The influence of the operator driving style in whole-body vibration exposure from wheel loaders in a limestone quarries

Gli effetti dello stile di guida nell’esposizione a vibrazioni del corpo intero nella conduzione di pale gommate per l’estrazione di calcare

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Introduction

Occupational exposure to whole-body vibration (WBV) is a widespread occupational risk factors that may cause adverse health effects or discomfort on operators driving machinery. It has been estimated that, in 2010, the 22.5% of the EU27 workers (21.6% for Italy) was exposed to mechanical vibrations for at least a quarter of their working times [Eurofound, 2010]. Approximately 4 to 7% of workers in Canada, United States and some European countries are exposed to potentially harmful whole-body vibration levels [Bovenzi, 1996]. The most widely accepted impact of exposure to WBV is an increased risk for low back pain [Seidel and Heide, 1986; Seidel, 1993; Wikström et al., 1994; Bovenzi, 1996], sciatic pain and degenerative changes in the spinal system [Wilder, 1993; Wilder and Pope, 1996], including...
intervertebral discs disorders. Even if there is not yet enough epidemiological evidence to outline a clear relationship between exposure to WBV and low back pain disorders (Bovenzi and Hulshof, 1998), occupational drivers frequently report problems from these spinal regions. After more than 20 years of discussion, on 22 June 2002, the European Commission published a Directive on exposure to vibration at workplace which defines “the minimum health and safety requirements” for the exposure of workers to the risks arising from vibration [Directive 2002/44/EC].

The directive obliges the employer to assess the risk and to identify the proper measures to be implemented in order to reduce the risk itself. If the exposure action value is exceeded, in addition to an health surveillance programme, the employer must take into account also the possibility of using other working methods that require less exposure to mechanical vibration, limitation of the duration and intensity of the exposure and it have to adequately inform and train workers in order to instruct them to use work equipment correctly and safely.

Mining industry is among the employment sectors with the highest risk to WBV exposure. Aim of this study is to analyse how much some variable, like driving style and ground conditions, can contribute to the daily WBV exposure. The work typically includes the loading of raw material on trucks, the handling of raw material in the yards of the quarry, the traveling at the quarry and the leveling of the roads. Two different wheel loaders with similar characteristics were assessed following the recommendations of the international standards guidelines ISO 2631-1 [ISO 2631-1, 1997] and the provisions of the Italian Decree-Law 81/2008 [D.Lgs. 81/2008].

Experimental procedure

A study sample of four wheel loader operators was selected from a milestone quarry extraction workers group. The operators had different individual characteristics with regard to the vehicles management: vehicle driving experience, enrolment in training events, dexterity (time spent by the operator to complete a specific task), etc.

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Table 1: main features of the tested wheel loaders

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Vehicle 1</th>
<th>Vehicle 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brand</td>
<td>Volvo</td>
<td>Volvo</td>
</tr>
<tr>
<td>Model</td>
<td>L 220 F</td>
<td>L 220 E</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>36.1 (4th gear)</td>
<td>32.8 (4th gear)</td>
</tr>
<tr>
<td>Tyres</td>
<td>29.5 R25</td>
<td>29.5 R25</td>
</tr>
<tr>
<td>Operating weight</td>
<td>32,320 kg</td>
<td>32,490 kg</td>
</tr>
<tr>
<td>Operating load</td>
<td>10,080 kg</td>
<td>10,080 kg</td>
</tr>
<tr>
<td>Floor</td>
<td>bad earth ground</td>
<td>bad earth ground</td>
</tr>
</tbody>
</table>

Acceleration was measured at the driver’s seat, using a SVAN 948 vibration analyser, coupled with a triaxial accelerometer PCB ICP 356B41 (weight 11 g, sensitivity 10,2 mV/(m·s²)). The analyser was set up to log frequency-weighted r.m.s. vibration levels, with time constant of 200 ms, dynamic range of 100 dB and frequency range from 0.8 Hz to 80 Hz.

The frequency-weighted root mean square acceleration (r.m.s.) was calculated using the expression:

\[ a_{w,T} = \sqrt{\frac{1}{T} \int_{0}^{T} a_{w}^{2}(t)dt} \]  \[ 1 \]

where \( T \) is the measurement time and \( w \) are the frequency weights \( w_x \) for x and y axes, and \( w_z \) for z axis as defined by ISO 2631-1.

Italian Decree-Law 81/2008 establishes that the evaluation of the risk to whole-body vibration exposure is based on evaluation of the daily exposure \( A(8) \) expressed as the equivalent continuous r.m.s. acceleration over an height hour period. It is calculated as the highest (r.m.s.) value of the frequency-weighted accelerations, determined on the three orthogonal axes following the expression:

\[ A(8) = a_{w,max} \sqrt{\frac{T}{8}} \]  \[ 2 \]

where \( a_{w,max} \) is the maximum value among \( 1.4 \cdot a_{w,x}, 1.4 \cdot a_{w,y} \) and \( 1 \cdot a_{w,z} \) for a seated or standing worker. No indication neither as regards on quality objectives nor comfort guidelines are provided.

ISO 2631-1, on the contrary, provides criteria both on the evaluation of risk to health and comfort conditions. For the latter estimation the quantity to be used is the vibration total value that is defined by the expression:

\[ a_v = \sqrt{k_x \cdot a_{wx}^2 + k_y \cdot a_{wy}^2 + k_z \cdot a_{wz}^2} \]  \[ 3 \]

where \( a_{wx}, a_{wy}, a_{wz} \) are the vibration values in the three
orthogonal axes $x$, $y$, $z$, and $k_x$, $k_y$, $k_z$ are constant values. Anyway, ISO 2631-1 presents some ambiguities [Griffin, 1998], one of them being the inclusion of different multiplying factors in the horizontal axes when considering health effects ($k_x = k_y = 1.4$) and comfort ($k_x = k_y = 1$). Once the accelerometric pillow was mounted on the driver’s seat, the measurement protocol consisted of performing the same task for all the operators, in the same place and for similar times. The experiment was repeated using both the wheel loaders. Each task was defined as the loading of raw material on lorries until the filling of the truck was completed. Each task was repeated an average of ten times per operator (requiring a total of about 30 minutes of work) and, for vibration exposure assessment, the mean weighted acceleration for each axis was considered.

In order to compare the vibration levels generated only by the working activity, every break between one loading to the next one (i.e. the waiting for the next truck) was excluded from calculations. The tests were performed on two days. During first day the ground was dry and compact; second day followed a period of some hours of rainy weather, making the ground muddy and slippery.

**Results and Discussion**

Concerning the risk assessment, the European Physical Agents (Vibration) Directive 2002/44/EC recommends an Exposure Action Value (EAV) of 0.5 m·s$^{-2}$ and an exposure limit value (ELV) of 1.15 m·s$^{-2}$ for WBV. Italian Decree-Law 81/2008 is less permissive with a ELV of only 1.00 m·s$^{-2}$; it also introduces the concept of “short-period exposure” (that is commonly interpreted as a period no longer than some 3-5 minutes for WBV measurements) with a limit value of 1.5 m·s$^{-2}$. For shorter daily exposures the magnitude of the action and limit values can be calculated assuming that two different exposures to vibration are equivalent when:

$$a_1 \cdot (T_1)^{1/4} = a_2 \cdot (T_2)^{1/4}$$

where $a_1$ and $a_2$ are the vibrations levels during the exposure times $T_1$ and $T_2$ respectively.

On the other hand, International Standard 2631 defines a “caution zone” consisting of a constant r.m.s. acceleration from 1 to 10 minutes (6.0 m·s$^{-2}$ and 3.0 m·s$^{-2}$ respectively for the upper and lower caution zone boundaries) and then acceleration falling following the equation [4], leading to upper and lower limit values of 0.87 m·s$^{-2}$ and 0.43 m·s$^{-2}$ for an 8-hour exposure time. The action and limit exposure values imposed by the Italian Decree-Law 81/2008 and the caution zone in ISO 2631 are shown in Fig. 2. With reference to the caution zone ISO 2631 provides that “for exposure below the zone, health effects have not been clearly documented and/or objectively observed; in the zone, caution with respect to potential health risks is indicated and above the zone health risks are likely”.

![Figure 2: WBV daily exposure limit (1.0 m·s$^{-2}$) and action value (0.5 m·s$^{-2}$) as the Italian Decree-Law 81/2008 and 3.0 and 6.0 m·s$^{-2}$ r.m.s. caution zone in ISO 2631](image)

A detailed analysis and comparison of the criteria assumed by the Directive 2002/44/EC and by the ISO 2631 is given by Griffin [Griffin, 2004]. The most important aspect that we only comment concerns the fact that while, at short duration (i.e. less than few minutes), the Physical Agents Directive allows exposure to excessively high vibration levels, they are avoided by ISO 2631.

ISO 2631 offers two alternative methods to evaluate the whole-body vibration exposure: the Maximum Transient Vibration Value (MTVV) and the Vibration Dose Value (VDV).

The former considers the maximum r.m.s. value of the frequency weighted acceleration recorded during the measuring time. The latter is based on the integration over the exposure time of the frequency weighted acceleration raised to the fourth power following the expression:

$$VDV = \sqrt[4]{\int_0^T \alpha_w^4(t) \, dt}$$

ISO 2631 suggest that for some exposures (i.e. continuous vibration with low crest factor) the VDV can be approximated by the “estimated vibration dose value” ($eVDV$) following the equation:

$$eVDV = 1.4 \cdot a_{r.m.s.} \cdot T^{1/4}$$

The MTVV method raises some concern because, from a hygienistic point of view, it counts as similar two vibrational phenomena characterized by the same maximum value regardless of the number of transients they have. A road with a hole would be judged in the same way as a road with a thousand holes [Peretti, 2005].

VDV method is the most sensitive to vibrational shocks and gives the total exposure to vibration because it is inherently a dose measure. Similarly to the r.m.s. caution zone, a VDV health caution zone is also defined by vibration dose values of 8.5 and 17 m·s$^{-1.75}$ for an 8-hour exposure period. MTVV and VDV are additional methods recommended especially when the “crest factor” is over nine, where the crest factor is the frequency-weighted peak magnitude to
r.m.s. average magnitude ratio. In the present study we did not find crest factors greater than nine, thus we restrict our consideration on the analysis of traditional r.m.s. measures; anyway we present MTVV and eVDV values as additional information.

The vibration magnitudes measured on the machines for all the operators, together with a description of the ground conditions and the working tasks are gathered in Table 3. The A(8) values reported in Table 3 are calculated assuming an exclusive use of the wheel loader for the whole shift of 8 hours and using the full extent of the measurements, that is inclusive also of the intervals between a truckload and the subsequent one. This explains the difference between the maximum r.m.s. value among 1.4·a_{w,x}, 1.4·a_{w,y} and 1·a_{w,z} (which are extrapolated from the working activity alone, without breaks) and the corresponding A(8).

In fact, the mine workers subjected to the tests presented in this article spend about 45 minutes a day driving each of the two wheel loaders examined, while in the rest of the work shift they work on other vehicles, including off-road vehicles, trucks, excavators and dumpers.

Fig. 3 shows the WBV levels measured on both the wheel loaders for the four operators. Drivers 1 and 3 present, on both the vehicles, the lowest vibration levels, while driver 4 is the one with the driving style generating the highest levels.

The correlation between the levels of the A(8) measured, for each operator, on the two vehicles (Fig. 4) is extremely high (R^2 = 0.995) and statistically significant (p-value = 0.002), demonstrating that the driving style plays a crucial role in the estimation of the daily exposure levels.

A test has been specifically performed in order to verify how much the ground conditions could affect the WBV levels.

The test was carried out on two consecutive days, asking the operator 1 to perform the same task (loading trucks) in the same place but under two different ground conditions.

**Table 3: Measurements results**

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>operator</th>
<th>task</th>
<th>terrain conditions</th>
<th>measur. time (min)</th>
<th>r.m.s. (m·s^-2)</th>
<th>eVDV (m·s^-1.75)</th>
<th>MTVV (m·s^-2)</th>
<th>A(8) (m·s^-2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L 220 E</td>
<td>1</td>
<td>loading trucks</td>
<td>dry, compact</td>
<td>60</td>
<td>0.67</td>
<td>0.66</td>
<td>0.35</td>
<td>0.76</td>
</tr>
<tr>
<td>L 220 E</td>
<td>2</td>
<td>loading trucks</td>
<td>dry, compact</td>
<td>18</td>
<td>0.80</td>
<td>0.71</td>
<td>0.69</td>
<td>1.03</td>
</tr>
<tr>
<td>L 220 E</td>
<td>3</td>
<td>loading trucks</td>
<td>dry, compact</td>
<td>35</td>
<td>0.70</td>
<td>0.63</td>
<td>0.39</td>
<td>0.78</td>
</tr>
<tr>
<td>L 220 E</td>
<td>4</td>
<td>loading trucks</td>
<td>dry, compact</td>
<td>18</td>
<td>0.94</td>
<td>0.75</td>
<td>0.55</td>
<td>1.02</td>
</tr>
<tr>
<td>L 220 E</td>
<td>1</td>
<td>loading trucks</td>
<td>muddy</td>
<td>60</td>
<td>0.74</td>
<td>0.61</td>
<td>0.40</td>
<td>0.79</td>
</tr>
<tr>
<td>L 220 E</td>
<td>1</td>
<td>travelling</td>
<td>dry, compact</td>
<td>12</td>
<td>0.75</td>
<td>0.78</td>
<td>0.38</td>
<td>0.86</td>
</tr>
<tr>
<td>L 220 F</td>
<td>1</td>
<td>loading trucks</td>
<td>dry, compact</td>
<td>32</td>
<td>0.66</td>
<td>0.63</td>
<td>0.39</td>
<td>0.76</td>
</tr>
<tr>
<td>L 220 F</td>
<td>2</td>
<td>loading trucks</td>
<td>dry, compact</td>
<td>25</td>
<td>0.80</td>
<td>0.67</td>
<td>0.58</td>
<td>0.94</td>
</tr>
<tr>
<td>L 220 F</td>
<td>3</td>
<td>loading trucks</td>
<td>dry, compact</td>
<td>20</td>
<td>0.68</td>
<td>0.53</td>
<td>0.47</td>
<td>0.77</td>
</tr>
<tr>
<td>L 220 F</td>
<td>4</td>
<td>loading trucks</td>
<td>dry, compact</td>
<td>18</td>
<td>0.93</td>
<td>0.72</td>
<td>0.53</td>
<td>0.99</td>
</tr>
</tbody>
</table>
During first day the ground was dry and compact; second day followed a heavy rain, making the ground muddy and slippery. Ground muddiness seems to be (Fig. 5) a minor contributor to the raising of vibration levels, causing an increase of the maximum level of vibration (along the X axis) by about only 10%.

In order to reduce the level of vibration transmitted to the whole body during the driving of a vehicle, in addition to the usual maintenance of the vehicle itself and the checking for the proper ergonomic set up of the seat, a possibility is to replace the seat for one equipped by anti-vibrating devices. Most of modern seats commonly incorporate adjustable air spring and damper suspension systems in the vertical (Z) axis and fixed mechanical spring and damper systems in the longitudinal (X) axis. Some manufacturers offer similar suspension systems also in the transverse (Y) axis. However, limited cab internal width and seat proximity to sidemounted controls, restrict available suspension system movement in this direction. The most recent developments was introduced by “active seats” that utilise combined electro-hydraulic and air suspension systems, featuring electronic sensing and electro-hydraulic controls, plus automatic sensing of vertical acceleration effecting dynamic adjustment of seat suspension system stiffness. These features are designed to reduce driver’s WBV still further. Reductions in Z-axis weighted r.m.s. acceleration (in comparison with a typical air suspension seat) of over 65% are claimed by some manufacturers [Dufner and Schick, 2002]. Thus, nowadays engineering solutions to reduce WBV levels are commonplace. Many authors demonstrated that the replacement of the seat, regardless of the type of vehicle, can lead to a significant reduction of the vibration levels, up to 90% [Malchaire et al., 1996; Scarlett et al., 2005]. However, since these types of technologically advanced seats are very expensive and most employers tend to avoid similar economic investments, especially when the fleet is relatively large, it seems advisable to evaluate for the existence of alternative ways to reduce vibration levels. The analysis of the driving style for operators 2 and 4 shows an increase of vibration levels especially along X and Z axes. This is a consequence of the way the two operators faced the heap of raw material: rather than putting the shovel under the material and then lifting and closing it to fill it, they pushed it roughly under the heap by horizontal movements. This way of operating increases the shaking, especially in the longitudinal direction, so increasing the levels of WBV along the X axis, without improving the efficiency of the action. It follows that the first and most economical, feasible and effective form of prevention, therefore, should begin by improving operators training, improvement to be implemented through specific driving courses and instruction in the use of the wheel loaders devices.

**Conclusion**

The results of the tests carried out on four operators driving two wheel loaders during the same working activity, in the same place and with the same ground conditions, indicate that the experience in the use of these vehicles is a relevant factor affecting the vibration doses. The differences in driving styles between different operators can lead to a corresponding difference of the daily exposure level up to 40%. Therefore, the organization of driving courses for vehicles operators seems to be a suitable and easy way to help in lowering the exposure risk. Moreover, this study highlights how measuring the exposure levels on only one operator, like the most experienced, could lead to potential relevant underestimations of the exposure risk for those workers who use the vehicles in a less correct way.

**Figure 4:** A(8) calculated for the four drivers on Volvo L 220 E wheel loader versus those on Volvo L 220 F

**Figure 5:** Average weighted RMS accelerations measured with different ground conditions: dry or muddy
In order to avoid underestimation of the exposure risk, it seems advisable the adoption of a criterion similar to that of the “job-based strategy measurements” indicated by the UNI EN ISO 9612:2011 for the evaluation of noise exposure. While this strategy is certainly more time consuming for the technician responsible for the risk assessment, on the other hand, the random sampling of a statistically significant number of subjects allows to reduce the likelihood of underestimating the exposure of those workers at the highest risk.

References


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