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Exposure to whole-body vibration and effectiveness of chair damping in high-power agricultural tractors having different damping systems in practice

Blootstelling aan trillingen en effectiviteit van stoeldemping bij hoog-vermogen agrarische tractoren met verschillende dempingsystemen in praktijksituaties

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Colophon

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In the area of human vibration evaluation and technology, ErgoLab Research has conducted earlier investigations. Their reports can be downloaded from www.ergolabresearch.eu, e.g.:
- Analysis of the exposure to whole-body and hand-arm vibrations using agricultural tractors (2007)
- Analysis of the exposure to whole-body and hand-arm vibrations during work in the green area (2007)
- Analysis of the exposure to hand-arm vibrations using petrol-engine chainsaws (2007)
- Antivibration gloves (2008)

Title	Exposure to whole-body vibration and effectiveness of chair damping in high-power agricultural tractors having different damping systems in practice
Author(s)	Huub H.E. Oude Vrielink
Report number	2009-10-1
ISBN-number	
Date of publication	November 2009
Confidentiality	This report can be downloaded for personal use from the website of ErgoLab Research: www.ergolabresearch.eu
Project code	
Price	-
Publisher	ErgoLab Research B.V. Alexanderweg 56 NL-6721 HH Bennekom
Telephone	+31 6 140 242 14
E-mail	huub.oudevrielink@ergolabresearch.eu
Internet	www.ergolabresearch.eu

Summary

European legislation defines maximum values, i.e. action and limit values, for exposure to whole-body vibration (WBV) for employees on a working day. The use of tractors is a main source of exposure to WBV in agriculture. Since long, it is known that high driving speed and unevenness of the surface contribute importantly to a too high exposure, as seen e.g. in contract work. It might be that improvements in damping of the cabin and/or axles in modern tractors have relieved the problem. The present testing was performed to underpin this improvement, if any, with objective data, and to investigate whether the use of these tractors in practice falls within the safety limits of the EU.

The research involved 7 heavy tractors (>130 kW) of different makes, all of them equipped with damped cabin and / or axles. The vibration damping configuration of all of them, including driver seat, was the standard configuration, according to the manufacturer. One conventional tractor without damping of axles or cabin was tested for comparison. In addition, a tractor was tested in which either an active seat or a conventional pneumatically damped chair was mounted. Each tractor was driven by two drivers, with and without loaded trailer and at two different speeds: 15 km/h constant, and 20-30 km/h variable. The test track was a square of 1.4 km, consisting of concrete plates with damaged surface. Each round was completed two times. Vibration evaluation was performed according to ISO (2631-1, 1997, 2631-5, 2004) on the seat. In addition, vibrations of the tractor cabin at the chair base were measured to determine the effectiveness of damping of the chair implemented ($SEAT_{rms}$-value). Driving comfort was evaluated using a 10-point ratio scale. Vibrations for both measurement sites were measured along 3 standard axes: X (longitudinal; a_{wx}), Y (lateral; a_{wy}), and Z (vertical; a_{wz}). During the tests, vibration results were displayed on-line digitally on a laptop computer and were stored. Processing of the data and calculation of definitive outcomes were performed off-line for each round, consisting of four straight tracks and three bends. For the interpretation of the vibration values measured into daily exposure values, it was assumed that the driving is performed during a full working day of 8 hours.

Variation in WBV between drivers and repetitions was small, so data for these were pooled. The X-axis appeared to be dominant, limiting the working time given the values specified by the EU. Only during low speed empty driving, the median exposure value over all tractors remained in the safe area (0.50 m/s^2). Trailer pulling and faster driving, independently, resulted in a strongly increased exposure to longitudinal vibration (reaching a median value over tractors of 1.39 m/s^2 during high speed trailer pulling). For the transverse and vertical axes, trailer pulling resulted in a small decrease of the vibration exposure, whereas the latter increased again as driving velocity was elevated.

The difference in exposure between the various tractors appeared considerable. Only one tractor was able to sufficiently damp for repetitive shocks. In general and mainly in the vertical direction, damping of cabin and / or axles resulted in a substantially lower vibration exposure during all experimental situations. The reduction depends strongly on the tractor make, reaching Z-axis exposure values of 0.51 – 0.57 m/s^2 for the best-performing tractors, for combined empty and

trailer pulling in the high speed situation. Subjective comfort rating identified the undamped tractor, aswell as the tractor damping the best both vibrations and shocks.
If the present testing, i.e. high and low speed driving loaded and empty, is considered to be representative for transport with a tractor, the exposure to whole-body vibrations is too high for a normal working day of eight hours. For the tractors performing the best, one may drive for approximately 4 hours before additional measures to reduce exposure are to be taken. In an attempt to improve vibration damping, attention should be payed to the effectivity of the chair. Seats appear to be effective in damping vertical vibration. In this respect, the active seat demonstrated an excellent performance. However, for most of the tractors, the longitudinal vibration is enhanced in stead of reduced by the chair mounted, expressed in a $SEAT_{rms}$ value of more than 100%.

Keywords: whole body vibration, WBV, exposure reduction, agriculture, contract work, tractor driving, suspension, effectiveness of damping systems, driving speed, road surface, ISO-2631-1, ISO-2631-5, SEAT, repetitive shocks.

Content

Preface

This document reports the testing by ErgoLab Research of various modern agricultural tractors on vibration exposure and comfort of the driver. The testing was the initiative of the farm machinery magazines Trekker, being a division of Reed Business, and Profi International. The initiative was fed by the lack of objective data on tractor make and configuration options for the exposure in practice of the driver to whole-body vibrations. ErgoLab Research, as being an independent research and consultancy agency and aiming to gather and transfer specialist knowledge, was asked to fill this gap, by means of firm data and clear presentation.

The following persons and companies are kindly acknowledged:

- the machinery magazines Trekker, Profi, and Profi International, for the financial support;
- Wageningen UR Animal Sciences Group and Applied Plant Research in Lelystad, The Netherlands, for providing part of their terrain and expertise to perform the testing;
- both drivers, Bas and Arend-Jan, for fulfilling their rounds and rounds and rounds;
- the suppliers and manufacturers of the machinery;
- Gerard Dekker (Trelleborg), for his advice in the right tyre pressure;
- Joost Martens (Martendo), for his support and advice in the right adjustments of the seats;
- Jochen Hemming (Wageningen UR Plant Research International), for his support in programming the LabVIEW application used for sampling and processing of the vibration data;
- National Instruments Helpdesk, for their fast and professional support in the substitution of part of the measurement equipment;
- Anton Looije (A&E Wageningen), for his assistance during the measurements.

1 Introduction

European and Dutch legislation define maximum values, i.e. action values and limit values, for whole-body vibration (WBV) and hand-arm vibration to which employees may be exposed on a working day. The legislation is meant to protect the employees from health damage due to exposure to vibrations. If the action value (0.5 m/s^2 for WBV) is exceeded, organisational and/or technical measures are to be taken and health surveillance is to be organised, to limit or reduce the exposure. In case of exceeding the limit value (1.15 m/s^2 for WBV), exposure should be brought back immediately to below this limit value.

The use of tractors is the main source of exposure to WBV for agriculture and agricultural contract work. In an earlier investigation (Oude Vrielink, 2007), it was concluded that all of the transport work over all but flat asphalt types of surfaces, with and without tender, at speeds over 15 km/h need attention in reducing vibration exposure. The measurements showed that surface unevenness and driving speed were the most important contributors to WBV exposure. Hence, in view of exposure reduction, it was advised to pay more attention to road surface and driving speed. Reducing the latter, however, directly conflicts with the economic benefits for the farmers and contractors and, therefore, is very unattractive. In addition, in the study of Oude Vrielink (2007) it was observed that damping of the tractor cabin and of the axles could contribute to a reduction of vibration exposure. At that time, however, the damping systems could only partly compensate for the effects of surface type and driving speed.

While the improvements of the damping systems proceeded, agricultural tractors are more and more fitted with vibration and shock absorbing systems, not only in view of more healthy working conditions for the driver, but also to achieve more comfort. In general, damping systems can be applied to the front and rear axles, to the cabin and to the seat. Both the application of mechanical (metal springs, rubber blocks) and hydraulic systems can be found. The latest developments comprise of an active control of the position and movement of cabin and/or seat. In the optimal situation, the damping characteristics of the driver seat and the vibration characteristics of the tractor cabin during use in practice are geared to one another in each of the three movement directions (i.e. horizontally forward-backward and sideward, and vertically). Based on the research mentioned earlier (Oude Vrielink, 2007), it can be doubted whether the damping systems of the tractors and those of the seats in all cases are optimally configured: it was shown that the vibration exposure as measured on the seat of many tractors was higher compared to that measured at the seat base.

Currently, there is a large number of agricultural tractors of different manufacturers and within the different power ranges equipped with vibration damping systems. However, many of the damping systems implemented in a desired model are optional. Hence, the decision for a future owner which machine to buy in which configuration, given his (or her, eventually) specific conditions in practice, cannot be made easily. This issue is further hampered by the lack of objective data of the consequence of the tractor make and the configuration options for the vibration exposure in practice. In other words, if a farmer plans to replace an older tractor, he cannot base his decision for a certain make and damping configuration on data measured in practice in a familiar situation.

In order to reduce the issue of alternative makes and configurations for the agricultural practice, testing of tractors must match their practical working situations. Given the many factors of influence on the vibration exposure, the testing would have become very extensive if all of these factors would have been involved. Therefore, it was decided to include only the most important contributing factors into the research. Current knowledge determined which factors were included. These factors and their influence have been described in more detail in Oude Vrielink (2007) in Dutch. A comprehensive overview of these factors and their implications for the present research are described in the following:

- A greater *mass of the vehicle* in theory diminishes the vibration emission (Stayner, 2003). In practice, however, the relation is not evident (Lines et al., 1995). In the present research, the tractors involved were all of heavy weight and as a group within a narrow range.
- As a consequence of the influence of mass, a more heavy *load* that is transported in theory will diminish the vibration emission. This is confirmed for forestry work (Rehn et al., 2005) and working with forklift trucks (Malchaire et al., 1996). However, if pulling a heavy and/or instable load on a trailer, this may enhance WBV exposure in the forwards-afterwards direction (Stayner, 2003, CEN/Tr/15172-1, 2005). This phenomenon was confirmed in earlier research (Oude Vrielink, 2007), especially at higher velocities. In the present research, therefore, testing was performed with and without pulling a heavily loaded trailer.
- It is evident that *unevenness of road and track* are of great importance for WBV exposure. This is described in several publications (Hostens and Ramon, 2003, Oude Vrielink, 2007). In the latter research, only during driving on a flat asphalt road, vibration exposure remained low for all tractor types. Hence, in the present research, it was chosen to do the test on an uneven paved local road consisting of concrete plates. At several points the concrete surface was damaged due to weather influences and heavy use.
- An increase in *driving speed* normally results in an increased WBV exposure (Lines et al., 1995, Hostens and Ramon, 2003, CEN/Tr/15172-2, 2005, Oude Vrielink, 2007). The latter research indicated that for many tractors, driving at speeds of 25 km/h and above over uneven surfaces leads to unacceptably high WBV exposure values, while speeds up to 15 km/h are acceptable in many cases. For the present research, these two driving velocity levels were chosen.
- In a previous study of Oude Vrielink (2007), it was demonstrated that *damping of the tractor cabin and of the axles* may contribute to a reduction of WBV exposure. One decade before, the same was described in an experimental study (Hansson, 1995). To which extent tractor cabin and axles damping contributes to a reduction of WBV exposure was the main topic of the present study. For the sake of comparison, also one tractor without damping of cabin and axles was involved, exemplary of the various not damped tractors that are still in use in practice and that are to be replaced in shorter or longer term.
- Various studies demonstrate a reduction in WBV exposure when using a mechanically or pneumatically *suspended chair* (Malchaire et al., 1996, Paddan and Griffin, 2002, Hostens

and Ramon, 2003). It is stressed, however, that this only holds if the suspension systems of the tractors and that of the chair are optimally configured. If this is not the case, vibration measured at the seat can be elevated compared to that of the seat base (Stayner, 2003, Oude Vrielink, 2007). In the present research, the tractors tested were equipped with their standard chair. For one tractor both an actively and a pneumatically damped seat have been investigated.

- The *tyres* of a tractor accommodate the unevenness of the surface, so perform like a basic suspension system. However, they do not absorb much of the vibration energy (Lines et al., 1995). To improve this, they should be larger and softer, so resulting in a larger rolling resistance (Lines et al., 1995). Whether the use of softer tyre material or reduces tyre pressure will result in a lowered WBV exposure is not a certainty. It will depend on the degree of lowering, if any, of the natural frequency of the vehicle (Stayner, 2003). Besides, a shift of the dominant vibration from vertical towards lateral might be expected. In the research performed previously, no clear effect of tyre type and pressure was found (Oude Vrielink, 2007). Therefore, in the present study, all tractors were fitted with the same type of tyres.
- Of possible influence on WBV exposure is the *body mass* of the driver (Huston et al., 1999). The lowest exposure was measured at the seat of the person with the highest body mass. Although it was not the aim of the present study to investigate the effect of body mass in detail, it was chosen to do the measurements with two drivers of clearly different body mass. The primary reason for choosing the two clearly different weights was that farmers in practice can easily identify themselves in one of both, or somewhere between.
- Finally, it is evident that the *task* itself has a large influence on WBV exposure. However, it is not clear whether it is the result of one or more of the factors described above. From earlier work, it is clear that the exposure may vary largely between different tasks (Lines et al., 1995, Scarlett et al., 2005, Oude Vrielink, 2007). In the present study, it was chosen to do the measurements during two tasks: empty driving and transporting a heavy loaded trailer.

The research presented here aimed to compare whole-body vibration exposure and seat damping between different high-power class agricultural tractors, one conventional without damping systems of axles and cabin, and 7 modern, fully damped vehicles, during empty driving and transportation of a heavy trailer on a paved, quite rough local track. The comparison was performed at two different driving speeds.

The following questions were aimed to be answered:

1. Does the application of damping systems in agricultural tractors result in a meaningful reduction of vibration exposure for the driver when driving on an paved rough track at speeds of approximately 15 and 25 km/h?
2. To what extent do modern, fully damped agricultural tractor makes differ in respect to vibration exposure? Is the difference meaningful?
3. Are the differences mentioned above retained during transport of a heavy trailer compared to empty driving?

4. Is the chair damping system of all of the tractors tested effective in further reducing the vibrations transmitted from cabin to seat?

2 Materials, methods and procedure

Exposure measurements have been performed during driving with different tractors on one track, at two different driving speeds with and without loaded trailer. The drivers were two experienced employees of the magazine Trekker, being part of Reed Business. The track was situated at the Waiboerhoeve, one of the experimental farms of Wageningen UR, Runderweg 8 in Lelystad, The Netherlands.

2.1 Drivers

The measurements were performed with two experienced drivers, both men of 34 and 49 years. Both were employees of magazine Trekker, and were experienced in driving tractors. Some personal characteristics are given in table 1. One of the drivers reported experienced complaints (pain of discomfort) in the shoulders during the 12 months preceding the measurements. These complaints were still there during the driving task, however, did not lead to a different driving behaviour, as appeared on inquiry. No complaints of other body regions were reported. The other driver was free of complaints.

Table 1: Personal characteristics of the drivers involved.

Driver	Age (years)	Length (m)	Body weight (kg)
1	34	1.73	75
2	49	1.71	91

2.2 Tractors and trailer

The research was performed with 10 tractors: see table 2. Of these, seven tractors that are fully suspended, i.e. front axle and rear axle or cabin, and of different makes are included. One common unsuspended tractor (number 8) was involved also for comparison. One tractor with active seat damping was included, while the same tractor was tested additionally with a conventional seat. Suppliers of the tractor producers were informed in advance and were asked to make the tractors available free of charge. In addition, they provided the technical instruction for the drivers. Tractors were selected in the high-power class: >130 kW. In addition, it was tried to involve as many different tractor makes as possible using the criterion that cabin and/or axles must be damped. Pictures of the machinery are given in the Annex C.

Table 2: Main characteristics of the tractors involved in the measurements.

Nr	Make, type	Building year	Mass (empty) (kg)	Power kW (pK)	Tyre type[1]	Axle-/cabin suspension[2]	Chair type[3]	Chair suspension, direction[4]
1	Deutz-Fahr M650 Profiline	2009	7500	133 (181)	F: 600/70 R30 Tre R: 650/65 R42 Tre	F: Hydro / pneum C: rubber + air	G msg 95 AL	X: Y: Z:
2	JCB 3230 Fastrac	200..	7980	162 (220)	F: 540/65 R34 Tre; R: 540/65 R34 Tre	FA: mech; RA: mech; C: not present; CF: rubber solid; CR: rubber solid	G msg 95 A	X: Y: Z:
3	Massey Ferguson 7495 Dyna-VT	2009	8040	140 (190)	F: 540/65 R30 Tre; R: 650/65 R42 Tre	FA: hydr./pneum Dana; RA: -; C: air suspension + Koni damper; CF: gelrubber at pivot; CR: 2 air bellows	G msg 95 AL	X: Y: - Z:
4	Case-IH Puma 195 CVX	2009	8400	145 (197)	F: 540/65 R30 Tre; R: 650/65 R42 Tre	FA: hydr./pneum.; RA: -; C: mechanical; CF: gelrubber at pivot; CR: spring + damper	G msg 95 G semi-automatic	X: Y: Z:
5	John Deere 7530	2009	7260	136 (185)	F: 540/65 R30 Tre; R: 650/65 R42 Tre	FA: hydr./pneum; RA: -; C: hydr./pneum.; CF: conical bearing; CR: 2 cylinders with accumulators	G msg 95 AL	X: Y: Z:
6	Claas Axion 820	2009	8620	135 (183)	F: 540/65 R30 Tre; R: 650/65 R42 Tre	FA: hydr./pneum Dana; RA: -; C: mechanical; CF: spring + damper; CR: spring + damper	G msg 95 AL	X: Y: - Z:
7	Fendt Vario 922	2009	10380	158 (215)	F: 540/65 R34 Tre; R: 650/65 R42 Tre	FA: hydr. pneum; RA: -; C: air suspension; CF: 1 air bellow; CR: 2 air bellows	G msg 97 EAC	X: Y: Z:
8	John Deere 7820	200..	8980	136 (185)	F: 540/65 R30 Mi; R: 650/65 R42 Mi	FA: x; RA: -; C: not present; CF: rubber solid; CR: rubber solid	S	X: Y: Z:
9	John Deere 7930	2009	8900	162 (220)	F: 600/70 R30 Mi Mach X-Bib; R: 710/70 R42 Mi XM 28	FA: 2; RA: -; C: not present; CF: rubber solid; CR: rubber solid	S e1 Active Seat	X: Y: Z:

10	John Deere 7930	2009	8900	162 (220)	F: 600/70 R30 Mi Mach X-Bib; R: 710/70 R42 Mi XM 28	FA: 2; RA: -; C: not present; CF: rubber solid; CR: rubber solid	S e11 1298 air-damped chair	X: Y: Z:

[1] Tre: Trelleborg; F: front; R: rear
[2] F: front axle; R: rear axle; C: cabin; CF: cabin front; CR: cabin rear
[3] G: Grammer; S: Sears
[4] X: frontal; Y: lateral; Z: vertical; -: not present

Table 3 shows the characteristics of the trailer, trailer load and front weight used when driving with the trailer. Pictures of trailer and front weight are given in the Annex C.

Table 3: Main characteristics of the trailer and front weight involved in the measurements.

Nr	Make, type	Empty mass (kg)	Loaded mass (kg)	Notes
1	Joskin Trans-SPACE 700023, BC150	7380	28060	Trailer with two axles; loaded material: soil; pressure on drawbar: 3660 kg
2	John Deere	1100	-	Front weight

2.3 Experimental set-up

2.3.1 Track, driving speed, and measurement sequence

All of the measurements have been performed while driving on the same track: a local paved road consisting of concrete plates and of which the surface was damaged at several points. Figure 1 gives an overview, depicted from Google Earth, of the track (left image) and the quality of the concrete path (right image). The total length of one round was slightly less than 1400 m.

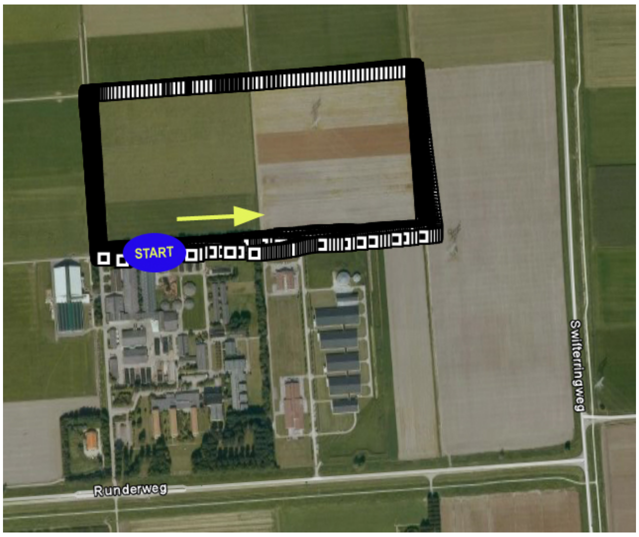

Figure 1: birds eye view of the test track location (left; copy of image obtained from Google Earth) and test track surface (right). In the image on the left, starting point and driving direction are indicated.

Each measurement per driver consisted of driving one complete round, from starting point to just before the 4th bend, immediately before the starting point. The track was driven always into the same direction. Two speeds were applied: driving slowly consisted of driving at 15 km/h all of the straight parts of the track. In the bends, the speed was slowed down. Driving at high speed consisted of driving at 25, 20, 30 and 20 km/h over the 1st, 2nd, 3rd, and 4th straight part of the track, respectively, again slowing down near and in the bends. After having completed the round at both speeds, both rounds were repeated once. This set of four measurements was done with and without loaded trailer, the order was arbitrary. Normally, the loaded or unloaded experiment was completed for both drivers, whereafter the second situation was tested.

2.3.2 Tyres

The suppliers were asked to mount a standard type of tyres for all tractors: see table 2. The size and make of the tyres for the tractors with axles and/or cabin damping suspension was kept the same except for the Fastrac. This tractor has four tyres of identical size. The unsuspended tractor, as well as the tractor with active seat damping, were fitted with tyres of a different make: Michelin in stead of Trelleborg. All tyres were kept at standard pressure: 150 kPa (1.5 bar; 1 bar = 100 kPa) for the front tyres, 180 kPa (1.8 bar) for the rear tyres.

2.4 Measuring devices and procedure

Procedures for the measurement of vibration exposure are very much standardized and described in ISO-directives. For the measurements documented here, the directives ISO-2631-1 (ISO-2631-1, 1997) and ISO 2631-5 (ISO-2631-5, 2004) have been followed. For the processing of the data, the directive ISO-8041 (ISO-8041, 2005) was used additionally.

WBV exposure of the driver was measured at the contact surface between driver and seat. In addition, driver's subjectively experienced vibration exposure and comfort was surveyed using a 10-point scale according to Borg (Borg, 1982): see Annex B. In parallel, measurements of vibration of the cabin at the chair base have been performed, to make clear if the seat is performing well within its suspended surrounding.
All vibration measurements were performed along the three basicentric axes X (frontal axis), Y (lateral axis) and Z (vertical axis). WBV upon the seat were measured using a Bruel & Kjær (B&K, DK) triaxial accelerometer 4322 PE, mounted in a rigid pad. The pad was fixed on the seat using adhesive tape (see figure 2, left panel), in a way that the ischia of the driver were positioned over the middle of the pad. Vibrations of the chair base were determined using a B&K triaxial accelerometer 4321, screwed tightly to the chair base using a bolt (Ø 8 mm) and a iron plate (4 mm thickness; see figure 2, right panel).

Figure 2: illustration of the mounting of the accelerometers on the seat (left) and at the chair base (right).

All signals, a total of 6 channels, obtained from the accelerometers were lead into two amplifiers (B&K, Nexus 2692) via shielded wires, where the signals were filtered: (high-pass: 1 Hz and 0.1 Hz, for seat and chair base, respectively; low-pass: 1000 Hz for both). The signals were then stored on a personal computer (PC; Dell Latitude D610, 2.0 GHz) via a16-bit A/D card (National Instruments, DAQ 6036E with BNC 2090) at a sample frequency of 4096 Hz. Information of the amplification of the signals was stored simultaneously. The signals were on-line frequency-weighted according to ISO-2631-1 (1997), and both raw as well as weighted signals were presented on the computer screen using a home-built LabView computer program (v. 8.0, National Instruments, US) that also uses Matlab routines (v. 6.5.1, The Mathworks Inc., US).

The complete measuring chain for each channel was calibrated immediately before the measurements using B&K calibrator 4291. During the measurements, the amplifiers and the computer were powered by external 12V batteries.

By pressing one of the function keys during the measurements, it could be registered which action (out of a set of predefined activities: straight drive, edge, turn, slow speed, fast speed, acceleration, slowing down, other) was just about to start. The value of the function key pressed was stored simultaneously with the acceleration data. Registration of this actual activity was done to speed up the analysis of the data afterwards, e.g. in finding the right moment for starting and stopping the analysis. The exact driving speed and position during the measurements was registered with help of a GPS receiver (Garmin GPS 60, Olathe, US), mounted at a side of the tractor. Position data were stored in the receiver at a frequency of 1 Hz. The clock of the personal computer and that of the GPS receiver were synchronised each day before starting the measurements. Data were transmitted from receiver to personal computer several times per day.

2.5 Data processing and statistics

2.5.1 Data processing

Stored data were processed off-line according to the following steps. Firstly, all raw signals were converted into frequency-weighted signals, according to ISO-directive 2631-1 (1997), using LabView and Matlab software. These frequency-weighted signals for both seat and chair base were inclusive the k-factor multiplication given in ISO-directive 2631-1 (1997): k=1.4 for horizontal (X,Y) vibration, k=1.0 for vertical (Z) vibrations. Thereafter, a running rms signal was calculated of each of the frequency-weighted signals, according to formula 1 below:

$$a\ (t_0) = \sqrt{\frac{1}{\tau} \cdot \int_{t_0-\tau}^{t_0} a^2(t) \cdot d(t)} \qquad (1)$$

in which a is the instantaneous acceleration value (in m/s^2) of the frequency-weighted vibration signal at time t and τ is the integration time. The latter was held constant at 1 s, according to ISO-2631-1 (1997).

As a second step, vibration signals (i.c. raw, frequency-weighted and running rms signal) were displayed together with the values of the function keys and driving speed data. Datasegments of the straight parts of the track and of the bends were selected separately. For the straight parts, the criterium was that the driving speed was at or very near (± 1 km/h) the target speed. The bends comprised both the deceleration and acceleration phase aswell as the bend itself. Root-mean-square (rms) vibration values of selected[1] segments (a_{wki}, in m/s^2) for the 6 frequency-weighted channels, and also for the three unweighted channels as measured at the chair base, were calculated according to

$$a_{wki} = \sqrt{\frac{1}{T} \cdot \int_{0}^{T} a_{wk}^2(t) \cdot d(t)} \qquad (2)$$

[1] In addition to the driving action, the signals were checked for abnormal appearance and overload. These data segments were removed.

in which $a_{wk}(t)$ is the instantaneous value in the direction *k* (k=X, Y of Z) of the vibration signal at time t and T is the duration of the i^e segment selected.

The European vibration directive 2002/44/EG (EU, 2002;) states that if WBV is evaluated the member states may apply the dose measure VDV (vibration dose value, in $m/s^{1.75}$) in stead of the rms value mentioned above. VDV is calculated according to

$$VDV_{ki} = \sqrt[4]{\int_0^T a_{wk}^4(t) \cdot d(t)} \tag{3}$$

in which VDV_{ki} is the VDV value of the i^e segment for vibration axis k. Action and limit values are 9.1 and 21 $m/s^{1.75}$, respectively.

For the rms WBV values (weighted) and vibratation values measured at the chair base (weighted and unweighted), the calculated values for the different segments (i = 1 to n) of the same driver during the same round were combined according to

$$a_{wk} = \sqrt{\frac{1}{T_0}\sum_{i=1}^{n} a_{wki}^2 T_i} \tag{4}$$

in which T_i is the duration of the i^{th} segment and T_0 is the total duration of all segments.

For the VDV values calculated, they were combined according to

$$VDV_k = \sqrt[4]{\sum_{i=1}^{n} VDV_{ki}^4} \tag{5}$$

To evaluate the effectivity of damping of the driver seat, the SEAT ("seat effective amplitude transmissibility") value was calculated, as described by Griffin (Paddan and Griffin, 2002). $SEAT_{rms}$ is the ratio, expressed as percentage, of the frequency-weighted rms acceleration value on the seat in one of the vibration directions a_w, and the frequency-weighted rms value at the chair base a_{sb} in the same direction:

$$SEAT_{rms} = \frac{a_w}{a_{sb}} \times 100\% \tag{6}$$

To evaluate the health effect of exposure to multiple shocks, ISO has developed directive ISO 2631-5 (2004). Unweighted accelerations measured on the seat are modeled and transformed into an acceleration response of the human spine. Peaks in the acceleration response are converted into a dose measure D_k (in m/s^2) for each of the acceleration directions k=X, Y of Z, according to

$$D_k = \left[\sum_i A_{ik}^6\right]^{1/6} \tag{7}$$

in which A_{ik} is the peak acceleraation of the i^{th} peak in the acceleration response.

The daily acceleration dose D_{kd} is then calculated by scaling the outcome of formula 7, D_k, to the normal daily exposure time, according to

$$D_{kd} = D_k \times \left(\frac{t_d}{t_m} \right)^{1/6} \tag{8}$$

in which t_d is the duration of the normal daily exposure and t_m the duration of the measurement.

To estimate an eventually negative health effect by exposure to shocks, the dose measure D_{kd} is then converted into an equivalent for static compression stress S_e (in MPa) and for the daily compression dose S_{ed} (in MPa) according to

$$S_e = \left[\sum_{k=x,y,z} (m_k D_k)^6 \right]^{1/6} \tag{9}$$

and

$$S_{ed} = \left[\sum_{k=x,y,z} (m_k D_{kd})^6 \right]^{1/6} \tag{10}$$

in which the following values for m_k are recommended: m_x = 0.015 MPa / (m/s^2), m_y = 0.035 MPa / (m/s^2), m_z = 0.032 MPa / (m/s^2). If the daily dose is indicative for the yearly exposure (i.e. 240 days / year), the ISO directive 2631-5 indicates that the risk for back injury is low if S_{ed} remains below 0.5 MPa. A high risk of injury develops if S_{ed} exceeds 0.8 MPa. If the number of exposure days per year is reduced, these limits are corrected according to the table 4 below.

Table 4: limits for daily compression dose S_{ed} at a variable number of days per year exposure to shocks measured. The values come form ISO-2631-5 (2004). S_{ed} in MPa. The coefficient is the factor for multiplication of S_{ed} limits for a whole year (240 days).

Days per year	240	120	60	30	10	5	2	1
Coefficient	1.00	1.12	1.26	1.41	1.70	1.91	2.22	2.49
Health injury probability								
low: S_{ed} <	0.5	0.6	0.6	0.7	0.8	1.0	1.1	1.2
present: S_{ed} <	0.8	0.9	1.0	1.1	1.4	1.5	1.8	2.0
high: S_{ed} >	0.8	0.9	1.0	1.1	1.4	1.5	1.8	2.0

2.5.2 *Interpretation of measured values to daily work*

During the season transporting using a tractor, loaded and unloaded, will occur normally during the whole working day. In practice, shorter and longer durations can be seen. In addition, the number of days per year and the season may vary. The current legislation, however, holds for every working day, and does not take into consideration that exposure may depend on the season. For this reason, the interpretation of the WBV exposure values measured into daily rms exposure, it is assumed that the task in practice will be performed for 8 hours, i.e. 28800 s. For the estimation of the health injury probability due to exposure to shocks, it is assumed that a driver is exposed for more than 120 days per year.

2.5.3 *Presentation of the data and statistics*

To compare persons, repetitions and experimental situations (driving speed and load), median values were calculated per tractor. The results are displayed as boxplots. A boxplot gives median values, interquartile ranges as box (hence, the box consists of 50% of the data) and full range as lines at both sides of the box. If, however, individual data are far beyond the main group of data, these are indicated in the figures as dots, indicating 'outliers'. Furthermore, in the figures, coloured lines indicate the levels of action and limit value for an eight-hour working day.

Statistical testing, if any, is done using SPSS (v.17.0). Before, testing, data were organized using Matlab (v. 6.5.1). Because only two drivers were involved, each of them completed two repetitions of the same situation, no statistical testing was done to demonstrate differences between the tractors involved: in fact, only two independent samples were present. Differences between repetitions, drivers, driving speeds and trailer transport were tested for the median values of the data pooled for all tractors using Wilcoxon's matched-pairs signed-ranks test. Differences were indicated to be statistically significant at p-values less than 0.05.

3 Results and discussion

3.1 Typical pattern

Figure 3 shows a typical pattern for driving the first half of the round at the highest speed while pulling a loaded trailer. The upper panel shows the WBV rms values for the three axes just after starting. The lower panel shows the actual driving speed, as measured by GPS. The pattern includes two straight parts and two bends. The peaks in the X-direction typically correspond to uneven parts of the track. Driving the bends mostly parallels a peak in the Y-direction.

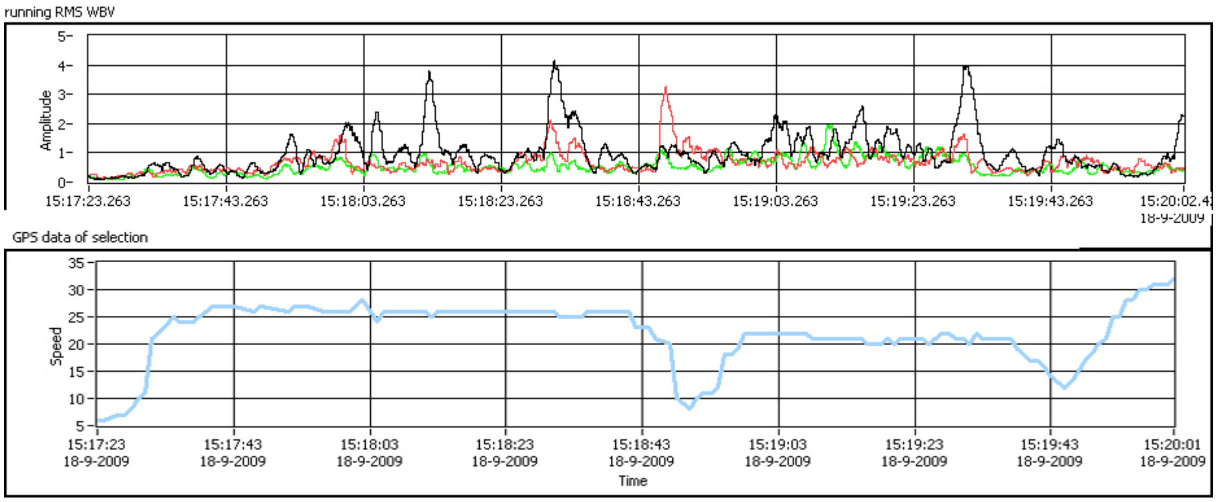

Figure 3: running rms signal for WBV in the X-direction (black line), Y-direction (red line), and Z-direction (green line), all shown in the upper panel, and measured driving speed (blue line, lower panel) for driving with a tractor pulling a loaded trailer over the first half of the test round.

3.2 Effect of repetitions and drivers

Figure 4 summarises the measured vibration values a_w per tractor and per round. The data are clustered for drivers, driving speed, and driving empty and with loaded trailer. As can be seen, the results, both the meadian values and range, of both repetitions are comparable and the differences appear to be non-systematic. For this reason, the data for the repetitions were clustered.

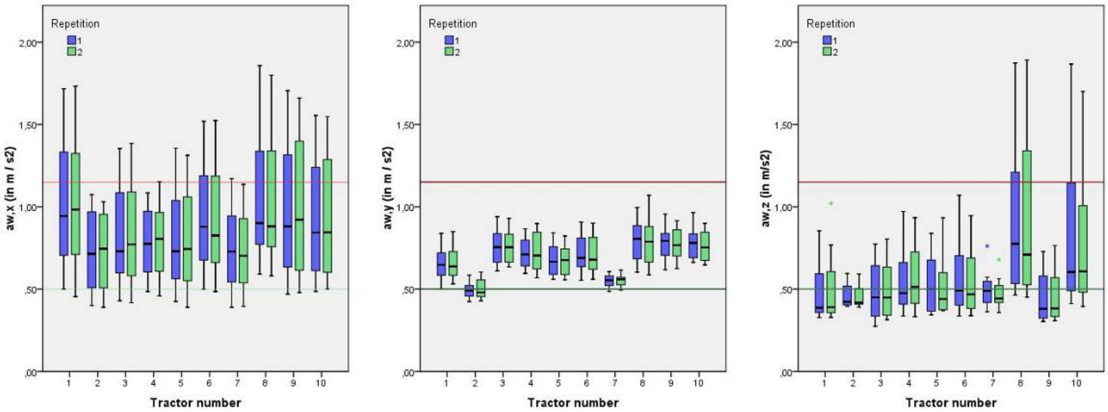

Figure 4: frequency-weighted WBV exposure in the X-direction (left), Y-direction (middle) and Z-direction (right panel) per tractor (horizontal axis) for driving the first and second round. The data displayed are clustered for both drivers, driving with and without trailer, and at high and low speed.

In figure 5, the difference in exposure of both drivers is displayed. As could be seen with repetitive driving, the effect of the driver was small, in the Y- and Z-direction appearing to be unsystematic. In the X-direction, the exposure for driver 1 appeared to be systematically higher ($p < 0.007$). Because the systematic difference was small (median value 0.88 m/s^2 for driver 1 compared to 0.77 m/s^2 for driver 2) compared to the range (which displays the effect speed and trailer), the data in the analysis for all vibration directions were pooled over drivers.

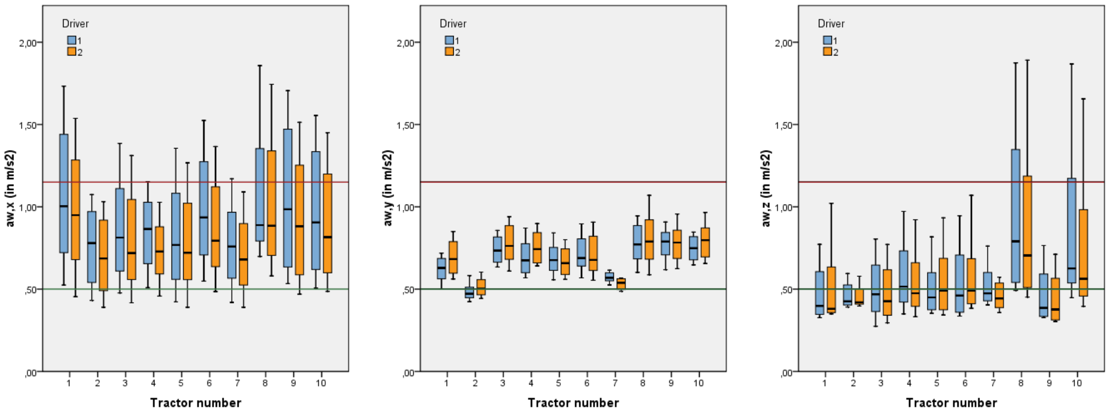

Figure 5: frequency-weighted WBV exposure in the X-direction (left), Y-direction (middle) and Z-direction (right panel) per tractor (horizontal axis) for each of both drivers. The data displayed are clustered for both repetitions, driving with and without trailer, and at high and low speed.

3.3 Effect of driving speed and trailer pulling

Figure 6 displays the driving speed realised per tractor, on average per round. At the lowest speed the diffences between the tractors were small. During driving at high speed, the speed of tractor 8 apparently was lower, compared to the others. This can be explained because with this tractor it was hardly possible to drive part of the track at 25 km/h. For safety reasons, the drivers chose to drive this part at lower speed. The average driving speed of some tractors (1, 2, 7, 9 and 10) tended to be slightly elevated.

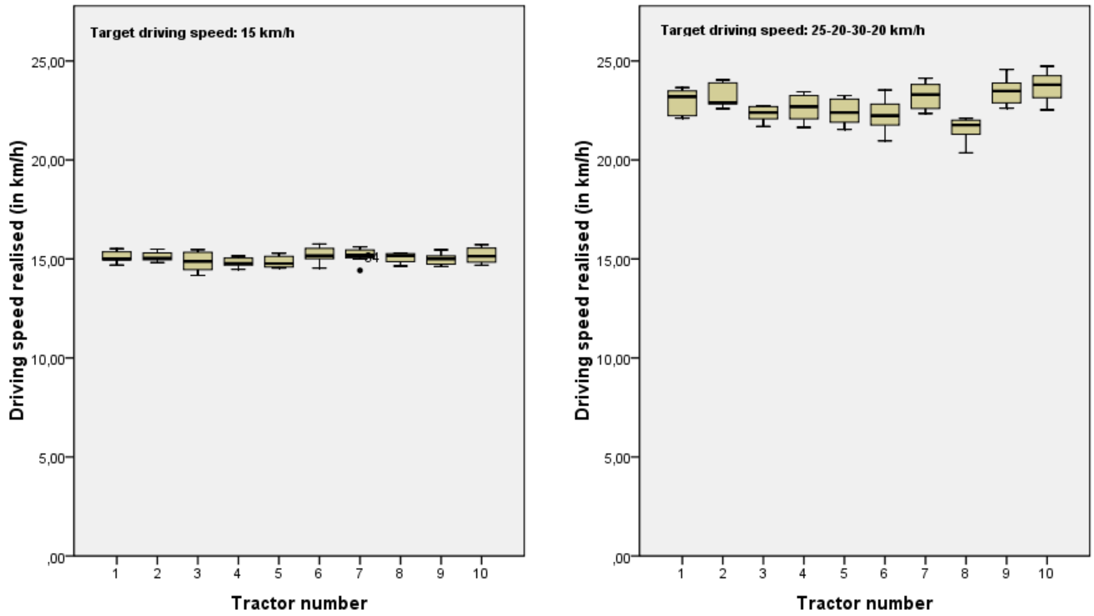

Figure 6: average driving speed realised for each round per tractor. The left panel shows the mean driving speed realised when driving the round at a target speed for the straight parts of 15 km/h. On the right, the same is shown for the higher (and variable) target driving speed. The data displayed are clustered for both drivers, repetitions, and driving with and without trailer.

The effect of driving empty or with loaded trailer at the two speed categories tested is shown in figure 7, pooled for all tractors. The general picture, among others demonstrated earlier by Oude Vrielink (2007), is that vibration exposure is elevated as driving speed increases. This holds for all exposure axes.

The effect of pulling a trailer is different for the various vibration axes. As can be seen in figure 7, pulling the trailer results in an elevation of the WBV exposure in the frontal axis, for both speeds, and this was present for all tractors. Over all tractors, the effect of trailer pulling on the a_{wx} was significant at both driving velocities: $p<0.005$ and $p<0.005$, for low and high speed, respectively. Trailer pulling resulted in a median increase of the a_{wx} from 0.50 m/s^2 to 0.75 m/s^2 at low speed and from 0.89 m/s^2 to 1.39 m/s^2 at the higher velocity round.

In the lateral direction, there was only a slight decrease going from empty driving to trailer pulling at both speeds: median values over all tractors of 0.66 m/s^2 and 0.59 m/s^2 ($p<0.008$), for low speed empty and loaded driving, respectively, and 0.87 m/s^2 and 0.72 m/s^2 ($p<0.005$) for high speed empty and loaded driving, respectively, were significantly different.

In the vertical direction Z and at the low speed, there was a slight decrease if pulling a trailer compared to empty driving: median values were 0.40 m/s^2 and 0.36 m/s^2, respectively. The difference was significant ($p<0.028$). In contrast, at high speed, trailer pulling resulted in a clear reduction ($p<0.005$) of vertical WBV exposure, from 0.82 m/s^2 to 0.50 m/s^2 (mean values over all tractors, for empty and loaded driving, respectively). It is likely that the increased mass, at the front due to the front weight and at the back due the the trailer, is responsible for this.

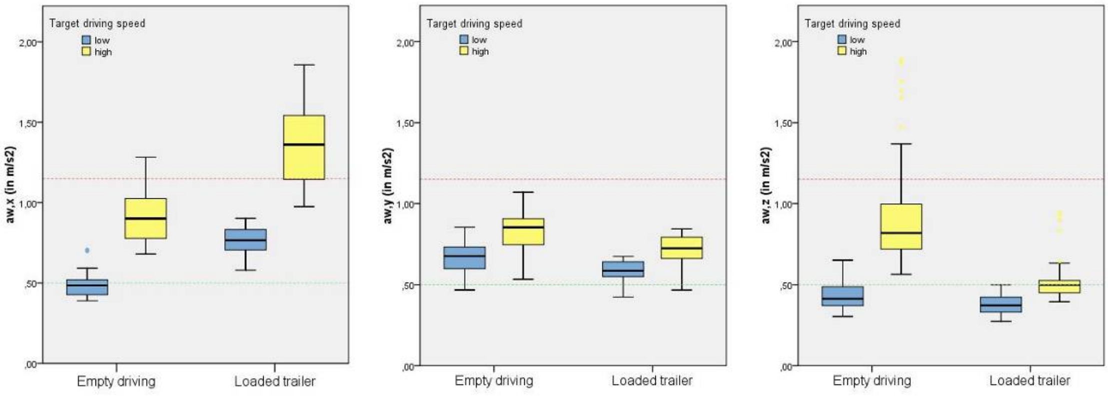

Figure 7: frequency-weighted WBV exposure in the X-direction (left), Y-direction (mddle) and Z-direction (right) for empty driving and pulling a loaded trailer (horizontal axis). For each category, the data are subdivided into the low (15 km/h; blue boxes) and high target speed (25-20-30-20 km/h; yellow boxes). The data displayed are clustered for tractors, drivers and repetitions. The horizontal lines indicate the action value (in green) and limit value (red) for a whole working day.

3.4 Differences between tractors and their seat damping

A general observation is that for most of the tractors, the longitudinal (X) axis appeared the one that is the most important for vibration exposure, both for empty driving and for pulling a loaded trailer at the highest speed (see figure 8). Some tractors, however, have a comparably high seat acceleration value in the vertical (Z) axis during empty driving: tractors 3, 4, and 6. The latter vibration values for the undamped tractors 8 and 10 were very high compared to those of the longitudinal axis.

The increase in vibration exposure as speed is elevated strongly depends on the vibration axis and, to a lesser extent, also on the tractor. In the Z-direction, the strongest speed effect is observed in the undamped cabin of tractor numbers 8 and 10, both during empty driving and, to a lesser extent, while pulling the trailer. In the same vibration direction, the tractors 2 and 7 demonstrate a relative limited increase in WBV exposure with increasing speed (see figure 8, lower panels). Also in the Y-direction (figure 8, middle panels), these tractors demonstrate a similar pattern, and showed to have the lowest exposure values at both speeds, loaded and unloaded. However, in the X-direction (figure 8, upper panels), the difference between the tractors is less clear. While during empty driving, even the undamped tractor cabins at the highest speed fall within the range of all damped cabins, in the situation with loaded trailer, tractor 4 performed similar at the highest speed compared to the numbers 2 and 7, already mentioned. Tractor number 9, mounted with the active seat, damps very well in the vertical direction, and behaves the best in the loaded situation. Along the frontal exis, however, the accelerations measured on the active seat are relatively high.

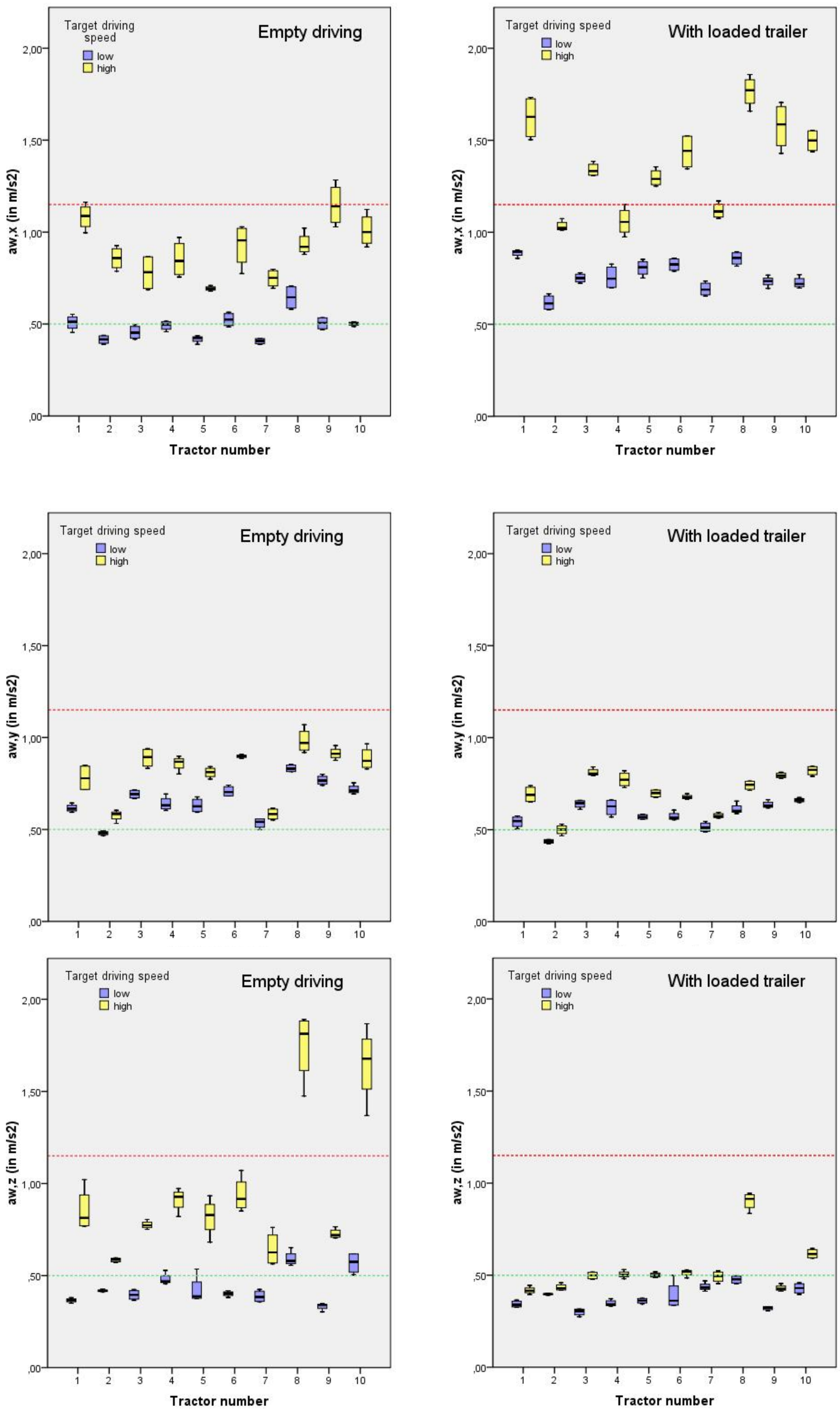
Target driving speed
low
high
Empty driving
With loaded trailer
aw,x (in m/s2)
aw,y (in m/s2)
aw,z (in m/s2)
Tractor number
,00
,50
1,00
1,50
2,00
1
2
3
4
5
6
7
8
9
10

Figure 8 (previous page): frequency-weighted WBV exposure in the X-direction (upper panels), Y-direction (middle panels) and Z-direction (lower panels) per tractor (horizontal axis) for empty driving (left panels) and driving with a loaded trailer (right panels). For each tractor, the data are subdivided into the low (15 km/h; blue boxes) and high target speed (25-20-30-20 km/h; yellow boxes). The data displayed are clustered for drivers and repetitions. The horizontal lines indicate the action value (in green) and limit value (red) for a whole working day.

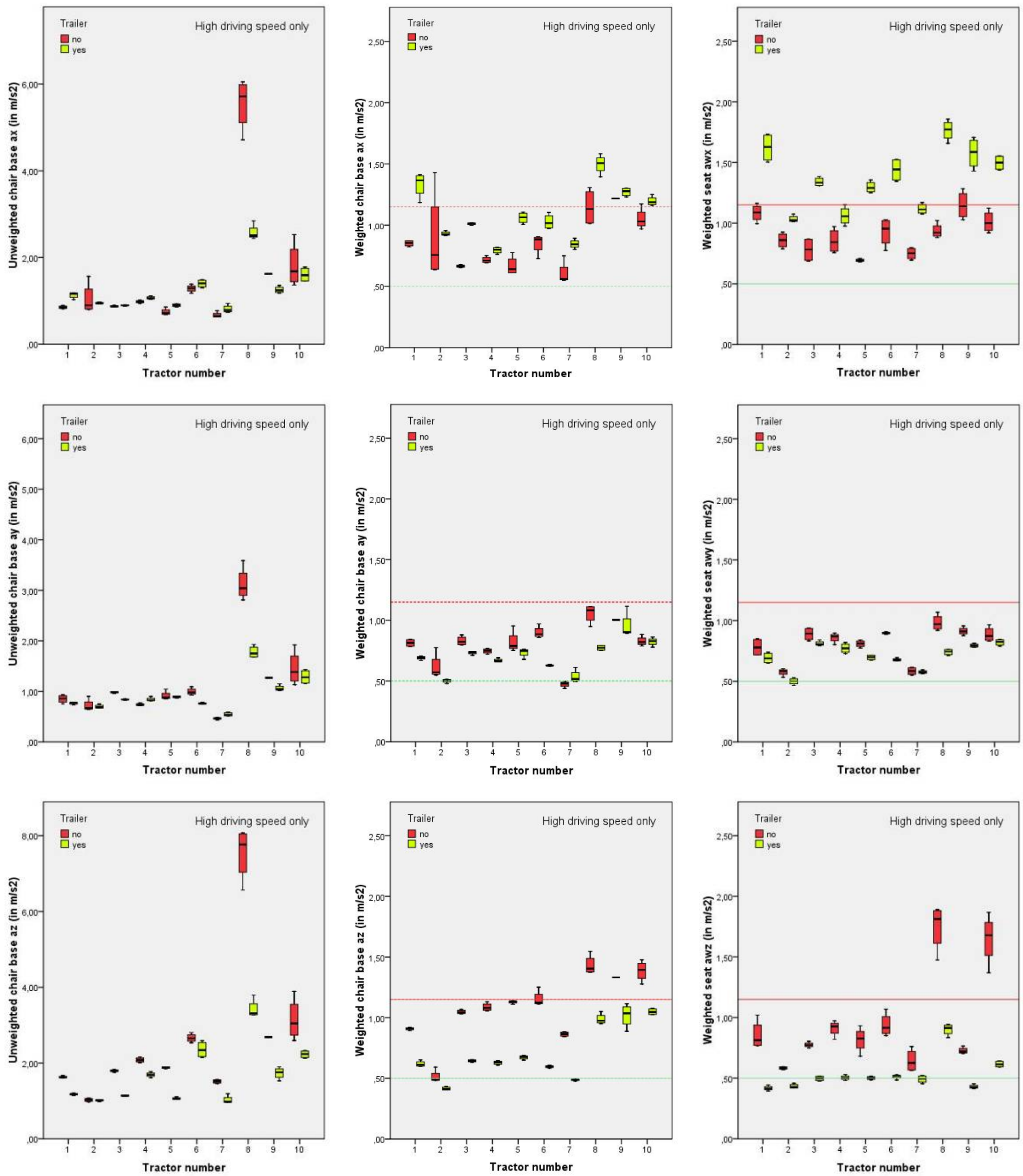

Figure 9: unweighted chair base acceleration (left panels), weighted chair base acceleration (middle panels) and weighted seat acceleration in the X-direction (upper), Y-direction (middle) and Z-direction (lower panels) per tractor (horizontal axis) for empty driving and driving with loaded trailer. The data displayed are clustered for both drivers and repetitions, and display high speed driving only. Note the different scale for the unweighted chair base data.

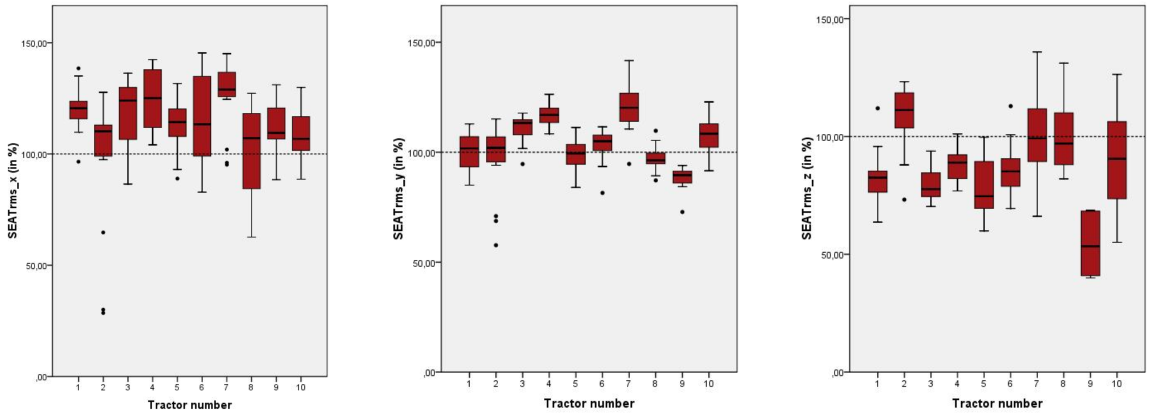

Figure 10: seat effective amplitude transmissibility, based on the weighted rms accelerations measured at the chair base and at the seat ($SEAT_{rms}$) for the X-direction (left), Y-direction (middle) and Z-direction (right panel) per tractor (horizontal axis). The data displayed are clustered for drivers, repetitions, speed and load.

In general, it appeared that the unweighted accelerations measured at the chair base, containing all vibrations between 0.1 Hz and 1000 Hz, were the highest in the vertical (Z) direction: see figure 9, left panels. Note that the data in the figure are displayed for the high velocity drive only. Furthermore, the accelerations of the chair base of the undamped tractor 8 seem to be much higher compared to the others. Also the unweighted chair base values of tractors 9[2] and 10 seem to be slightly elevated, probably due to the lack of cabin suspension. The tractors 2 and 7 performed the best, considering both the empty and loaded drive in the Z-direction.

The middle panels of this figure 9, seen vertically, demonstrate the effect of frequency-weighing: those acceleration frequencies that are considered to be most harmful to the human body are allowed to pass predominantly. It is striking that the difference between the undamped tractors and the damped ones is reduced strongly. If considering the X-axis accelerations, the spread for empty and loaded driving is large, for which reason there appears to be no clear distinction between the tractors. For weighted chair base accelerations in the Z-direction, tractor 2 performed the best.

The right panels of figure 9 show the weighted seat accelerations during high velocity driving. The differences with the weighted chair base accelerations are relatively small for most tractors, most of all for the Y-axis. For the Z-axis, the seat accelerations are somewhat lower, compared to the chair base, again for most of the tractors. The most striking observation is the strongly reduced weighted vibration value for tractor 9, the active seat. In contrast, in the longitudinal direction X, seat accelerations seem to be elevated compared to those of the chair base, especially for the loaded driving.

This is reflected in the $SEAT_{rms}$ value, displayed in figure 10 (X-axis: left panel): median values for all tractors are over 100%, indicating an enhancement of the horizontal vibration on the seat.

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[2] Due to a technical problem, some of the measurement data series at the chair base for tractor 9, empty driving, appeared to be unreliable during data analysis. These data series were removed from the results.

The data displayed are pooled over load, speed, drivers and repetitions. For the Y-axis, data spread around 100%, indicating no clear damping effect of the chair. For the Z-axis, the $SEAT_{rms}$ value for five tractors remains well below 100%, indicating the chair further reduces the accelerations of the cabin. However, for the tractor 2 an increase in vibration on the seat was found. This is mainly the result of the empty driving test. However, overall this tractor has a low level of vibrations of the cabin, compared to the other tractors tested, so the consequences of the transmissibility of the seat remain restricted. For a lesser extent, this holds also for tractor 7, which has an overall median $SEAT_{rms}$ value for the Z-axis of around 100%.

In contrast, the $SEAT_{rms}$ value for the active seat (tractor 9) was the lowest by far, so it performed the best in the vertical direction. Among the horizontal axes, the differences were less obvious.

3.5 Subjectively experienced local discomfort

In figure 11, the median scores for subjectively experienced discomfort for low back, upper back and neck after completing one complete round are given. The data are pooled for both speeds and drivers, so each box plot consists of four data points.

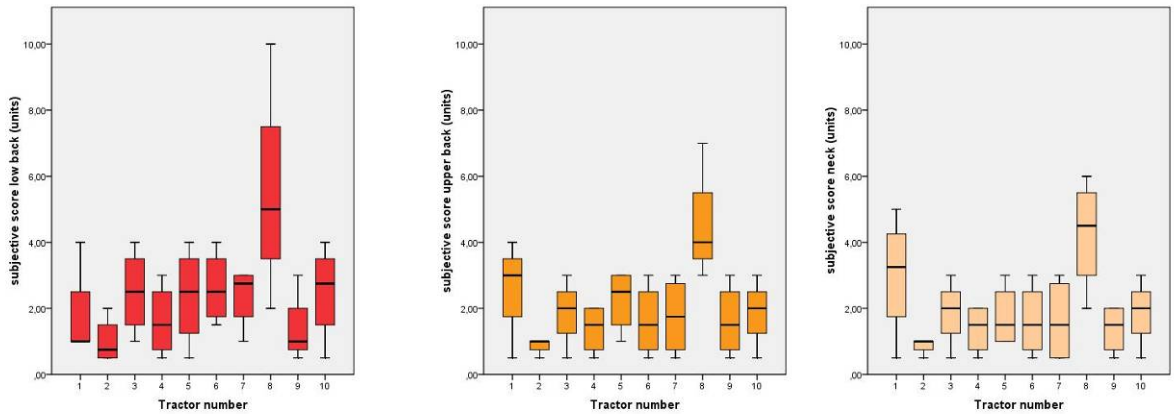

Figure 11: subjective score of local discomfort experienced at the low back (left), upper back (middle), and neck (right) per tractor (horizontal axis) after completing one round driving with loaded trailer. The data displayed are clustered for drivers and speed.

The pattern for the body regions seems comparable. Tractor 2 and tractor 9 were experienced to be most comfortable (lowest discomfort score), while the undamped tractor 8 scored most uncomfortable.

3.6 Interpretation towards a working day

In the Annex A, the rms, VDV and spinal compression data are given per tractor, for both speed categories and accumulated. In addition, total measurement duration, average driving speed, and number of rounds are given. The exposure values are given for each vibration axis. Static compression values D, S_e and S_{ed} are calculated according to ISO-2631-5 (2004). The vibration dose values VDV (8h) and S_{ed} are calculated under the assumption that the exposure of driving on the tractor endures a whole working day of 8 hours (i.e. t_d = 28800 s). In practice, working days of longer and shorter duration may occur.

The accumulated data, i.e. the combined results for both driving speeds, comprise of a total of 16 rounds or approximately 1½ hours of data per tractor. One half of the data is empty driving; the other half is pulling a loaded trailer. The mean driving speed was between 18 and 19 km/h, and consisted of driving straight at constant velocities between 15 and 30 km/h, accelerations and decelerations, and driving bends. If this driving pattern on the track tested is considered to be representative for transport work with a tractor, as e.g. in contract work, then the following statements hold:

- None of the tractors tested meets the requirements of the EU standard 2002/44/EU for a safe use without further action (i.e. a_w at any axis remains below the action limit) for a whole working day.
- For none of the tractors, even for the undamped tractor 8, it is necessary to stop further driving before a total of 8 hours is reached, because of exceeding the limit value of 1.15 m/s^2.
- For all of the tractors, the critical vibration exposure is the one in the longitudinal (X) direction[3]. Tractor 7 has the lowest exposure value, and 3:55h (h:min) may be driven before the action limit is reached. Tractors 2 and 5 follow closely: 3:45h and 3:41h, respectively. In this respect, tractors 1, 9 and 8 showed the highest vibration exposure values, limiting the time-to-action to 2:09h, 2:27 h and 2:31h, respectively.
- For all of the tractors having a damped cabin or axles, the vertical vibration (Z-axis) remains below the action value, so driving may be comfortably endured for eight hours or more. On the tractor 8, which has an undamped cabin, however, the driver is exposed to a considerably higher vertical vibration, so that action must be taken after 3:38h. Tractor 9, having mounted an active seat, reaches the lowest value for vertical vibration exposure.
- If the exposure to multiple shocks is evaluated, and it is assumed that transport work is performed for 120 days per year (see table 4), non of the tractors except the undamped tractor number 8, has a daily compression dose S_{ed} over 0.6 MPa, indicating the risk injury because of exposure to shocks is low. The lowest value by far (S_{ed} =0.38 MPa) is obtained driving in tractor 2, hence giving the highest protection against shock exposure.

[3] There is one exception: tractor number 3, which has a slightly higher value of vibration exposure along the Y-axis (see Annex A).

An evaluation comparable with the one given above can be done assuming the high driving speed rounds are representative for transport work with a tractor. Again, a total of 120 days per year of transport work is assumed. This scenario leads to the following additional statements:

- For two of the damped tractors, and for the undamped ones, one may not drive for a whole working day, because the limit value of 1.15 m/s^2 of the EU standard 2002/44/EU is exceeded. For tractor numbers 1, 6, and 8, 9, and 10 the maximum working time per day is 6:00h, 7:30h, 5:55h, 5:45h, and 6:38h, respectively, because of the serious vibrations along the longitudinal (X) axis.
- For all of the tractors, without exception, the critical vibration exposure is the one in the longitudinal (X) direction. Tractor 7 has the lowest exposure value, and 2:17h (h:min) may be driven before the action limit is reached. Tractors 2, 4, and 5 follow closely: 2:09h, 2:08h, and 2:05h, respectively. In this respect, tractors 1, 8, 9, and 10 showed the highest vibration exposure values, limiting the time-to-action to 1:08h, 1:07h, 1:05h and 1:15h, respectively.
- For all of the tractors, also the vertical vibration (Z-axis) increases over the action value. Tractors 2, 7, and 9 have the lowest values: 0.51, 0.54, and 0.57 m/s^2, respectively. Tractors 4 (0.70 m/s^2) and 6 (0.72 m/s^2) are the highest of the damped tractors. The tractor number 8 reaches a value of 1.31 m/s^2.
- Evaluating exposure to multiple shocks, as above assuming transport work is performed for 120 days per year, only tractor number 2 leaves the daily compression dose S_{ed} under 0.6 MPa, indicating the risk injury because of exposure to shocks is low. In this scenario, tractor numbers 9, 3, 4, 5, and 6 demonstrate a medium risk for injury because of exposure to shocks. Tractors 8, 10, 1, and 7 have a high risk of injury due to shocks, showing measured S_{ed} values of 1.61, 1.32, 1.14, and 0.92 MPa, respectively. The latter value means that working with this undamped tractor 8 even for only one working week imposes a high risk of injury on the driver!

4 Conclusions and recommendations

From the measurement results, the following conclusions can be drawn:

- Damping of cabin or axles of a tractor reduces the exposure to whole-body vibrations transmitted via the seat and improves comfort compared to an undamped cabin during driving over rough surface.
- The difference in exposure between the various tractor makes is considerable. Only one tractor is able to sufficiently damp for repetitive shocks.
- Pulling a heavily loaded trailer has a damping effect on the vertical vibrations, compared to empty driving. In contrast, the horizontal vibrations are enhanced in that situation. This effect is present for all tractors; however, the extent to which reduction and enhancement occurs is quite different for the tractors tested.
- The dominant vibration axis limiting the working time, given the limits specified by the EU, is the longitudinal (X) one.
- If the present testing is considered to be representative for transport with a tractor, the exposure to whole-body vibrations is too high for a normal working day of eight hours. For the tractors performing the best, additional measures to reduce exposure should be taken after approximately 4 hours of driving.
- In an attempt to improve vibration damping, attention should be payed to the effectivity of the chair. For most of the tractors, the longitudinal vibration is enhanced in stead of reduced by the chair mounted.
- An active seat mounted in a tractor seems to be very effective in reducing the vibration exposure in the vertical (Z) direction. However, improvements should be made, in order to reduce the vibrations in the horizontal plane.

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Samenvatting

Europese en Nederlandse wetgeving definiëren maxima, dat wil zeggen actiewaarde en grenswaarde, voor de blootstelling aan lichaamstrillingen waaraan werknemers op een willekeurige werkdag mogen worden blootgesteld. Het gebruik van landbouwtrekkers wordt als een belangrijke oorzaak gezien van blootstelling aan lichaamstrillingen. Al langer is bekend dat hoge rijsnelheid en ongelijke ondergrond belangrijk bijdragen aan een verhoogde blootstelling. Deze factoren spelen bijvoorbeeld in het loonwerk. Het kan zijn dat in moderne trekkers de verbetering in demping van cabine of assen het blootstellingprobleem aanmerkelijk heeft verminderd. Het huidige onderzoek wil deze eventuele verbetering onderbouwen met harde en objectieve data. Bovendien was het doel te bepalen of het normaal gebruik van deze trekkers in de praktijk binnen de door de EU gestelde grenzen valt voor een werkdag.

Het onderzoek is uitgevoerd met 7 zware trekkers (>130 kW) van verschillende fabrikanten, alle voorzien van een geveerde cabine en / of van de wielassen. De testconfiguratie, met inbegrip van de stoel, van iedere trekker was steeds de standaardconfiguratie volgens de fabrikant. Eén conventionele trekker, zonder demping van cabine of assen, werd ter vergelijking in de test meegenomen. Bovendien is een trekker met ongeveerde cabine getest waarin een "active seat" of een normale luchtgeveerde stoel was gemonteerd. Elke trekker werd bestuurd door twee chauffeurs, en er werd getest met en zonder beladen kipper bij twee rijsnelheden: 15 km/u constant en 20-30 km/u variabel. Het testparcours was rechthoekig, ongeveer 1.4 km lang, en bestond uit betonnen platen die door weer en gebruik op vele plaatsen beschadigd waren. Het geheel was te vergelijken met een slechte B-weg. Elke ronde werd twee keer afgelegd. De trillingen zijn volgens voorschrift (ISO-2631-1, 1997 en ISO-2631-5, 2004) gemeten op de stoelzitting. Bovendien zijn trillingen van de cabine aan de stoelbasis gemeten om de effectiviteit van demping van de stoel ($SEAT_{rms}$) te bepalen. Rijcomfort werd gemeten met behulp van een 10-punt ratioschaal. Alle trillingen zijn per meetpunt bepaald in 3 richtingen X (voor-achter; a_{wx}), Y (zijwaarts; a_{wy}), en Z (verticaal; a_{wz}). De data zijn tijdens de metingen online digitaal weergegeven en opgeslagen. Verwerking gebeurde offline zodat gegevens per ronde, i.e. vier rechte paden en drie bochten, werden verkregen. Voor een interpretatie van de meetdata naar dagblootstellingen is ervan uit gegaan dat de combinatie van de testen normaal gesproken gedurende een volledige werkdag van 8 uren zou plaatsvinden.

De spreiding in de uitkomsten tussen de chauffeurs en tussen de herhalingen bleek klein, zodat de data daarvan bij elkaar gevoegd zijn. De X-as bleek de dominante trillingsas. Deze trillingen bleken de werktijd, gegeven de limieten van de EU, te beperken. Alleen tijdens onbeladen rijden op lage snelheid bleef de mediane trillingwaarde over alle tractoren in het acceptabele gebied: 0.50 m/s^2. Zowel het trekken van een beladen kipper als het verhogen van de rijsnelheid had, onafhankelijk van elkaar, een sterk verhoogde blootstelling tot gevolg (waarbij voor de combinatie van hoge rijsnelheid en getrokken kipper een mediane waarde over alle trekkers van 1.39 m/s^2 werd bereikt). Voor zijwaartse en verticale trillingen resulteerde het trekken van een kipper in een bescheiden vermindering van de trillingblootstelling. Snelheidsverhoging, echter, had in alle gevallen een verhoogde blootstelling tot gevolg.

Het verschil in blootstelling tussen de verschillende trekkers bleek aanzienlijk. Slechts één trekker bleek de schokken voldoende te kunnen dempen. In het algemeen, en hoofdzakelijk in de verticale richting, bleek demping van assen en / of cabine samen te gaan met een aanzienlijk lagere trillingblootstelling tijdens alle experimentele situaties. De vermindering hing sterk af van het trekkermerk. Voor de best presterende trekkers was de blootstellingwaarde in de Z-richting, mediaan over het rijden met en zonder kipper en bij hoge snelheid alleen, 0.51 – 0.57 m/s^2. Subjectief ervaren comfort bleek het laagst in de ongeveerde trekker en het hoogst voor de trekker die zowel de trillingen als schokken het beste dempte.

Als de huidige test, d.w.z. lage en hoge snelheid rijden met en zonder beladen kipper, representatief beschouwd wordt voor transportwerkzaamheden met een trekker, dan is de blootstelling aan lichaamstrillingen te hoog voor een normale 8-urige werkdag. Met de best gedempte trekkers kan ongeveer 4 uur gereden worden. Daarna zijn additionele maatregelen nodig om de blootstelling te beperken.

Een aanbeveling richting fabrikanten om de trillingsblootstelling verder te verminderen betreft de effectiviteit van de stoel. De meeste stoelen blijken de trillingen van de cabine in verticale richtng verder af te zwakken ($SEAT_{rms}$ < 100%). Een uitstekende prestatie wordt wat dit betreft neergezet door de active seat. Echter, voor bijna alle tractoren werd de trilling in longitudinale richting juist versterkt door de stoel: bij alle trekkers bleek de $SEAT_{rms}$ waarde voor voor-achterwaartse trillingen meer dan 100% te bedragen.

Indexwoorden: lichaamstrillingen, WBV, blootstelling vermindering, agrarische sector, loonwerk, trekker werk, vering, effectiviteit van dempingsystemen, rijsnelheid, wegdek, ISO-2631-1, ISO-2631-5, SEAT, repeterende schokken.

Annex A – Measurement values of WBV exposure during driving of the test tractors

Terms used:

reference axis	: exis of the vibration measurement
t_m	: total measuring time in s
average speed	: average driving speed in km/hour
meas. (n)	: number of measurements (rounds)
a_w	: frequency-weighted rms acceleration (including k-factor) for WBV in m/s^2
VDV	: vibration dose in $m/s^{1.75}$
D	: acceleration dose according to ISO-2631-5 (2004) in m/s^2
S_e	: equivalent of static compression stress according to ISO-2631-5 (2004), in MPa
t_d	: assumed exposure time on a working day in s
8h VDV	: vibration dose over a working day of 8 hours, given t_d, in $m/s^{1.75}$
S_{ed}	: equivalent of daily static compression dose according to ISO-2631-5 (2004), in MPa

Tractor 1: uneven track driving, including 3 bends, empty and pulling trailer

reference axis	experimental situation	t_m (s)	average speed (km/h)	meas. (n)	a_w (m/s^2)	VDV ($m/s^{1.75}$)	D (m/s^2)	S_e (MPa)	t_d (s)	8h VDV ($m/s^{1.75}$)	S_{ed} (MPa)
x					0.710	6.42	9.48			15.71	
y	low speed	3217	15.2	8	0.584	5.04	7.52	0.27	28800	12.32	0.48
z					0.358	3.06	3.24			7.51	
x					1.329	9.55	14.13			25.93	
y	high speed	2121	23.3	8	0.724	5.55	9.07	0.59	28800	15.08	1.14
z					0.601	7.85	15.00			21.37	
x					0.963	8.09	11.93			20.39	
y	accumulated	5338	18.7	16	0.642	5.28	8.10	0.29	28800	13.43	0.55
z					0.389	3.50	3.56			9.06	

Tractor 2: uneven track driving, including 3 bends, empty and pulling trailer

reference axis	experimental situation	t_m (s)	average speed (km/h)	meas. (n)	a_w (m/s^2)	VDV ($m/s^{1.75}$)	D (m/s^2)	S_e (MPa)	t_d (s)	8h VDV ($m/s^{1.75}$)	S_{ed} (MPa)
x					0.509	4.30	5.97			10.44	
y	low speed	3272	15.0	8	0.459	3.75	5.24	0.19	28800	9.11	0.34
z					0.407	3.49	3.62			8.50	
x					0.966	7.04	9.20			19.22	
y	high speed	2051	23.2	8	0.539	4.01	6.26	0.22	28800	10.94	0.44
z					0.511	3.79	4.29			10.41	
x					0.730	5.68	7.88			14.76	
y	accumulated	5322	19.1	16	0.484	3.92	5.58	0.20	28800	9.89	0.38
z					0.420	3.50	3.64			8.63	

Tractor 3: uneven track driving, including 3 bends, empty and pulling trailer

reference axis	experimental situation	t_m (s)	average speed (km/h)	meas. (n)	a_w (m/s^2)	VDV ($m/s^{1.75}$)	D (m/s^2)	S_e (MPa)	t_d (s)	8h VDV ($m/s^{1.75}$)	S_{ed} (MPa)
x					0.615	5.44	9.47			13.22	
y	low speed	3310	14.8	8	0.659	5.49	8.39	0.29	28800	13.35	0.53
z					0.339	2.89	2.80			7.02	
x					1.088	8.30	12.01			22.34	
y	high speed	2174	22.4	8	0.835	6.24	10.35	0.36	28800	16.79	0.71
z					0.638	5.02	5.47			13.53	
x					0.752	6.40	9.80			15.68	
y	accumulated	5484	18.6	16	0.755	6.12	8.75	0.31	28800	15.87	0.58
z					0.450	3.74	3.79			9.67	

Tractor 4: uneven track driving, including 3 bends, empty and pulling trailer

reference axis	experimental situation	t_m (s)	average speed (km/h)	meas. (n)	a_w (m/s^2)	VDV ($m/s^{1.75}$)	D (m/s^2)	S_e (MPa)	t_d (s)	8h VDV ($m/s^{1.75}$)	S_{ed} (MPa)
x					0.606	5.31	8.30			12.89	
y	low speed	3331	14.8	8	0.636	5.51	7.60	0.27	28800	13.39	0.48
z					0.412	3.39	3.56			8.21	
x					0.970	7.26	10.28			19.65	
y	high speed	2061	22.7	8	0.822	6.25	9.88	0.36	28800	17.01	0.71
z					0.699	5.18	7.56			14.02	
x					0.791	6.34	9.21			15.61	
y	accumulated	5392	18.4	16	0.703	5.79	8.85	0.31	28800	14.32	0.58
z					0.495	3.80	4.36			10.07	

Tractor 5: uneven track driving, including 3 bends, empty and pulling trailer

reference axis	experimental situation	t_m (s)	average speed (km/h)	meas. (n)	a_w (m/s^2)	VDV ($m/s^{1.75}$)	D (m/s^2)	S_e (MPa)	t_d (s)	8h VDV ($m/s^{1.75}$)	S_{ed} (MPa)
x					0.598	5.24	7.59			12.73	
y	low speed	3273	14.9	8	0.585	5.14	7.33	0.26	28800	12.53	0.47
z					0.375	4.20	4.08			10.21	
x					0.980	6.97	9.82			18.90	
y	high speed	2116	22.4	8	0.751	5.61	8.57	0.40	28800	15.22	0.79
z					0.632	10.97	11.94			29.85	
x					0.737	5.83	8.55			14.85	
y	accumulated	5389	18.4	16	0.671	5.22	7.59	0.29	28800	13.57	0.54
z					0.475	5.34	7.15			13.86	

Tractor 6: uneven track driving, including 3 bends, empty and pulling trailer

reference axis	experimental situation	t_m (s)	average speed (km/h)	meas. (n)	a_w (m/s^2)	VDV ($m/s^{1.75}$)	D (m/s^2)	S_e (MPa)	t_d (s)	8h VDV ($m/s^{1.75}$)	S_{ed} (MPa)
x					0.675	5.85	8.86			14.32	
y	low speed	3197	15.3	8	0.645	5.58	7.31	0.26	28800	13.60	0.47
z					0.401	3.37	3.68			8.28	
x					1.188	8.63	12.59			23.31	
y	high speed	2171	22.3	8	0.789	5.97	8.74	0.43	28800	16.18	0.83
z					0.720	7.52	12.02			20.38	
x					0.846	7.18	10.64			17.75	
y	accumulated	5368	18.4	16	0.694	5.58	7.49	0.27	28800	14.22	0.51
z					0.473	3.99	6.16			10.30	

Tractor 7: uneven track driving, including 3 bends, empty and pulling trailer

reference axis	experimental situation	t_m (s)	average speed (km/h)	meas. (n)	a_w (m/s^2)	VDV ($m/s^{1.75}$)	D (m/s^2)	S_e (MPa)	t_d (s)	8h VDV ($m/s^{1.75}$)	S_{ed} (MPa)
x					0.540	4.69	7.48			11.47	
y	low speed	3231	15.1	8	0.524	4.56	6.17	0.23	28800	11.12	0.42
z					0.419	3.91	5.68			9.59	
x					0.937	7.26	11.61			19.76	
y	high speed	2138	23.3	8	0.576	4.19	6.52	0.47	28800	11.28	0.92
z					0.535	5.36	14.72			14.53	
x					0.715	5.91	8.78			14.75	
y	accumulated	5370	19.0	16	0.557	4.32	6.46	0.28	28800	11.28	0.53
z					0.467	4.51	8.37			11.58	

Tractor 8: uneven track driving, including 3 bends, empty and pulling trailer

reference axis	experimental situation	t_m (s)	average speed (km/h)	meas. (n)	a_w (m/s^2)	VDV (m/s$^{1.75}$)	D (m/s^2)	S_e (MPa)	t_d (s)	8h VDV (m/s$^{1.75}$)	S_{ed} (MPa)
x					0.765	6.88	11.34			16.70	
y	low speed	3204	15.1	8	0.729	5.83	7.68	0.31	28800	14.25	0.57
z					0.529	4.95	8.82			12.24	
x					1.338	9.52	14.59			25.52	
y	high speed	2242	21.6	8	0.847	6.12	8.65	0.84	28800	16.44	1.61
z					1.313	11.40	26.06			30.56	
x					0.891	7.39	13.53			18.69	
y	accumulated	5446	18.2	16	0.796	6.09	8.13	0.43	28800	15.58	0.80
z					0.742	6.41	12.88			16.58	

Tractor 9: uneven track driving, including 3 bends, empty and pulling trailer

reference axis	experimental situation	t_m (s)	average speed (km/h)	meas. (n)	a_w (m/s^2)	VDV (m/s$^{1.75}$)	D (m/s^2)	S_e (MPa)	t_d (s)	8h VDV (m/s$^{1.75}$)	S_{ed} (MPa)
x					0.625	5.43	8.32			13.27	
y	low speed	3192	15.0	8	0.703	5.58	6.89	0.24	28800	13.73	0.44
z					0.325	2.92	4.05			7.16	
x					1.358	9.08	12.87			25.06	
y	high speed	1980	23.5	8	0.849	5.84	8.33	0.33	28800	16.32	0.66
z					0.574	6.43	7.98			17.89	
x					0.902	6.85	10.12			17.79	
y	accumulated	5172	19.0	16	0.777	5.84	7.60	0.27	28800	15.38	0.51
z					0.382	3.48	4.60			9.13	

Tractor 10: uneven track driving, including 3 bends, empty and pulling trailer

reference axis	experimental situation	t_m (s)	average speed (km/h)	meas. (n)	a_w (m/s^2)	VDV (m/s$^{1.75}$)	D (m/s^2)	S_e (MPa)	t_d (s)	8h VDV (m/s$^{1.75}$)	S_{ed} (MPa)
x					0.607	5.31	7.50			12.96	
y	low speed	3199	15.2	8	0.683	5.50	7.11	0.29	28800	13.48	0.53
z					0.486	4.32	7.88			10.59	
x					1.263	8.72	12.05			23.82	
y	high speed	2059	23.7	8	0.840	6.05	9.71	0.67	28800	16.57	1.32
z					1.077	10.04	19.33			27.69	
x					0.844	6.76	10.46			17.54	
y	accumulated	5258	19.2	16	0.767	5.87	8.23	0.35	28800	15.65	0.67
z					0.606	4.85	8.35			13.09	

Annex B – Judgement Experienced Local Discomfort

Please indicate on the body diagram attached for each of the body regions (indicated in blue) – as far as any discomfort is experienced – the intensity of discomfort according to the values given in the table below. For helping judging the appropriate score value, many of them are coupled to anchor expressions (source: Borg, 1982).

Score experienced local discomfort	
Anchor expression	*Value*
Nothing at all	0
Very, very weak (just noticable)	0,5
Very weak	1
Weak (light)	2
Moderate	3
Somewhat strong	4
Strong (heavy)	5
	6
Very strong	7
	8
	9
Very, very strong (almost maximal)	10
Maximal	*

Annex C – The machinery used

1. Deutz-Fahr M650 Profiline

2. JCB 3230 Fastrac

3. Massey Ferguson 7495 Dyna-VT

4. Case-IH Puma 195 CVX

5. John Deere 7530

6. Claas Axion 820

7. Fendt Vario 922

8. John Deere 7820

Trailer: Joskin Trans-SPACE 700023, BC150

Front weight: John Deere

9. + 10. John Deere 7930

Sears e1 Active Seat