

# Noise and Vibration Risk Assessment for the Operators of Crawler Loaders

Eleonora CARLETTI\*, Francesca PEDRIELLI

*C.N.R.-IMAMOTER*

*Institute for Agricultural and Earthmoving Machines of the National Research Council of Italy*

Via Canal Bianco, 28 – 44124 Ferrara, Italy

\*Corresponding Author e-mail: eleonora.carletti@cnr.it

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During work, earth-moving machines generate significant levels of noise and vibration that can be harmful for the operators; therefore the analysis of the noise and vibration conditions at the driving position is of great importance for the risk assessment. Compact loaders have become a pressing challenge as they are extremely hazardous referring to noise and vibration emissions, especially in their crawler version where further relevant noise and vibration are generated by the hard contact between track belt and ground.

This paper reports the results of investigations carried out on three crawler compact loaders in different operating conditions. The main purpose was to investigate the noise and vibration values transmitted to the operators in some working conditions and use these data to obtain reliable estimates of the exposure to noise, to whole-body and to hand-arm transmitted vibrations, as well as to evaluate the related risk levels. Vibration signals transmitted to the operator were acquired on the seat and the machine control lever in accordance with the procedures specified in ISO 2631-1 and ISO 5349-1. At the same time, noise signals were acquired at the operator's ear following the procedure reported in ISO 11201. Vibration signals were also acquired on the cabin floor with the main purpose to evaluate the effectiveness of the machine seats in reducing the vibration transmission. Finally, the noise and vibration exposure risks were evaluated on the basis of the health and safety requirements established in 2003/10/EC and 2002/44/EC Directives.

**Keywords:** noise exposure; whole-body vibration; hand-arm vibration; maximum exposure time; seat transmissibility.

## 1. Introduction

It is well known that noise and vibrations generated by earth-moving machines during work can have very harmful effects on operators. Studies performed in the United States of America on workers exposed to noise levels over 85 dB(A) showed that the kinds of occupation that present the highest risk for hearing damage in terms of numbers of over-exposed workers are manufacturing, transportation, military, construction, agriculture and mining (SUTER, 2007). From Australian data, it has been estimated that around 20.1% of the workforce regularly works with a noise exposure above 85 dB(A) and 9.4% above 90 dB(A); these estimates include also operators of mobile machines (WILLIAMS, 2013). A review of noise-induced hearing loss in Eastern European countries also reports sim-

ilar values (PAWLACZYK-LUSZCZYNSKA *et al.*, 2013). Noise exposure to these high noise levels over long periods of time produce permanent hearing loss but also short exposure to high noise can have detrimental effects on operators in terms of their working efficiency, excessive stress and higher probability to make mistakes and have accidents (KRISTIANSEN *et al.*, 2009; LI *et al.*, 2016; ERIKSSON *et al.*, 2018).

On the other hand, operators of mobile machines are also exposed to high vibration levels which can cause discomfort or pathological consequences depending on the exposure duration (VANERKAR *et al.*, 2008; BIÉRET *et al.*, 2009; MANSFIELD *et al.*, 2009; DE LA HOZ-TORRES *et al.*, 2017).

Two different types of vibration exposure mainly affect operators of these machines: the whole-body transmitted vibration (WBV) occurring as the body is

supported on a vibrating surface (seat/floor), and the hand-arm transmitted vibration (HAV) mainly involving the contact between the machine driving lever/steering wheel and the operator's hand-arm system. Exposure to WBV often combined with an incorrect prolonged driving posture can lead to musculoskeletal disorder and low back pains (BOVENZI, HULSHOF, 1999; BHIWAPURKAR *et al.*, 2018). On the other hand, exposure to HAV can lead to the risk of developing HAVS disease (hand-harm vibration syndrome) which includes circulatory, sensory and musculoskeletal disorders (BOVENZI, 2010; ESMAEELPOUR *et al.*, 2018; POOLE *et al.*, 2019). Many other studies can be found in literature reporting also other negative effects of exposure to vibration such as changes in blood pressure, heart rate, physical symptoms (tiredness, yawning, sleepiness, tired eyes, and absentmindedness), mental symptoms (irritation, loss of patience, distracted attention), and nervous symptoms (headache, backache, dizziness, nausea, and stiff shoulders) (ZIMMERMANN, COOK, 1997; ZIMMERMANN *et al.*, 1997; KUBO *et al.*, 2001; LJUNGBERG, NEELY, 2007).

This paper reports the results of an experimental study dealing with the noise and vibration conditions at the operator station of crawler compact loaders. This type of mobile machine has become very popular and the EU market expectations foresee a further growth of sales in the next years (Committee for European Construction Equipment, 2018). This major success is mainly due to the great operating flexibility of this machine: it can be equipped with a crawler or a wheeled locomotion system and it can be easily fitted with different attachments. Consequently, it becomes suitable to a variety of different tasks in very different environments: from building restorations in urban areas to road maintenance works, or to mining and construction industry works. Unfortunately, in the face of so great versatility, compact loaders turn out to be the worst mobile machines referring to noise and vibration emission levels. The operator station, indeed, is just over the engine compartment and there is not enough room for the implementation of suitable isolation solutions. Therefore, operators are exposed to high levels of noise and vibration and the situation could be even worse for the crawler version of these machines, due to the effects of the hard contact between track belt and ground.

The main purpose of this study is to investigate in depth the noise and vibration values transmitted to the operators in some working conditions and use these data to obtain reliable estimates of the noise and vibration exposure values as well as the relevant risk for the operators. The experimental assessment of the exposure to noise and vibration turns out to be of particular interest; very often, indeed, the assessment of the exposure values for these machines are not based on actual measurements but rather on the information provided by machine manufacturers according to the provisions of the "Machinery Directive" (Directive 2006/42/EC). Unfortunately, these declared values generally refer to simulated working conditions and then are lower than the values really measured, leading to underestimation of the risk. Referring to the HAV values, a specific Technical Report was published by the European Committee for Standardization (CEN/TR 15350, 2013) in order to limit the effects of not reliable data in the assessment of the risk exposure. This report proposes the use of multiplication factors but unfortunately it does not solve the problem, leading to values that overestimate the measured ones (RIMMEL *et al.*, 2008).

## 2. Relevant legislation

Nowadays in Europe two directives are in force regarding the protection of workers against occupational hazards due to noise and vibration in the workplace: the Directive 2003/10/EC on the minimum health and safety requirements regarding the exposure of workers to the risks arising from noise and the Directive 2002/44/EC on the minimum health and safety requirements regarding the exposure of workers to the risks arising from hand-arm and whole-body vibrations.

As to Directive 2003/10/EC, it introduces measures and obligations for employers in order to protect workers from risks to their health and safety arising from exposure to noise. It defines the physical parameters serving as risk predictors (the daily noise exposure level and the peak sound pressure value) and it defines the threshold values reported in Table 1.

As to Directive 2002/44/EC, it introduces measures protecting workers from risks to their health and safety arising from exposure both to whole-body and hand-arm vibrations. For this purpose it sets the

Table 1. Noise exposure limit values and action values (Directive 2003/10/EC).

Reference parameter	$L_{EX, 8h}$ [dB(A)]	$p_{peak}$ [Pa]	$Lp_{peak}$ (ref. 20 $\mu$ Pa) [dB(C)]
Lower exposure action value	80	112	135
Upper exposure action value	85	140	137
Exposure limit value	87	200	140

threshold values reported in Table 2 for the physical parameters defined as risk predictors: the daily exposure limit values above which workers must not be exposed and the daily exposure action values above which vibration control measures have to be taken.

Table 2. Vibration exposure limit values and action values (Directive 2002/44/EC).

Reference parameter	$A(8)_{HAV}$ [m/s <sup>2</sup> ]	$A(8)_{WBV}$ [m/s <sup>2</sup> ]
Daily exposure action value	2.5	0.5
Daily exposure limit value	5	1.15

For both European directives, employers are allowed to perform the risk assessment of noise and vibration not only on the basis of measurement results but also on the basis of available data and information. This peculiarity makes weaker the effectiveness of these directives as it opens the possibility of underestimating the real vibration risk when using the declared values.

In some countries, however, the national law has set stricter requirements than those of the directive and many complementary methods can be found for the control of exposure to noise and vibration.

### 3. Material and methods

#### 3.1. Machines under test

A series of noise and vibration measurements were performed on three crawler compact loaders from different brands (machines A, B and C). All these machines were new, had similar mechanical power (45–50 kW) and a 4 stroke internal combustion engine. They were all tested in their standard configurations, without any optional items. Besides the typical sources of noise and vibration of compact loaders (engine, cooling system, transmission system), the crawler version of these machines has relevant sources of vibration strictly related to the specific locomotion system. They are mainly generated by the periodic impact of the driving sprocket on the moving track belt when the vehicle is in motion; in addition, significant vibrations can also be generated by the interactions between the track belt and other mechanical parts: the idler wheels, the support roller, as well as the ground.

#### 3.2. Operating conditions

The operating conditions for noise and vibration tests were accurately chosen taking into account two main requirements:

- **repeatability:** to guarantee that the repeated noise and vibration measurements on the different machines are performed in the same operating conditions in order to have a meaningful comparison of the results;

- **representativeness:** to have operating conditions as close as possible to some real phases of the typical work of compact loaders.

Consequently, the “forward travel mode” at constant speed was chosen as it simulates one phase of the real work cycle of a loader and can be easily repeated, as suggested by ISO 6395; in addition, for each machine, different test site surfaces and machine arrangements were chosen for the repetition of the noise and vibration measurements:

- **smooth surface:** a surfaced path, 1000 m long, simulating the typical ground on which the machine moves when it works in urban environments;
- **rough surface:** a standardised artificial track, 100 m long, simulating extreme working conditions on rocky irregular terrains. The artificial track fulfils the provisions of ISO 5008 and consists of two parallel strips formed of wooden slats. The movement of the crawler machine on this artificial track causes very extreme vibration conditions but its use turns out to be particularly useful for comparative purposes;
- **with ballast:** machine configuration with a 870 kg ballast in the bucket (simulating the typical transportation of material);
- **without ballast:** machine configuration without any ballast in the bucket (simulating the movement without any material).

In all the above conditions, except on the standardised artificial track, noise and vibration measurements were repeated at two constant velocities: at low velocity (in the range 5–7 km/h, depending on the machine) and at high velocity (in the range 11–13 km/h, depending on the machine). On the standardised artificial track, measurements were performed only at low velocity due to the extreme vibration conditions that would be dangerous for the operator safety and the machine integrity.

In each operating condition the acquisitions were repeated three times to detect the variability of the signal. The acquisition time was the same for all the measurements (42 s) and this was imposed by the length of the artificial track. In order to minimise the influence of the operator driving “style” on the generated vibration levels (COSTA, AREZES, 2009), the machines were always driven by the same operator, having significant experience in driving these types of vehicles.

#### 3.3. Noise and vibration measurements

An LMS acquisition system (Siemens Industry Software NV, Leuven, Belgium) with two 8-channel modules (V8-E LMS SCADAS) was used for noise and vibration acquisitions.

Sound pressure levels were measured using two 1/2” microphones (class 1) placed at the right and left ears

of the operator according to the procedure indicated in ISO 11201 standard. All the noise measurements were performed simultaneously to the vibration measurements.

The whole body vibration signals were acquired following the procedure described in ISO 2631-1 standard. An ICP tri-axial accelerometer (100 mV/g sensitivity) was oriented according to the reference system indicated in the standard (longitudinal axis  $x$ , transversal axis  $y$ , vertical axis  $z$ ). It was inserted in a semi-rigid rubber plate and fixed on the seat surface by adhesive tape. The acceleration values over time were recorded and the frequency content was limited to the range 0–400 Hz.

The hand-arm vibrations were measured following the procedure described in ISO 5349-1 standard. An ICP tri-axial accelerometer (100 mV/g sensitivity) was rigidly fixed to the control lever by a specific connector. The same coordinate system as that of the WBV accelerometer was chosen as the control lever was rigidly fixed to the cabin frame (see Fig. 1a). The acceleration values over time were recorded and the frequency content was limited to the range 0–1000 Hz.

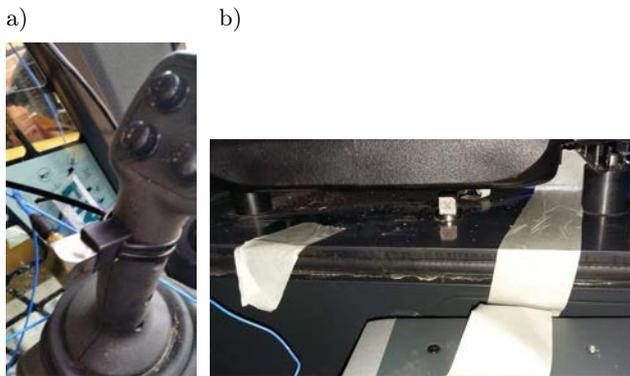


Fig. 1. Accelerometer position on the control lever (a) and on the cabin floor (b).

A further accelerometer (100 mV/g sensitivity) was fixed on the cabin floor (see Fig. 1b) at the base of the seat by a magnet, with the main purpose to evaluate the effectiveness of the machine seats in reducing the vibration transmission.

The time histories of the acceleration signals on the control lever, the seat surface and the cabin floor were acquired without any frequency-weighting for each axis.

#### 4. Data analysis

Data analysis and elaborations were performed by the LMS Test.Lab software (version 16.1, Siemens Industry Software NV, Leuven, Belgium) with the following main targets:

- the analysis of the noise levels at the operator's ear position and the HAV and WBV values;

- the assessment of the daily noise and vibration exposure values for each operating condition and the assessment of the related risk level;
- the assessment of the damping capability of the seats (using the "Seat Effective Amplitude Transmissibility – SEAT" calculated along each axis);
- the assessment of the maximum allowed exposure time resulting from the combined exposure to noise and vibration.

##### 4.1. Noise

For each operating conditions, the C-weighted peak sound pressure level and the A-weighted equivalent sound pressure level ( $L_{Aeq}$ ) at the left and right ears were recorded. For both parameters the highest value (left/right) was taken.

As to noise exposure, the provisions indicated in the Directive 2003/10/EC apply. In the hypothesis of an 8-hour work-shift with the same operating condition, the general equation (Eq. 1) applicable to several tasks ( $j = 1, \dots, N$ ) with a  $L_{Aeq,j}$  level and a  $T_j$  duration:

$$L_{EX, 8h} = 10 \lg \sum_j \frac{T_j \cdot 10^{\frac{L_{Aeq,j}}{10}}}{T_{ref}} \quad [\text{dB(A)}] \quad (1)$$

is strongly simplified and the  $L_{Aeq}$  level of that operating condition becomes equal to the daily noise exposure level ( $L_{EX, 8h}$ ) in dB(A).

##### 4.2. Hand-arm vibration levels

For the assessment of the hand-arm transmitted vibration levels to which the operator is exposed, the provisions indicated in the Directive 2002/44/EC apply. The acceleration components along the three orthogonal axes were frequency weighted (Eq. (2)) according to the sensitivity curves reported in the ISO 5349-1 standard in order to reflect the assumed importance of different frequencies:

$$a_{hwi} = W_h \sqrt{\frac{1}{T} \int_0^T a_i^2(t) dt} \quad [\text{m/s}^2], \quad (2)$$

where  $i$  is the subscript indicating the axis ( $i = x, y, z$ );  $W_h$  is the weighting factor given in the ISO 5349-1;  $T$  is the duration of the measurement (s);  $a_i$  is the rms acceleration along the  $i$  axis ( $\text{m/s}^2$ ).

The injury potential of hand-arm transmitted vibration is therefore calculated in terms of the vector sum of the components previously calculated with Eq. (2):

$$a_{hwv} = \sqrt{(k_x a_{hwx})^2 + (k_y a_{hwy})^2 + (k_z a_{hwz})^2} \quad [\text{m/s}^2] \quad (3)$$

with  $k_x = k_y = k_z = 1$  under the assumption that vibration is equally detrimental in each of the three directions.

As to Annex A of Directive 2002/44/EC, the assessment of the level of exposure to hand-arm vibration is based on the calculation of the daily exposure value normalised to an eight-hour reference period,  $A(8)_{\text{HAV}}$ , using Eq. (4):

$$A(8)_{\text{HAV}} = \sqrt{\frac{\sum_j (a_{hwvj}^2 T_j)}{T_{\text{ref}}}} \quad [\text{m/s}^2], \quad (4)$$

where  $a_{hwvj}$  is the vector sum of the accelerations for the  $j$ -th task;  $T_j$  is the exposure time for the  $j$ -th task.

In the hypothesis of an 8-hour work-shift with the same operating condition, Eq. (4) strongly simplifies and the acceleration vector sum of that operating condition becomes equal to the daily exposure value  $A(8)_{\text{HAV}}$ .

#### 4.3. Whole body vibration levels

For the assessment of the whole body vibration levels to which the operator is exposed, the provisions indicated in the Directive 2002/44/EC apply. To take into account the effect of the WBV exposure to human body, the frequency content of the vibration acceleration was weighted with the human vibration sensitivity curves reported in ISO 2631-1.

The evaluation of the weighted root-mean-square acceleration expressed in metres per second squared ( $\text{m/s}^2$ ) was calculated in accordance to Eq. (5):

$$a_{wi} = W_i \sqrt{\frac{1}{T} \int_0^T a_i^2(t) dt} \quad [\text{m/s}^2], \quad (5)$$

where  $i$  is the subscript indicating the axis ( $i = x, y, z$ );  $W_i$  is a dimensionless weighting factor given in ISO 2631-1: for  $i = x$  and  $i = y$ ,  $W_i = W_d$ ; for  $i = z$ ,  $W_i = W_k$ ;  $T$  is the duration of the measurement (s);  $a_i(t)$  is the acceleration acquired for the  $i$  axis ( $\text{m/s}^2$ ).

As to Annex B of Directive 2002/44/EC, the assessment of the level of exposure to whole-body vibration is based on the highest (rms) value of the frequency-weighted accelerations determined on three orthogonal axes ( $1.4a_{wx}$ ,  $1.4a_{wy}$ ,  $a_{wz}$  for a seated or standing worker), as reported in Eq. (6):

$$a_w = \max_i \{k_i \cdot a_{wi}\} \quad [\text{m/s}^2], \quad (6)$$

where  $i$  is the subscript indicating the axis ( $i = x, y, z$ );  $k_i$  is a dimensionless multiplying factor set at 1.4 for the  $x$  and  $y$  axes and set at 1 for the  $z$  axis.

Then, Directive 2002/44/EC requires the calculation of the daily exposure value normalised to an eight-hour reference period,  $A(8)_{\text{WBV}}$ , calculated with a formula equal to that reported in Eq. (4) with  $a_{hwvj}$  replaced by  $a_{wj}$ . In the hypothesis of an 8-hour work-shift with the same operating condition, the general

equation applicable to several tasks with a  $a_{wj}$  value and a  $T_j$  duration, is strongly simplified and the acceleration value of that operating condition becomes equal to the daily exposure value  $A(8)_{\text{WBV}}$  as shown in Eq. (7):

$$A(8)_{\text{WBV}} = \sqrt{\frac{\sum_j (a_{wj}^2 T_j)}{T_{\text{ref}}}} \quad \xrightarrow{\text{for } j=1} \quad A(8)_{\text{WBV}} = a_{w1} \quad [\text{m/s}^2]. \quad (7)$$

#### 4.4. Seat Effective Amplitude Transmissibility (SEAT)

Further investigations were performed in order to better evaluate the amount of vibration transmitted to the operator through the seat. In particular, the Seat Effective Amplitude Transmissibility (SEAT) was calculated along each axis ( $x, y, z$ ) as the ratio between the weighted acceleration measured on the seat surface (output) and the corresponding value measured on the cabin floor (input), in the frequency range 0–80 Hz:

$$T_i = \frac{a_{wi,S}}{a_{wi,F}}, \quad (8)$$

where  $i$  is the subscript indicating the axis ( $i = x, y, z$ );  $a_{wi,S}$  is the weighted root-mean-square acceleration on the seat cushion along the  $i$  axis;  $a_{wi,F}$  is the weighted root-mean-square acceleration on the cabin floor along the  $i$  axis.

In principle, the SEAT is a parameter which intrinsically characterise the seat (GRIFFIN, 1986; NIEKERK *et al.*, 2003). This is true if the SEAT is calculated in laboratory tests using the ISO 10326-1 standard but this is almost never true when it is calculated from in-field measurements. The SEAT values, really, depend on the frequency content of the vibrations measured on the cabin floor and therefore on the operating conditions (kind of activity, surface irregularities, speed, etc.) and on the vehicle characteristics, such as suspension system and seat settings. In addition, the variability of the SEAT values depends also on several aspects related to the driver: the weight, the posture assumed while performing a given activity, as well as voluntary and involuntary movements (PERETTI *et al.*, 2019). However, although their many limitations, the SEAT values turn out to be very important when the purpose is to compare the amount of transmitted vibrations through the seat on different machines in the same conditions. SEAT values  $<1$  indicate that the seat attenuates the vibrations transmitted from the floor while values  $>1$  indicate that the seat amplifies them.

### 5. Results

#### 5.1. Noise exposure

Table 3 and Fig. 2 show the daily noise exposure levels ( $L_{EX,8h}$ ) for all the machines and the operating conditions. Taking into account that the measurements were repeated three times, the levels reported are the arithmetic mean between the three repetitions as well as the corresponding standard deviation levels.

On the smooth surface the  $L_{EX,8h}$  levels are always higher than the lower exposure action value but lower than the upper exposure action value. At low velocity  $L_{EX,8h}$  levels range from 80.4 dB(A) to 81.9 dB(A) and no significant differences are observed between the “with/without” ballast conditions.  $L_{EX,8h}$  significantly grows as the speed increases with regard to both the “with/without” ballast configurations. The levels range from 83.7 dB(A) to 84.4 dB(A) in the condition “without ballast” and from 82.8 dB(A) to 85.0 dB(A) in the condition “with ballast”. Only for machine A the difference between the “with/without” ballast conditions is significant in terms of  $L_{EX,8h}$  level and the condition “with ballast” shows a lower noise exposure level.

On the rough surface the measurements were performed only at the lowest velocity due to the extremely high vibrations generated by the impact be-

tween the machine track belt and the wooden track strips. Despite this low velocity, the noise exposure levels are generally very high. Only machine A shows levels lower than the upper exposure action value, while machines B and C have both  $L_{EX,8h}$  levels almost always well over the noise exposure limit. It is worth noting that significant differences can be found between the “with/without” ballast conditions, with  $L_{EX,8h}$  levels much higher when the machine has a ballast in the bucket.

In terms of noise risk, on average, machine A shows lower exposure levels and then guarantees safer conditions than machines B and C; this different behaviour has a significant impact especially in extreme working conditions.

The variability of data between the three repetitions is always very limited, with a standard deviation ranging from 0.1 dB to 0.7 dB.

#### 5.2. HAV exposure

According to the procedure indicated in ISO 5349-1, the HAV exposure values  $A(8)$  are calculated assuming that vibration in each of the three directions  $x, y, z$  is equally detrimental and then the same multiplying factor  $k = 1$  can be used to calculate the vector sum level from the vibration components along the three axes.

Table 3. Mean level (and standard deviation) of the  $L_{EX,8h}$  [dB(A)].

Surface	Velocity	Ballast	Machine		
			A	B	C
Smooth surface	low	without	81.9 (0.1)	80.6 (0.3)	80.4 (0.3)
		with	81.5 (0.7)	81.1 (0.3)	80.8 (0.4)
	high	without	83.8 (0.1)	84.4 (0.5)	83.7 (0.2)
		with	82.8 (0.1)	85.0 (0.3)	84.1 (0.1)
Rough surface	low	without	83.5 (0.3)	88.4 (0.4)	85.6 (0.5)
		with	84.5 (0.5)	92.6 (0.3)	90.9 (0.4)

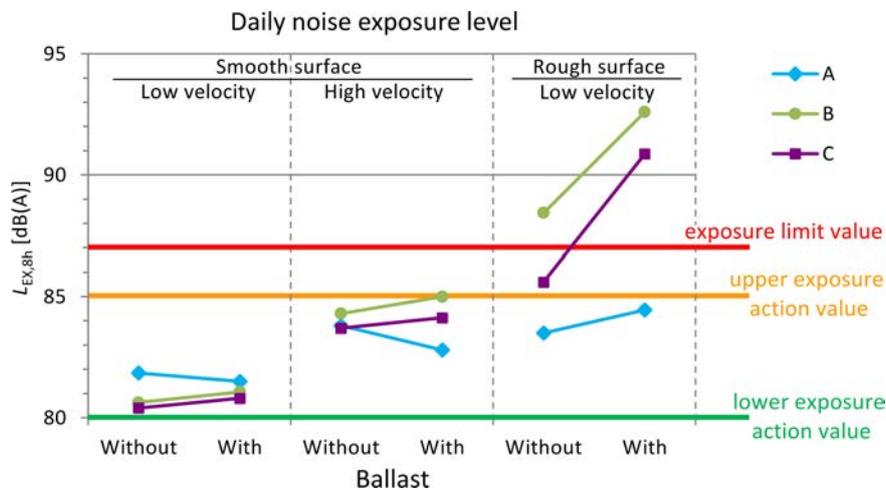


Fig. 2. Daily noise exposure levels for different operating conditions.

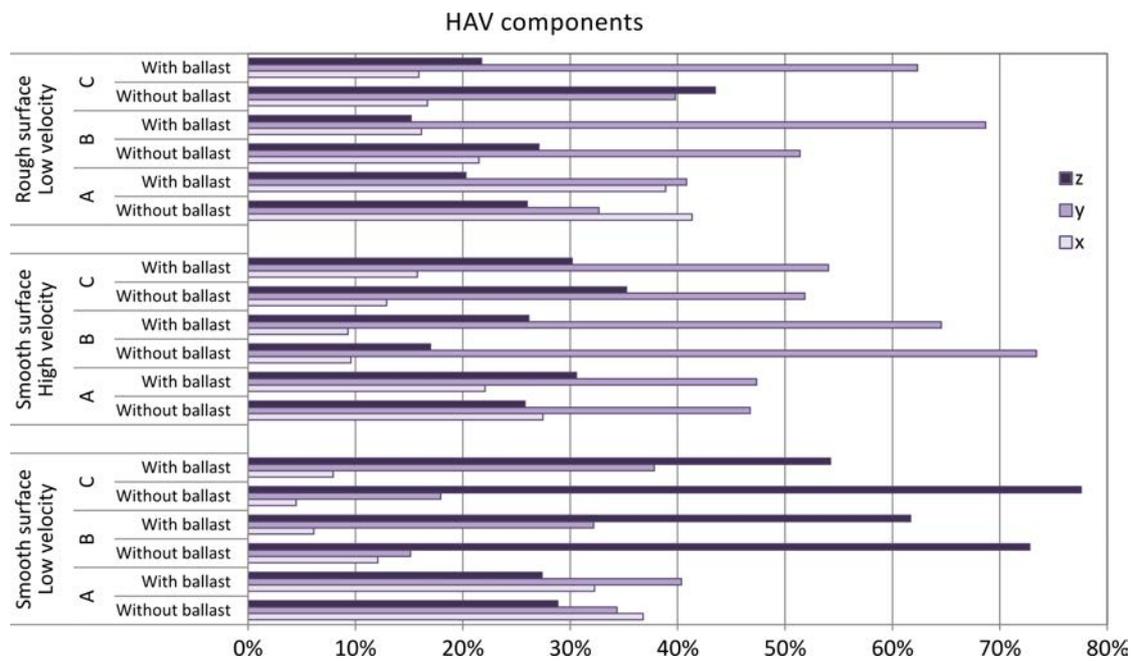


Fig. 3. Percentage distribution among the axes for the HAV accelerations.

Results of this study showed that the above hypothesis is not always satisfied for these kinds of machines. The balance among the three vector components is much more evident in the graphical representation given in Fig. 3 where the percentage contribution of each component to the overall acceleration value is shown for all the operating conditions. The vibration components along  $x$ ,  $y$ ,  $z$  give a similar contribution to HAV exposure values only for machine A, especially at low velocity, both on smooth and rough surfaces. For machine B and C, on the contrary, it is evident that the  $z$  component (vertical axis) is always predominant (from 54% to 78%) on the smooth surface at low velocity and the  $y$  component (transversal axis) is almost always predominant (from 40% to 73%) in all the other operating conditions.

Table 4 and Fig. 4 show the daily HAV exposure values ( $A(8)_{HAV}$ ) for all the machines and the operating conditions. The values reported are the square root of the arithmetic mean of the squares of  $a_{wv}$  for the three repetitions as well as the corresponding standard deviation values.

On the smooth surface it is worth noting that the  $A(8)_{HAV}$  values significantly decrease with the increase in speed with regard to both the “with/without ballast” configurations. Consequently, at low velocity the exposure values are always higher than the exposure action value (except for few cases); in the configuration “without ballast” the values range from  $2.31 \text{ m/s}^2$  to  $2.97 \text{ m/s}^2$  while in the configuration “with ballast” from  $1.95 \text{ m/s}^2$  to  $4.31 \text{ m/s}^2$ . On the contrary, at high velocity the  $A(8)_{HAV}$  values are always below the exposure action value; in the configuration “without ballast” the values range from  $1.60 \text{ m/s}^2$  to  $1.92 \text{ m/s}^2$  while in the configuration “with ballast” from  $1.66 \text{ m/s}^2$  to  $2.48 \text{ m/s}^2$ .

On the rough surface, as expected, the  $A(8)_{HAV}$  values become extremely high, always significantly higher than the exposure action value. Furthermore, for machines B and C the  $A(8)_{HAV}$  values are always much higher than the exposure limit value:  $7.70 \text{ m/s}^2$  and  $7.93 \text{ m/s}^2$  “without ballast”;  $12.29 \text{ m/s}^2$  and  $14.95 \text{ m/s}^2$  “with ballast”.

Table 4. Mean value (and standard deviation) of the  $A(8)_{HAV}$  [ $\text{m/s}^2$ ].

Surface	Velocity	Ballast	Machine		
			A	B	C
Smooth surface	low	without	2.84 (0.22)	2.31 (0.12)	2.97 (0.80)
		with	1.95 (0.17)	4.31 (0.18)	3.30 (0.94)
	high	without	1.78 (0.11)	1.60 (0.03)	1.92 (0.14)
		with	1.66 (0.12)	1.81 (0.10)	2.48 (0.11)
Rough surface	low	without	4.15 (0.18)	7.70 (0.07)	7.93 (0.27)
		with	5.12 (0.21)	14.95 (0.46)	12.29 (0.2)

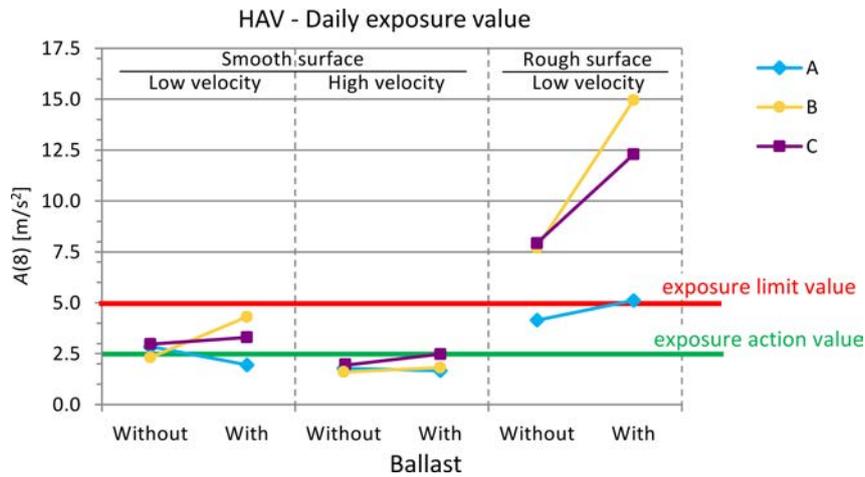


Fig. 4. Daily HAV exposure values for different operating conditions.

In terms of HAV risk, on average, machine A shows lower exposure values and then guarantees safer conditions than machines B and C, in all the tested working conditions. This different behaviour has significant impact especially in extreme working conditions.

As to the variability of data among the three repetitions, the standard deviation itself could be meaningless. More significant could be the coefficient of variation, defined as the ratio between the standard deviation and the mean value, often expressed as a percentage and also known as relative standard deviation (RSD). As shown in Table 5, the RSD ranged from 1% to 28.3% with the lowest values on the rough surface (from 1% to 4.4%) and the highest values on the smooth surface at low velocity (from 4.2% to 28.3%). The cells have a background colour with dif-

ferent grades of shades to help detecting the variability of figures: the higher the % value, the darker the background colour.

5.3. WBV exposure

Table 6 and Fig. 5 show the average (square root of the arithmetic mean of the squares) over the 3 repetitions for the  $A(8)_{WBV}$  exposure values for each machine and operating conditions, calculated according to Eq. (7). In the same table the standard deviations are also reported (in brackets). The relative standard deviations (RSD) ranged from 0.5% (machine C “with ballast” on the rough surface) to 58.3% (machine C “with ballast” on the smooth surface at low velocity).

Table 5. Relative standard deviation of the  $A(8)_{HAV}$ .

Surface	Velocity	Ballast	Machine		
			A [%]	B [%]	C [%]
Smooth surface	low	without	7.8	5.0	26.9
		with	8.7	4.2	28.3
	high	without	6.4	1.7	7.1
		with	7.3	5.6	4.4
Rough surface	low	without	4.4	1.0	3.4
		with	4.2	3.0	1.6

Table 6. Mean value (and standard deviation) of the  $A(8)_{WBV}$  [m/s²].

Surface	Velocity	Ballast	Machine		
			A	B	C
Smooth surface	low	without	0.27 (0.07)	0.25 (0.04)	0.29 (0.02)
		with	0.23 (0.02)	0.37 (0.01)	0.64 (0.37)
	high	without	0.17 (0.01)	0.26 (0.01)	0.33 (0.01)
		with	0.20 (0.02)	0.33 (0.02)	0.47 (0.02)
Rough surface	low	without	0.55 (0.02)	1.38 (0.08)	1.36 (0.27)
		with	0.65 (0.10)	2.17 (0.32)	1.62 (0.01)

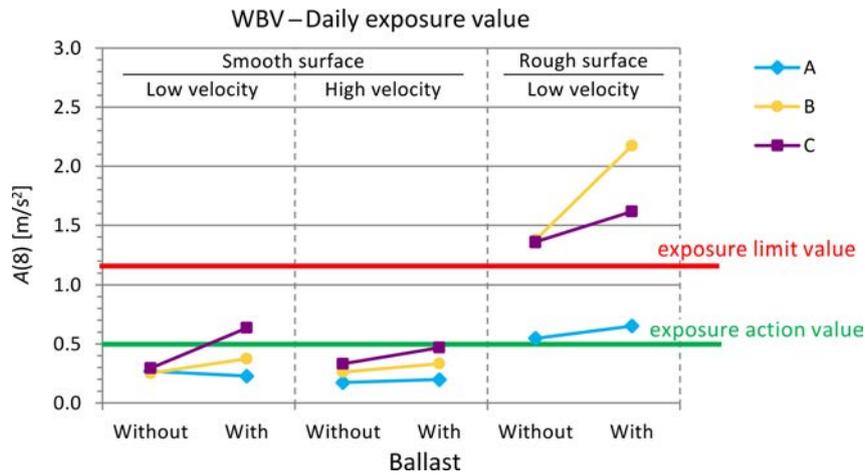


Fig. 5. Daily WBV exposure values for different operating conditions.

On the smooth surface, the  $A(8)_{WBV}$  values are always lower than the exposure action value, with the only exception of machine C, at low velocity, “with ballast”, where  $A(8)_{WBV}$  is equal to  $0.64 \text{ m/s}^2$ . At low velocity  $A(8)_{WBV}$  values range from  $0.23 \text{ m/s}^2$  to  $0.64 \text{ m/s}^2$  while at high velocity from  $0.17 \text{ m/s}^2$  to  $0.47 \text{ m/s}^2$ .  $A(8)_{WBV}$  values did not show significant variations as the velocity increases.

On the rough surface only machine A shows values slightly above the exposure action value. The other two machines B and C have  $A(8)_{WBV}$  values above the exposure limit value either “without ballast” ( $1.38 \text{ m/s}^2$  and  $1.36 \text{ m/s}^2$ , respectively) or “with ballast” ( $2.17 \text{ m/s}^2$  and  $1.62 \text{ m/s}^2$ , respectively). Finally, it is worth noting also that  $A(8)_{WBV}$  values are generally higher “with ballast” than “without ballast”; this behaviour being more prominent on the rough surface.

In terms of WBV risk, on average, machine A shows lower exposure values and then guarantees safer conditions than machines B and C, in all the tested working conditions. This different behaviour has a significant impact especially in extreme working conditions.

#### 5.4. Seat performance

In compact loaders the seat plays an important role in reducing the vibration transmitted from the cabin to the operator’s back and then to reduce the risk due to the exposure to WBV values. The different behaviour of the tested machines referring to the transmission of WBV vibration and the fact that all of them mounted the same type of seat (pneumatic suspended seat), it makes relevant the comparison of their performances. In this respect, a deeper investigation was performed on the machines under test with the purpose to quantify the amount of vibration energy transmitted from the cabin floor to the seat for each machine. For this purpose, the single-number index qualifying the seat isolation efficiency (SEAT) was used (Eq. (8)). Ac-

ording to its definition, this index takes into account the three main factors determining the vibration isolation effectiveness of a seat: the input vibration spectrum, the seat transfer function and the human response to the vibration. In this study the SEAT index was calculated along each axis ( $x, y, z$ ) and the averaged rms transmissibility values along each axis are shown in Table 7 and Fig. 6, in all the different operating conditions.

Table 7. Averaged rms transmissibility values for different operating conditions.

Surface	Velocity	Ballast	Axis	Machine		
				A	B	C
Smooth surface	low	without	$x$	0.68	1.51	1.19
			$y$	1.38	1.13	1.36
			$z$	0.08	0.36	0.45
		with	$x$	0.77	0.95	1.06
			$y$	1.26	1.67	1.36
			$z$	0.38	0.32	0.71
	high	without	$x$	0.40	1.56	1.64
			$y$	1.36	1.34	1.19
			$z$	0.22	0.45	0.43
		with	$x$	0.52	1.32	0.85
			$y$	1.40	1.37	1.10
			$z$	0.20	0.43	0.35
Rough surface	low	without	$x$	0.81	1.31	1.42
			$y$	0.82	1.35	1.26
			$z$	0.17	0.27	0.30
		with	$x$	0.93	1.23	1.29
			$y$	0.85	1.61	0.97
			$z$	0.15	0.27	0.23

The transmissibility values along  $z$  axis are always less than 1 (from 0.08 to 0.71 depending on the machine). Values along  $y$  axis are almost always higher

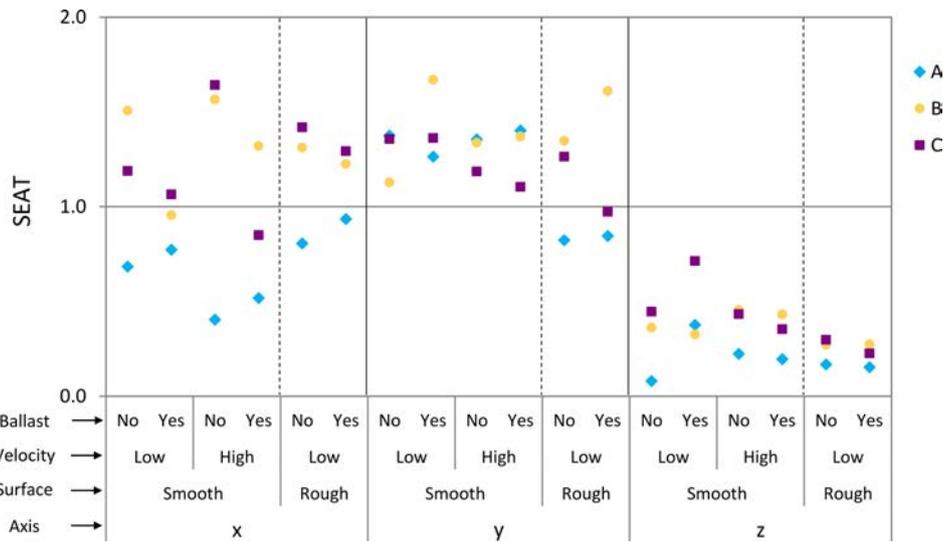


Fig. 6. SEAT transmissibility values along each axis.

than 1 and range from 0.82 to 1.67. Referring to the values along  $x$  axis, machine A has always values less than 1 (ranging from 0.40 to 0.93) while the other machines have values ranging from 0.95 to 1.64.

The comparison of the SEAT values confirm the effectiveness of the seat suspension system of all the machines in reducing the acceleration values along the  $z$  axis but also the lack of damping, or even the increase, of the  $x$  and  $y$  components. On the other hand, a previous study from the authors showed that in some working conditions the accelerations measured on the cabin floor had their highest values on the horizontal plane ( $x$  and  $y$  axes) rather than on the vertical plane ( $z$  axis) (CARLETTI, PEDRIELLI, 2018) and the same result was also found by other studies on vibration transmitted by tractors during translations on different kind of surfaces (DEBOLI *et al.*, 2017; PERETTI *et al.*, 2019). Consequently, vibration components along  $x$  and  $y$  axes should not be neglected but rather carefully considered as they are very harmful for the human body (MANSFIELD, MAEDA, 2011). There is a critical need to develop more effective controls to address non-vertical WBV exposures, especially given the fact that these non-vertical components have been associated with harmful effects such as increased biomechanical loading, subjective discomfort, head acceleration, and reduced visual acuity (GRIFFIN, BRETT, 1997; HIROSE *et al.*, 2013; HORNG *et al.*, 2015).

### 5.5. Maximum exposure time

The above results show that none of these crawler machines could assure the operators of safe working conditions when working in an 8-hour work-shift. The noise and vibration exposure levels, indeed, are generally higher than the established action values and very often vibration values are also higher than the limit

values, especially in extreme working conditions (artificial track). Without any redesign of these machines so as to give priority in reducing the risks at source, the reduction of the risk arising from exposure to noise and vibration can be obtained only by reducing the time of exposure in order to guarantee exposure levels below the action values.

Table 8 shows the maximum exposure time, in hours, that allows observance of the action values for the noise at the operator's ear (80 dB(A)) as well as for the vibrations transmitted to the hand-arm and the whole-body systems ( $2.5 \text{ m/s}^2$  and  $0.5 \text{ m/s}^2$ , respectively). The figures in bold are those determining the maximum exposure time resulting when the combined exposure to the different physical agents has to be considered. It is worth noting that the purpose of Table 8 is to give an overview of the problem and for this reason no uncertainty analysis was performed on the measured noise and vibration exposure values. However, in real cases, each legal decision aimed at reducing the working time requires the assessment of the "expanded uncertainty"  $U$  which defines an interval about the averaged exposure value within which measured exposure values can be confidently expected to lie. The value of the "expanded uncertainty" is obtained by multiplying the "combined standard uncertainty" (which includes the measurement uncertainty value) by the desired coverage factor.

Looking at the maximum exposure time for all the operating conditions, the strictest time restriction is never determined by the whole body vibration. It is given by the noise exposure (9 cases out of 18) or by the hand-arm vibration exposure (9 cases out of 18).

As to the different surfaces, figures in Table 8 reveal that on the smooth surface at high velocity, noise is the dominant physical agent, with values ranging from 2.53

Table 8. Maximum exposure time determined by different risk factors (NOISE, HAV, WBV).

Surface	Velocity	Ballast	Machine	$T_{\max\text{-NOISE}}$ [h]	$T_{\max\text{-HAV}}$ [h]	$T_{\max\text{-WBV}}$ [h]
Smooth surface	low	without	A	<b>5.23</b>	6.19	
			B	<b>6.91</b>		
			C	7.30	<b>5.66</b>	
		with	A	<b>5.66</b>		
			B	6.26	<b>2.70</b>	
			C	6.65	<b>4.58</b>	4.96
	high	without	A	<b>3.33</b>		
			B	<b>2.97</b>		
			C	<b>3.41</b>		
		with	A	<b>4.20</b>		
			B	<b>2.53</b>		
			C	<b>3.09</b>		
Rough surface	low	without	A	3.57	<b>2.91</b>	6.68
			B	1.15	<b>0.84</b>	1.05
			C	2.20	<b>0.80</b>	1.08
		with	A	2.87	<b>1.91</b>	4.71
			B	0.44	<b>0.22</b>	0.42
			C	0.66	<b>0.33</b>	0.77

hours to 4.20 hours, while vibrations (both HAV and WBV) have acceleration values even lower than the action value and therefore do not impose any limitation in time. On the rough surface, HAV is the dominant physical agent with values equal to 1.91 hours and 2.91 hours for machine A (“with” and “without ballast”, respectively) and ranging from 0.22 hours to 0.84 hours for machine B and C. These latter values are definitely low and they impose the work under these extreme conditions (simulated by the rough surface) to be limited to no more than 13 minutes to 50 minutes.

As to the different machines, if the results of one condition (on smooth surface, at low velocity “without ballast”) are excluded, a clear trend appears: machine A has the highest maximum exposure times and machine B has the lowest ones. In terms of exposure times the presence of ballast causes a decrease in allowable exposure times with respect to the configuration “without ballast”, in almost all the conditions.

## 6. Conclusions

This study highlights how noise and vibrations constitute a significant risk factor for the health of the operators and how its amount varies significantly. None of the tested crawler machines assured safe working conditions in their standard configurations when working in an 8-hour work-shift.

Noise and vibration levels/values, indeed, were generally higher than the established action levels/values and on the rough surface they were very often also higher than the limit levels/values. The SEAT values

confirmed the effectiveness of the seat suspension system of all the machines in reducing the acceleration values along the  $z$  axis but also the negative effect of the seat on the vibration components along the  $x$  and  $y$  axes. The exposure to whole body vibrations was less critical than the exposure to noise and hand-arm vibrations: the strictest time restrictions, indeed, were never given by WBV values but rather by noise levels for almost all the tests on the smooth surface and by HAV values for all the tests on the rough surface.

It is authors’ opinion that the risk assessment should be based on experimental data acquired in the actual scenario rather than on data provided by manufacturers or from online databases which often underestimate noise and vibration values. Additionally, there is a need for joint scientific efforts to clarify the prerequisite for adequate risk assessments, especially in the case of HAV and WBV. The evaluation methods concerning health risks, comfort and performance due to WBV, described in ISO 2631-1 (frequency weighting, multiplying factors) and used in application of the EU directive, are currently under critical discussion. Moreover, in the field of HAV, more research is needed to check the validity of the frequency weighting curves and to take into account co-factors such as the coupling between hand and tool.

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