Operator Exposure to Noise and Whole-Body Vibration in a Fully Mechanised CTL Forest Harvesting System in Karst Terrain

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Abstract

In recent decades fully mechanised cut-to-length forest harvesting systems have spread from flat and gentle to steep and rough terrain. To analyse the potential adverse impact of these changes on operator health, an observational study of exposure to noise and whole-body vibration (WBV) was carried out in karst terrain. The results showed that, in contrast to exposure to noise, the exposure of harvester and forwarder operators to WBV exceeds the daily exposure action value specified in the European Directive. Differences between work sites may contribute up to 8.7 dB(A) to noise exposure and up to 0.28 m/s^2 and 6.0 m/s$^{1.75}$ to WBV exposure when working with forwarders and harvesters. Aside from technical upgrades of machines, reduction of exposure to both WBV and noise, while simultaneously maintaining high productivity, requires careful selection of work sites and adapted work organisation.

Keywords: forestry, ergonomics, exposure to noise, exposure to whole-body vibration, CTL harvesting

1. Introduction

Fully mechanised cut-to-length harvesting (CTL) is most frequently related to the use of a combination of two forestry machines: a harvester, which fells a tree and processes it into logs, and a forwarder, which transports the logs from a forest to a forest road or an auxiliary storage site. CTL technology has spread from flat and wet terrain to more difficult terrain (Gellerstedt and Dahlin 1999). Today, CTL technology is also used on very steep and rocky terrain, where working with the above-mentioned machines is made possible through the use of winches or wire systems (Visser and Stampfer 2015). Terrain and soil can negatively affect the application of typical ground-based harvesting systems. For example, sinkholes and rocks exposed in karst terrain often limit or even prevent the use of CTL technologies (Pičman et al. 2011).

In addition to increasing productivity (Nordfjell et al. 2010), modern harvesting and forwarding machines have also improved safety and health at work (Axelsson 1998). However, despite technological and ergonomic improvements, some risks are still relatively high and some new risks have emerged. Exposure to whole-body vibration (WBV) during harvesting with harvesters and extracting with forwarders is between 0.1 and 2.0 m/s^2 (EU 2008, Gerasimov and Sokolov 2014, Jack et al. 2010, Pitts 2006, Rehn et al. 2005b, Rothschild et al. 2002, Sherwin et al. 2004a). Although exposure of operators to noise is lower than the threshold that directly affects hearing (Gerasimov and Sokolov 2014, Messingerová et al. 2005, Seixas et al. 1999), monotonous noise at the same engine speed interrupts their work (Rieppo et al. 2002, Synwoldt and Gellerstedt 2003). Stationary work, poor posture and quick cyclic repetition of work operations increase the risk of »new« diseases such as repeated injury syndrome (Axelsson and Pontén 1990).

Previous research established that factors such as vehicle speed, driving style, machine design and geometry, belt and chain type, suspension type, power transmission to the wheels, mass distribution, position of the driver's seat and the seat features (Tiemessen et al. 2007, Zylberstein 1980) affect the exposure of operators of forestry machinery to WBV. The most important terrain factors contributing to WBV exposure are ground unevenness and ground capacity (Rehn et

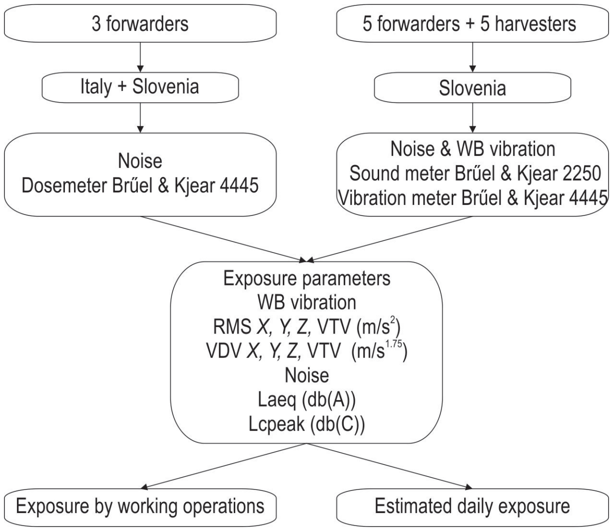

Fig. 1 Study flow chart

al. 2005a, Warkotsch 1994). Demanding terrain conditions potentially also increase the exposure of operators to noise, in particular through higher engine loads and through structural borne noise that occurs as a result of the vehicle/surface interaction (Harrison 2004).

Since operator exposure not only depends on the particular model of machine and on the operators themselves but also on the working conditions in which the machine operates, the aim of this observational study was to analyse the exposure of harvester and forwarder operators to noise and WBV in karst terrain. In addition to its topographical characteristics, karst terrain also includes terrain features such as carbonate bedrock, a thin layer of soil and increased presence of obstacles. Previous research suggests that operator exposure will be higher in these working conditions than on soft soils and flat terrain.

2. Materials and methods

The research comprised two separate studies. The first study was conducted in the northern part of Italy and southern part of Slovenia and examined the exposure of forwarder operators to noise. The second study was carried out in the southern part of Slovenia and measured the exposure of forwarder and harvester operators to WBV and noise. The latter examined exposure at the same work sites. Exposure is presented in the results per individual work operation and as an assessed daily 8-hour exposure (Fig. 1).

2.1 Object description

The study sites were located in the karst area of Italy and Slovenia, where calcareous rocks dominate the parent material (Fig. 2). In terms of phytocenology, they are classified as Dinaric fir-beech forests, submontane beech forests and thermophilic beech forests. Slope and stoniness (share of forest area (%) covered with stones) of the terrain varied between sites and averaged 14% and 10%, respectively (Table 1).

The research included six different types of forwarders, with weights ranging from 11 to 18 tons and load capacities from 9 to 14 tons. Forwarders used in

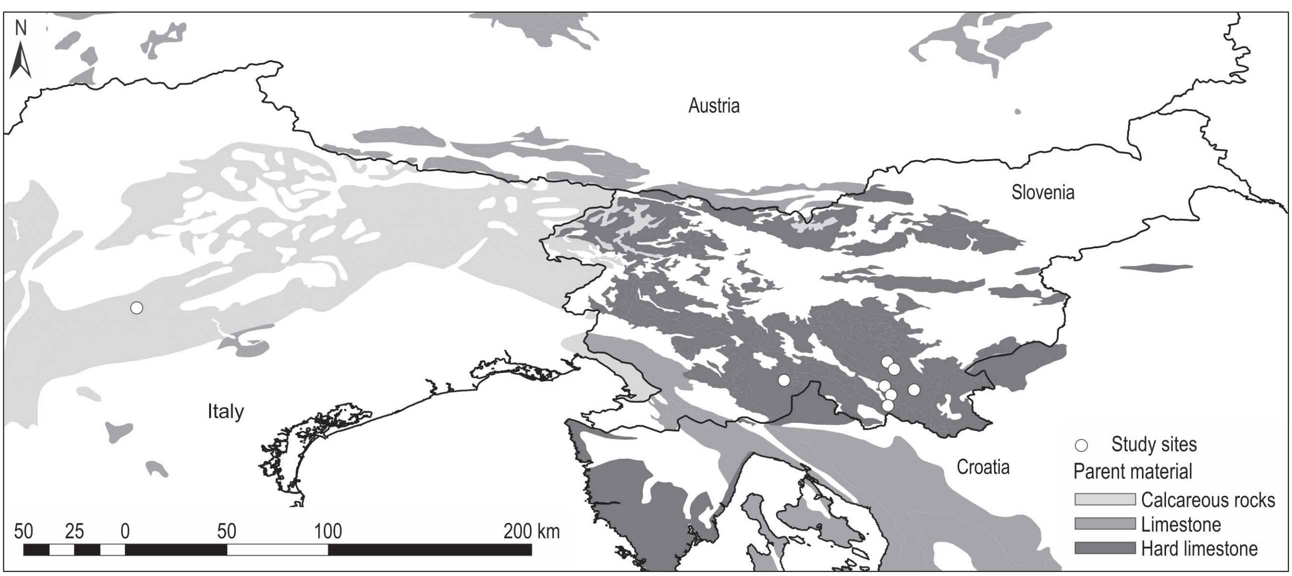

Fig. 2 Study site locations according to parent material (Source: European Soil Database)

Table 1 Type of measurements and site characteristics

Site	Exposure	Country	Phytocoenological type	Slope %	Stoniness %
1	Noise	I	Omphalodo-Fagetum	15	5
2	Noise	SI	Omphalodo-Fagetum	36	15
3	Noise	SI	Omphalodo-Fagetum	21	5
4	Noise & WBV*	SI	Hedero-Fagetum	0	8
5	Noise & WBV	SI	Hedero-Fagetum	9	8
6	Noise & WBV	SI	Hedero-Fagetum	9	3
7	Noise & WBV	SI	Hedero-Fagetum	11	8
8	Noise & WBV	SI	Abieti-Fagetum Ostryo-Fagetum	14	30

* During forwarding only WBV data were successfully recorded

the research were of different ages, from new machines to 15-year old machines, with an average of 6875 operating hours or 1623 hours per year. Additional accessories used by eight-wheel forwarders during the work also varied. Some were equipped only with continuous tracks, some with continuous tracks and tyre chains, some even with only one tyre chain and some completely without additional fittings. Workers operating the machines were 32.3 years of age on average and had from several weeks to 8 years of work experience in wood extracting with forwarders (Table 2).

Five harvesters weighing between 18 and 24 tons were included in the research. Their average age was 6.8 years, while their average operating time was 10 675 hours or 1496 hours per year. Unlike forwarders, harvesters were uniformly equipped with additional accessories, i.e. tracks at the front and tyre chains at the back. Operators were 30.4 years old on average and had from 1 to 10 years of work experience in operating harvesters (Table 3).

Forty-eight cycles of wood extraction were recorded in total and involved mainly downhill forwarding. The distance of loaded driving, i.e. the distance between the last loading of logs in the forest and the landing site, was between 20 and 570 metres per individual cycle or 230 metres on average. During the

Table 2 Forwarder and operator characteristics

Site	Forwarders					Operators	
	Type	Age of machine year	Operating hours h *	Accessories		Age year	Work experience year
				Front	Back		
1	John Deere 1110 E	2	3700	–	–	50	5
2	John Deere 1210 E	1	1760	Chains	Tracks	25	3.5
3	John Deere 1410 D	6	10 380	Chains	Tracks	29	<1
4	John Deere 1410 D	7	11 500	Chains	Tracks	28	2
5	John Deere 1210 E	2	3285	Chains	Tracks	27	2
6	Timberjack 810 B	15	/	–	Chain	30	<1
7	Cat EcoLog 564 B	7	7500	Tracks	Tracks	27	8
8	Valmet 840.3	6	10 000	Tracks	–	42	5

Table 3 Harvester and operator characteristics

Site	Harvesters					Operators	
	Type	Age of machine year	Operating hours h *	Accessories		Age year	Work experience year
				Front	Back		
4	John Deere 1470 D	7	11 000	Tracks	Chains	25	4
5	John Deere 1470 E	2	2800	Tracks	Chains	32	3
6	Cat EcoLog 580	13	12 500	Tracks	Chains	30	8
7	Cat EcoLog 580C	8	16 400	Tracks	Chains	31	1
8	Valmet 941.1	4	/	Tracks	Chains	34	10

* Values from machine counter

Table 4 Working conditions

Site	Forwarding						Harvesting	
	Operating conditions			Load characteristics			Load characteristics	
	Cycles, n	Logging direction	Logging distance m *	Coniferous, %	Logs, n	Volume, m^3	Logs, n	Volume, m^3 **
1	8	Downhill	160	100	231	122	/	/
2	10	Downhill	210	80	440	136	/	/
3	6	Downhill	130	40	170	46	/	/
4	5	Downhill	260	100	571	61	65	14
5	5	Downhill, uphill	270	100	508	60	188	27
6	4	Flat	390	85	490	35	167	72
7	5	Downhill, uphill	310	97	555	50	106	21
8	5	Downhill	210	0	401	55	54	71

* Distance of driving loaded; ** Data from on-board computer

study, 3366 logs or 565 m^3 of wood (mostly coniferous) were extracted from the forest. During harvesting, 580 logs or 205 m^3 of wood (assessed by the harvester's on-board computer, Table 4) were felled. Beech and spruce trees to be processed were either standing or lying due to glaze ice. At work site 8, some trees were felled by a feller and processed by a machine. Harvesters used skid trails for driving between site parts and drive off-road (harvester trails) when harvesting individual trees. Density and location of trails enabled successful harvesting of timber damaged by ice storm.

2.2 Measurement methods and instruments

Measurements of exposure to noise were performed with two different noise meters, i.e. at the first three work sites with a Bruel & Kjaer 4445 dosimeter and at the other work sites with a Bruel & Kjaer 2250 noise meter. Since the variations of exposure to noise in CTL harvesting are predictable for a workday and repeated from one day to another, there are no significant differences in measured exposure levels between the two methods (Hetu and Rheault 1987).

According to the ISO 9612:2009 standard, a microphone was mounted up to 0.1 m from the operator's ear in dosimetry and from 0.1 to 0.4 m in the method using the noise meter. In practice, this meant that the operator had a microphone fixed on his shoulder, or a microphone together with a noise meter was attached to the windscreen with a holder.

To measure the WBV load, a Bruel & Kjaer 4447 vibration meter and a Bruel & Kjaer 4542 accelerometer were used together with a 4515-B-002 seat adapter. According to the ISO 2631:1997 standard, frequency-weighted data were measured at the seat, i.e. in the *X* (forward-backward), *Y* (left-right) and *Z* (up-down) directions.

Measurements of noise and WBV load were conducted simultaneously. The continuous method of time study was used to segment the recorded exposure data of work operations.

The distance of loaded driving was measured with a Garmin 60 SCx GPS receiver with an accuracy of 10 meters. The efficiency of wood extraction performed with forwarders was assessed by counting logs during loading and assessing their volume. The volume was assessed by sampling the logs and measuring their diameters or through an assessment of transport capacity. The number of produced logs in harvesting was acquired from the time study, while the volume assessment was obtained by an on-board computer.

2.3 Data processing and indicators

The noise load indicators included the equivalent sound level (Lp,Aeq) and peak value of sound level (Lp,Cpeak), while the vibration load was assessed by RMS and VDV values per individual axis and in total (VTV). Noise and WBV data logging was set to 1 second. Equations stated in international standards (ISO 9612:2009, ISO 2631:1997) were used to calculate total daily exposure and exposure during work operations.

To assess the daily exposure to noise and WBV in harvesting and forwarding, the structure of productive time was recorded, while the value 1.39 was used as a coefficient of unproductive time, as defined in the national norms of forest work and in the Annex to the Decree on concessions for the exploitation of forests owned by the Republic of Slovenia (2016). The calculation of daily exposure to noise assumed that the machine was turned off during unproductive time, and that the exposure to noise equalled 60 dB(A) or the level of noise during conversation (Hansen 2005).

2.4 Statistical analyses

According to the purpose of the research, an individual work operation was used as a sample unit for statistical analyses. As per the ISO 9612:2009 standard, statistical analyses were conducted using energy averages, i.e. the values of exposure to noise by individual operation were antilogarithmic, while the values of exposure to WBV were squared. In addition to descriptive methods, a robust unequal variances *t*-test (Welch's *t*-test) and Tamhane's T2 test in the post-hoc analysis were used due to non-homogeneity of variances. For all statistical analyses IBM SPSS Statistics Version 21 and MS Excel 2010 were used.

3. Results

3.1 Exposure of forwarder operator to noise and WBV

When one-second-long exposure values were taken into consideration, the exposure of an operator to noise during forwarding ranged between 50.0 and 108.6 dB(A) or 70.2 and 131 dB(C). The highest average Lp,Aeq exposure to noise among all work operations was measured during delays, i.e. personal or interference time (Björheden and Thompson 2000), where an operator often waited for the completion of other tasks with his cabin door open (Table 5). Among the operations conducted during productive time, exposure to noise was the highest while driving and moving the machine, i.e. 3.1 to 9.6 dB(A) higher than in operations where the machine was stationary and work was performed with a crane. The differences in exposure to noise by work operation were statistically significant.

Similarly, differences between work sites were also significant, with the greatest difference being 8.7 dB(A). The lowest exposure was recorded at work sites 3, 4 and 5. Given that the same machine was used at work sites 2 and 5, the results indicate that, due to different work conditions (e.g. slope and stoniness of the terrain) and different operators, the exposure to noise significantly (p=0.001) differs by 8.4 dB(A).

The highest RMS one-second value of the exposure of a forwarder operator to WBV by individual direction reached 4.75 m/s^2, while the VDV value, referenced to 8-hour exposure, was 80.51 m/s$^{1.75}$. The average exposure to WBV during productive time was the highest in the Y (0.33–1.00 m/s^2) direction and thus 50% (36–74%) higher than in the X direction and 90% (83–109%) higher than in the Z direction. VDV exposure displayed a similar pattern, with values in the Y direction ranging from 7.88 to 21.19 m/s$^{1.75}$, while differences in exposure between the other two axes were comparable (52% or 30–81% and 72% or 20–95%). According to exposure to WBV by individual axis direction, work operations during productive time may be divided into three groups. The first group includes loaded and empty driving, where driving speed and engine loads are highest. The second group is characterized by slow movements during wood loading and unloading, while the third comprises two work operations: loading and unloading, where the machine is not moving and the work is performed by a crane. The exposure by individual direction was 53% (32–89%) higher in the first group than in the second, with the exception of VDV exposure in the Z direction, where the exposure during movements was 7% higher than during loaded driving. On average, exposure in the third group was 142% (71–218%) lower than that in the first group and 66% (30–140%) lower than that in the second. Differences in exposure to vibration by individual work operation were statistically significant.

The differences in exposure to WBV among work sites are significant and may differ up to 77% (71–96%) on average. The highest exposure to WBV was recorded on work sites 6 and 8. At work site 6, the work was executed with a small, old machine which was operated by the least experienced worker of all those participating in the research. In contrast, a very experienced worker operated the machine at work site 8. For this reason, the work on very rocky terrain and on trails covered by a thick layer of logging residues of deciduous trees (Table 1 and 4) was fast and efficient (33.8 m^3/PMH) at this work site.

3.2 Exposure of harvester operator to noise and WBV

The exposure of harvester operators to noise during work ranged from 53.6 to 95.3 dB(A) or from 80.0 to 132.4 dB(C). The highest average Lp,Aeq exposure to noise during all work operations performed with the harvester was also recorded during interference time, where an operator waited for a feller to execute his work and later communicated with him (Table 6). During this time, the machine operated at idle speed, the operator was in the cabin and the cabin door was

Table 5 Forwarder operator exposure to noise and WBV

						WB vibration exposure																
	RT min	SS n	Lp Cpeak dB(C)	Lp,Aeq dB(A)		SS n	RMS X m/s^2		RMS Y m/s^2		RMS Z m/s^2		RMS VTV m/s^2		VDV X[3] $m/s^{1.75}$		VDV Y[3] $m/s^{1.75}$		VDV Z[3] $m/s^{1.75}$		VDV VTV[3] $m/s^{1.75}$	
			Max	M	SD		M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Operation																						
Driving empty	207.9	57	122.8	75.5	4.9	29	0.58	0.12	1.00	0.21	0.54	0.18	1.28	0.36	11.70	2.20	21.19	4.02	12.98	4.11	28.24	7.40
Driving loaded	171.2	49	122.3	75.3	5.4	23	0.51	0.14	0.82	0.21	0.39	0.10	1.04	0.34	10.91	2.67	17.90	4.01	9.16	2.77	23.22	6.66
Driving while loading and unloading	227.5	521	124.8	70.0	4.3	333	0.38	0.10	0.53	0.15	0.29	0.12	0.71	0.25	8.30	2.03	11.82	2.87	9.81 (6.90)	3.09	16.68	5.36
Loading	588.7	483	131.0	66.9	3.5	319	0.25	0.06	0.34	0.10	0.19	0.05	0.46	0.15	6.40	1.46	8.30	2.20	4.45	1.25	11.64	3.48
Unloading	240.9	126	126.1	65.8	3.1	54	0.23	0.05	0.33	0.09	0.17	0.04	0.43	0.14	5.54	1.20	7.88	2.06	4.08	1.12	10.60	3.06
Moving tops and branches	11.0	9	107.2	66.4	3.0	0	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
Delay inside the cab[2]	20.4	22	130.2	78.3	8.4	10	0.15	0.07	0.17	0.07	0.14	0.07	0.27	0.15	5.25	1.90	5.48	1.94	5.50	2.49	9.53	4.40
Significance of means differences	–	–	–	Yes	–	–	Yes	–	Yes	–	Yes	–	Yes	–	Yes	–	Yes	–	Yes	–	Yes	–
Productive time	1436.3	–	131.0	71.3	–	–	0.37	–	0.58	–	0.31	–	0.75	–	8.10	–	13.57	–	8.31	–	18.08	–
Site																						
1	243.1	156	124.4	70.9	4.6	0	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
2	266.1	251	124.6	73.5	5.5	0	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
3	215.9	180	117.0	65.5	2.8	0	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
4	179.6	202	124.8	64.8	2.9	202	0.27	0.07	0.39	0.12	0.22	0.11	0.52	0.22	6.09	1.39	9.86	2.51	10.73 (6.42)	3.38	15.33	5.22
5	171.8	194	113.0	65.1	2.1	194	0.30	0.08	0.41	0.16	0.27	0.13	0.57	0.26	6.51	1.50	10.30	3.01	7.13	2.70	14.77	5.36
6	138.3	95	131.0	73.2	2.5	183	0.43	0.10	0.59	0.14	0.26	0.08	0.78	0.23	9.68	1.97	13.04	2.67	6.62	2.08	17.58	4.61
7	154.5	95	128.7	68.6	1.7	95	0.22	0.06	0.38	0.14	0.21	0.06	0.48	0.21	5.38	1.30	11.06	3.25	6.29	2.22	13.95	5.09
8	98.4	94	130.2	70.9	2.4	94	0.42	0.13	0.67	0.23	0.37	0.16	0.87	0.38	9.38	2.36	15.64	4.27	8.73	3.18	20.33	7.32
Significance of means differences	–	–	–	Yes	–	–	Yes	–	Yes	–	Yes	–	Yes	–	Yes	–	Yes	–	Yes	–	Yes	–
Daily exposure level[1]	480.0	–	131.0	70.0 [78.1]	–	–	0.31	–	0.49	–	0.26	–	0.64	–	8.10	–	13.57	–	8.31	–	18.08	–

Legend: RT – recorded time, SS – sample size (number of operations), M – energy average, SD – standard deviation, [1] estimated exposure referenced to 8-hour working day where total delay coefficient of 1.39 (i.e. 134.7 min) and noise and vibration exposures set to 60 dB(A), 0 m/s^2 and 0 $m/s^{1.75}$ during delay time were used, [2] not included in daily exposures and in equality of means testing, [3] values referenced to 8-hour working day, () – exposure with extreme value (39.09 $m/s^{1.75}$) removed from the analysis, [ ] – estimated daily exposure level for unproductive time set to measured noise level during forwarding of 82.9 dB(A)

open. During productive time, exposure to noise was highest while driving on trails and thus 1.2 or 1.4 dB(A) higher than that during the operations with the lowest values of exposure, i.e. moving logging residues and driving between trees. The differences in exposure to noise by work operation of productive time were not statistically significant.

In contrast, the differences between the work sites proved significant. In particular, this applied to the differences in exposure between work sites 5 and 8, where the difference was 3.8 dB(A). The comparison between respective work sites revealed that the terrain was more rocky at work site 8 (Table 1). At this work site, harvesting of large deciduous trees (Table 4) resulted in higher engine loads.

The highest RMS (one-second) value of the exposure to WBV, regardless of vibration direction, amounted to 4.45 m/s^2, while the VDV value, referenced to 8-hour exposure, amounted to 93.55 $m/s^{1.75}$. In driving between sites and trees, the highest exposure of a harvester operator to WBV was measured in the *Y* direction, while in the *X* direction it was highest during positioning, felling and processing. RMS and VDV exposure were always lowest in the *Z* direction. Compared to other operations of productive time, exposure to WBV during work operations involving machine movements was 62% higher on average (21–159%). Differences between exposures were statistically significant in almost all individual directions (except for VDV *Z*) and in total (VTV).

Exposure to WBV by work site ranged between 0.20 and 0.68 m/s^2 or between 4.08 and 15.71 m/s$^{1.75}$. Except for work site 4, exposures were highest in the *Y* direction and lowest in the *Z* direction. Differences in exposure to WBV between work sites were significant. The highest exposures were recorded at work site 6, where harvesting was performed by the oldest machine.

Due to non-significant differences between work sites and notwithstanding large differences in the exposure to WBV, VDV exposure in the *Z* direction while working with forwarders as well as harvesters was examined in detail. The results showed that large differences in exposure at work sites 4 and 6 were the consequence of shocks while moving the machines (Table 5 and 6). By eliminating only one operation with an extremely high level of exposure (39.09 m/s^{1,75} and 39.89 m/s^{1,75}), exposure at work sites 4 and 6 decreased by 67%.

By comparing daily noise exposure levels of harvester and forwarder operators (Table 5 and 6), where it was determined that 72% of workday time was productive and 28% was unproductive, it was established that exposure level was higher during forwarding than during harvesting. The main reason was higher exposure during driving, where noise levels exceeded 75 dB(A). Nevertheless, exposure to noise during forwarding and harvesting did not exceed the lower action value determined in the European legislation (EU 2003). Daily exposure to WBV was similar during har-

Table 6 Harvester operator exposure to noise and WBV

		Noise exposure				WB vibration exposure																
	RT min	SS n	Lp Cpeak dB(C)	Lp,Aeq dB(A)		SS n	RMS X m/s^2		RMS Y m/s^2		RMS Z m/s^2		RMS VTV m/s^2		VDV X[3] m/s^{1,75}		VDV Y[3] m/s^{1,75}		VDV Z[3] m/s^{1,75}		VDV VTV[3] m/s^{1,75}	
			Max	M	SD		M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Operation																						
Driving between site parts, (on trails)	18.3	11	124.7	69.1	1.6	13	0.66	0.08	1.04	0.19	0.34	0.07	1.28	0.28	12.46	1.20	21.47	3.39	6.83	1.51	27.86	4.86
Driving between trees	147.0	287	124.9	67.9	2.1	391	0.61	0.10	0.80	0.18	0.26	0.07	1.04	0.26	12.21	2.08	17.47	3.79	9.29 (5.52)	2.34	24.00	6.25
Positioning, felling processing	292.4	392	123.7	68.2	2.3	476	0.43	0.08	0.40	0.11	0.20	0.04	0.62	0.17	9.84	1.94	11.43	2.71	4.46	1.15	16.77	4.68
Moving tops and branches	115.1	303	132.4	67.6	2.3	369	0.49	0.10	0.48	0.13	0.21	0.06	0.72	0.19	10.06	1.88	11.06	2.66	4.64	1.23	17.12	4.57
Moving logs	5.3	6	111.5	68.6	2.6	8	0.47	0.07	0.47	0.11	0.22	0.05	0.70	0.16	9.23	1.34	10.10	2.30	4.57	1.22	16.00	3.78
Delay inside the cab[2]	2.3	2	131.4	76.0	7.9	2	0.07	0.00	0.17	0.03	0.07	0.02	0.19	0.05	1.63	0.07	4.61	1.17	1.46	0.10	6.31	2.11
Significance of means differences	–	–	–	No	–	–	Yes	–	Yes	–	Yes	–	Yes	–	Yes	–	Yes	–	No	–	Yes	–
Productive time	578.1	–	132.4	68,0	–	–	0.50	–	0.57	–	0.22	–	0.79	–	9.88	–	13.19	–	6.35	–	18.45	–
Site																						
4	70.3	158	124.7	68.6	1.6	158	0.46	0.08	0.40	0.11	0.20	0.05	0.65	0.17	9.76	1.71	9.54	2.32	4.42	1.08	16.84	4.48
5	152.5	464	132.4	66.5	2.1	464	0.52	0.11	0.59	0.20	0.20	0.05	0.82	0.29	11.25	2.25	15.71	4.34	4.54	1.21	20.42	6.34
6	176.8	292	126.9	68.7	1.1	292	0.53	0.14	0.68	0.21	0.28	0.08	0.91	0.34	11.39	2.51	15.51	4.07	10.01 (5.96)	2.52	23.10	7.42
7	126.6	/	/	/	/	258	0.51	0.09	0.53	0.14	0.20	0.05	0.76	0.21	10.19	1.75	11.71	2.75	4.08	0.95	16.99	4.44
8	54.3	87	131.4	70.3	2.0	87	0.46	0.08	0.57	0.11	0.25	0.05	0.77	0.18	9.64	1.74	11.56	2.09	5.02	1.02	18.12	4.19
Significance of means differences	–	–	–	Yes	–	–	Yes	–	Yes	–	Yes	–	Yes	–	Yes	–	Yes	–	No	–	Yes	–
Daily exposure level[1]	480.0	–	132.4	66.9 [77.7]	–	–	0.42	–	0.48	–	0.19	–	0.67	–	9.88	–	13.19	–	6.35	–	18.45	–

Legend: RT – recorded time, SS – sample size (number of operations), M – energy average, SD – standard deviation, [1] estimated exposure referenced to 8-hour working day where total delay coefficient of 1.39 (i.e. 134.7 min) and noise and vibration exposures set to 60 dB(A), 0 m/s^2 and 0 m/s^{1,75} during delay time were used, [2] not included in daily exposures and in equality of means testing, [3] values referenced to 8-hour working day, () – exposure with extreme value (39.89 m/s^{1,75}) removed from the analysis, [ ] – estimated daily exposure level for unproductive time set to measured noise level during forwarding of 82.9 dB(A) vesting and forwarding and highest in the *Y* direction, with exposure levels of 0.48 and 0.49 m/s^2 or 13.19 and 13.57 $m/s^{1.75}$. Both VDV exposures exceeded the lower action value defined in the European legislation (EU 2002).

4. Discussion

The use of CTL technologies in difficult working conditions represents a potential risk to the health of operators of harvesting and forwarding machines. Previous research has shown that, in addition to the model of the machine, the operator and the unevenness of the ground, certain stand characteristics are among the main factors that affect the exposure of forwarder and harvester operators to WBV (Rehn et al. 2005a, Sherwin et al. 2004a) and potentially also to noise, since the initial source of the noise and vibration is often the same (i.e. the engine). Thus, the aim of the research was to establish the level of exposure of harvester and forwarder operators to noise and WBV in working conditions in karst areas with undulating topography, hard carbonate bedrock, increased presence of obstacles and a higher share of deciduous trees in the growing stock.

The results show that the daily exposure of forwarder and harvester operators to noise in karst areas is generally comparable to that established in previous studies conducted in different countries (Gerasimov and Sokolov 2014, Messingerová et al. 2005, Seixas et al. 1999, Sowa and Leszczyński 2007). In accordance with the aforementioned studies, we also established that exposure is higher when the machine is moving than during crane operation and that exposure to noise during harvesting is generally lower than during forwarding. Conversely, the study showed that, on average, exposure to noise in karst areas is higher than that in the boreal forests of northwest Russia, which are on level terrain and clay soils (Gerasimov and Sokolov 2014). In particular, higher levels of exposure occur when machines are moving, in which case exposure is up to 2.9 dB(A) higher during forwarding and up to 5.3 dB(A) higher during harvesting.

The exposure of the harvester operator to WBV in karst areas is significantly higher than that established by previous studies conducted in Sweden and Northwest Russia (Gellerstedt 1998, Gerasimov and Sokolov 2014, Rothschild et al. 2002). On average, exposure during driving and during felling and processing is over 4 times higher than that in the boreal forests of Northwest Russia (Gerasimov and Sokolov 2014) and 2 times higher than that in the forests of Ireland (Sherwin et al. 2004a). In contrast, exposure to WBV during harvesting is comparable to that established in the UK (Pitts 2006). The unevenness of the terrain is the main reason that the exposure during movements is higher in the Y direction, whereas for crane operation, the highest exposure is in the *X* direction. In contrast to some previous studies (Sherwin et al. 2004a), exposure in the *Z* direction was from 40 to 90% lower than that in the other two directions. This indicates that the proper seat selection is a potential factor influencing WBV (Tiemessen et al. 2007).

Operator exposure to WBV in the karst area was significantly higher than that measured on flat terrains of Northwest Russia (Gerasimov and Sokolov 2014) and somewhat lower than that measured in the northern part of Sweden, where the majority of the surface was classified as very smooth or as a surface with moderate numbers of obstacles from 10–30 cm and separate obstacles up to 50 cm (Rehn et al. 2005a). Comparisons of work operations show a similar pattern. Compared to previous research, exposure (Gellerstedt 1998, Gerasimov and Sokolov 2014, Häggström et al. 2016, Pitts 2006) was higher during driving, particularly unloaded driving. Compared to the study of Rehn et al. (2005a), RMS VTV values of exposure were lower for almost all operations.

As in the previous research, exposure to WBV (Gellerstedt 1998, Pitts 2006) is highest in the *Y* direction for all work operations due to the unevenness of the ground surface during driving and due to the alternating side (lateral) loading while working with a crane. VDV values of WBV, which are higher than those established in other studies (Rehn et al. 2005a), indicate the presence of shocks. This is likely due to greater surface rockiness, although other factors may also contribute to vibration exposure.

As has already been established in previous research (Rehn et al. 2005a), the high variability of exposure to WBV and noise at work sites is the consequence of working conditions, machines and operators. Difficult working conditions, such as steep terrain, increased rockiness or large dimensions of trees, require higher system power, which is provided by engines and power train subsystems. Machines differ in terms of type, age, weight, engine power, construction, and serial and optional equipment, which directly or indirectly influence exposure to noise and vibration. Thus, it was established, for example, that self-levelling cabins reduce operator exposure to noise (Gellerstedt 1998), while higher tyre pressure increases exposure to WBV (Sherwin et al. 2004b). Track harvesters have significantly higher WBV levels than tyre harvesters (Schettino et al. 2019). Operators' subjective experiences during combined exposure to noise and WBV

(Ljungberg et al. 2004) may have a large impact on exposure through their method of work and behaviour, with driving speed having been recognized as one of the most influential factors (Zylberstein 1980). In terms of our research, the aforementioned factors may contribute 3.8 dB(A) or 8.7 dB(A) to noise exposure and 0.28 m/s^2 (41%) or 5.8 and 6.0 $m/s^{1.75}$ (37% and 39%) to WBV exposure during operations carried out with forwarders and harvesters.

Notwithstanding large differences in noise exposure between work sites and a higher level of exposure compared to CTL harvesting in boreal forests, the daily exposures to noise during forwarding and harvesting do not exceed the action or limit values defined in the EU legislation (EU 2003). The assessment of daily exposure is also, to some extent, the result of the methodology used. According to the study method, all additional sources of noise during productive time, such as the radio and air conditioner, as well as other sources that could significantly increase exposure to noise (Messingerová et al. 2005, Seixas et al. 1999), were excluded. Furthermore, due to safety at work and consumption of energy, we presumed that during unproductive time the machines were turned off and the noise did not exceed 60 dB(A). This presumption is only partly true, since in the first three days of our study, where the exposure to noise was determined with dosimetry, we established that exposure to noise outside the cabin was significantly higher than that inside the cabin, i.e. 82.9 dB(A). The main reason for the high level of exposure was the presence of a worker in close proximity to the operating machine during the maintenance of the machine and interference time. By taking into account the measured exposure in unproductive time, the daily exposure of the harvester operator and forwarder operator increases to 77.7 dB(A) and 78.1 dB(A), respectively. These noise levels are still lower than the lowest action value of daily exposure. However, this level would be exceeded if exposure to noise in unproductive time exceeded 85 dB(A).

In contrast to exposure to noise, the assessment of the daily exposure of harvester and forwarder operators to WBV according to the vibration dose value (VDV) indicator exceeds the action value but not the limit value defined in the EU legislation (EU 2002). Exposure, which is usually highest in the *Y* direction, exceeds the action value overall, and, taking into account the 28% share of unproductive time, also at the majority of work sites.

Although exposure to noise does not present a direct threat to operator health, the continuous noise of the engine and computer may be disturbing to the worker (Rieppo et al. 2002, Synwoldt and Gellerstedt 2003). Thus, in addition to changes to machine design, measures to reduce exposure to noise must be directed towards the reduction of engine noise in particular. By reducing engine noise, the exposure of the operator during productive time would decrease as well, where the work is performed from the cabin of the machine, and also during unproductive time, where the majority of work tasks are executed outside the cabin. This, in addition to safety and energy consumption considerations, underscores the importance of the practice of turning off the machine during unproductive time.

Exposure to WBV may be reduced by implementing organisational measures and design solutions. CTL technology is used at work sites where the level of unevenness of the surface is low and at work sites which are more accessible by forest roads. In areas with low forest road density, the total daily exposure to WBV would also increase due to the extended time of exposure during movement of the machine. To a certain extent, the operator may compensate for more demanding working conditions by increasing working speed. However, this may be realistically expected only in cases where the expected work effects and resulting payment are harmonised with working conditions. In addition to negative consequences on productivity (Nicholls et al. 2004), longer working days also increase exposure to WBV. In particular, this applies to the vibration dose value (VDV), where the exposure is summed over the entire workday. In addition to decreasing working time, job rotation is a reasonable measure for reducing exposure (Synwoldt and Gellerstedt 2003). Job rotation between harvester and forwarder operators alone is not suitable, since their work is too similar in terms of mental and physical loads and, as established in the study, in terms of exposure to noise and WBV. Design solutions must be directed in particular to reduce exposures of operators in both horizontal directions (*X* and *Y*) where exposure is highest. One possible solution is the use of seats that also absorb vibration in the horizontal direction (Jack and Oliver 2008).

Comparison of the study results with those of other research is hampered by the lack of adequate information on surface conditions. Since there are different terrain classifications around the world, the consistent use of a uniform international classification that could be based on one of the existing classifications, e.g. the widely used Swedish classification (Berg 1992), or a new classification based on LiDAR elevation data, would enable comparison of the results of different studies.

We believe that the greatest deficiency of the study is the lack of data on exposure to noise during unproductive time. Thus, for example, only one hammer strike on the metal body of a machine during maintenance work could be the reason for exceeding the daily exposure limits. Further research on operator exposure to noise should be based on several whole-day measurements, taking into account all potential sources of noise. Studies of exposure to WBV should also be carried out over the course of several working days, since the study showed that shocks may significantly increase VDV exposure to vibration.

5. Conclusions

The study showed that the exposure of harvester and forwarder operators to noise and WBV in karst areas is lower compared to exposure in harvesting systems with a lower degree of mechanization (Cheţa et al. 2018, Jack et al. 2010, Poje et al. 2016) and higher than exposure in fully mechanised CTL harvesting on flat terrains (Gerasimov and Sokolov 2014). The uncertainty related to this statement is a result of the lack of data on working conditions in the previous research and the time component, since over time technologies change, resulting in changes of the ergonomic characteristics of machines.

The exposure of operators to noise, when working in karst areas, does not exceed the limit for daily exposure to noise defined in the EU legislation. However, noise may disturb the operators and consequently affect productivity. If machines are not turned off when operators work outside the cabin, exposure may significantly increase and approach the limit value of daily exposure. The main sources of noise are ground roughness and the engine, and as a result, exposure is highest when machines are moving.

Contrary to noise exposure, WBV exposure during mechanised harvesting and forwarding exceeds the action value of daily exposure defined in the EU legislation. In general, exposure is highest when machines are moving, namely in the Y direction. When working with a crane installed on the harvester, exposure is highest in the X direction. Exposure in the Z direction is always the lowest. Individual shocks may significantly increase exposure to WBV.

Users and manufacturers of machines for mechanised logging and skidding of wood must continue to strive to reduce exposure to noise and WBV, since CTL technology is gradually replacing traditional technologies (i.e. chainsaw and ground-based skidding machines) due to its high productivity rate, higher level of safety, reduced need for employment and relatively higher independence from weather conditions, even in more demanding working conditions. Exposure to noise could be most effectively reduced by decreasing engine noise, thereby reducing operator exposure to noise in the cabin, and in terms of prevention, when the method of work is inappropriate, also outside the cabin. To reduce exposure to WBV while maintaining high productivity, further technical improvements of machines, careful selection of work sites and adapted work organisation are required.

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