding does not correspond to the results of our research. Higher WBV of an empty machine may be caused by the terrain, when they might arise due to the combination of unloaded forwarder and uneven terrain as a result of greater deflection of the unloaded lighter trailer. According to Santos et al. (2020), higher WBV values during the drive without load are caused by higher travel speed. Chen et al. (2003) maintain that WBV can be also affected by the operator's length of practice and experience as it appeared that the level of WBV is decreasing with the increasing experience of the operators. This might have been another factor affecting the results of our study. Amongst other things, the results of our research show that when compared with driving in the forest stand and on the forest road, the size of WBV was smaller when driving on the asphalt road. This corresponds to the results published by Tiemessen et al. (2007), who found out that a smooth asphalt surface generates lower WBV intensity for drivers than a rough surface with potholes across which the operator moved for most of the workday in our research.

The lowest WBV values were recorded in the work operations of Loading and Unloading. During these work operations, the forwarder operator was most frequently exposed to low WBV values as compared with other work operations of timber forwarding. The reason was that the machine did not move during these operations and the generation of WBV by driving was thus eliminated. Moreover, during the loading and unloading, the trailer was secured against motion and overturning by means of retractable struts. Mean WBV were 0.261534 $m \cdot s^{-2}$ (Loading) and 0.262122 $m \cdot s^{-2}$ (Unloading). These values do not exceed the admissible limit of exposure. Poje et al. (2019) found that the exposure of operator to WBV at forwarding is the smallest in loading and unloading, which corresponds to the results of our research. In the study published by Marzano et al. (2017), in which ergonomic conditions of forwarder and harvester operators were assessed, the values of WBV ranged from 0.27 to 0.70 $m \cdot s^{-2}$. Thus, it is possible to state that the mean value of vibrations in the work operations of Loading and Unloading was lower than the lowest value recorded in our research. The minimum and maximum values of WBV recorded during the measurements were 0.100000 $m \cdot s^{-2}$ and 4.100000 $m \cdot s^{-2}$ WBV. The result does not correspond to the results by Marzano et al. (2017), with the minimum value being lower and the maximum value higher as compared with our research.

Rehn et al. (2004) claim that exposure to large WBV may induce repeated tension of peripheral nerves in the upper extremities. According to Rehn et al. (2009), high WBV can cause pain in the arms and neck. According to Tiemessen et al. (2007), WBV can be reduced by factors that can be referred to as factors of a design nature such as, for example, design of machine undercarriage, and factors such as the operator's skills and behaviour. WBV can also be mitigated by lower pressure in the tyres, which is documented by the research by Sherwin et al. (2004), who found that higher pressure in tyres increased the exposure of operators to WBV. According to Langer et al. (2012), one of the factors that could help reduce WBV is regular training of operators and improved organization of work technology. There is a great number of methods of how to reduce WBV and it should be pointed out that the issue has to be given increased attention in order to create the safe environment for operators that would not be risky to their health.

The issue of whole-body vibrations is very comprehensive in logging technology and results of various authors cannot be compared with high accuracy. Any comparison can only be indicative because, as mentioned by Poje et al. (2019), the machines differ in types, weight, age, design, and engine output as well as in the specific optional or standard equipment. All these differences can influence the rate of WBV affecting the machine operators.

CONCLUSIONS

It was seen during our research that the most balanced vibrations affecting the machine operator are those generated in the Stationary position. The maximum value of vibrations reaching up to 4.100000 $m \cdot s^{-2}$ was recorded during the work operation of Drive in the stand. The minimum lowest value (0.100000 $m \cdot s^{-2}$) was recorded in the same operation and an identical value was also seen during Loading. In general, the highest vibrations affect the machine operator during Drive with the load, and the lowest vibrations affect the machine operator during Loading and Unloading. The machine operator was almost exposed to different values of vibrations during the whole process of timber forwarding using the general-purpose wheeled tractor with a timber trailer (forwarding trailer with tractor as a prime driver). More precisely, during work operations the operator is exposed to diverse vibrations for 92.48% of time.

In conclusion, it should be noted that whole-body vibrations should be given increased attention as the operator is undoubtedly the most important link in the production process in forestry. The results of this study showed a frequent occurrence of unacceptable WBV values during the workday of the operator, which can impair their health and work safety. The subject of further research should therefore be the reduction of high WBV values.

Author Contributions

Conceptualization, D.S. and L.S.; methodology, D.S. and L.S.; software, V.M.; validation, V.M; formal analysis, V.M.; investigation, D.S. and L.S.; resources, D.S.; data curation, V.M.; writing—original draft preparation, D.S.; writing—review and editing, D.S.; visualization, D.S., V.M., L.S.; project administration, D.S.; funding acquisition, L.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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