Final report RT tractor WBV test

Exposure to whole-body vibrations of drivers of a roll-on / roll-of (RORO) tractor during unloading of a ship and different transporting tasks

Blootstelling aan lichaamstrillingen van chauffeurs van een roll-on / roll-off (RORO) trekker tijdens het lossen van een schip en verschillende transporttaken

Huub H.E. Oude Vrielink

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Colophon

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- Exposure to whole-body vibration of drivers of state-of-the-art self-propelled wide area rotary mowers (2013);
- Comparison of high-power agricultural tractors: effect of whole-body vibration exposure during a standardized test in practice (2012).

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Summary

To test the consequences of the roll-on / roll-off (RORO) tractor RT for the exposure to whole-body vibrations (WBV) of the driver, a test was performed during the execution of normal RORO work tasks: unloading of a ship, transportation of laden and empty trailers, driving solo, and sitting in a stationary machine with the engine running idle. Two different types of cabin suspension were tested: an air spring and a massive rubber cone. The test was performed in the Amsterdam harbour area on a normal working day. The driving surface consisted of even tarmac pavement with some sinks for the drainage of rain water. The test made use of two professional drivers, who reported to perform the work on the average for 6 hours per working day.

Vibrations were measured on the seat in full accordance with ISO directives (2631-1, 1997; 2631-5, 2004; 8041, 2005) along the three standard axes (X, Y, and Z for the fore-aft, lateral and vertical direction, respectively). In addition, vibrations of the floor of the tractor cabin were measured to determine the effectiveness of the seat damping. Vibration signals were displayed and stored digitally on a laptop computer. Processing of the data occurred off-line and included only the moments the driver was seated. In parallel to the vibration measurements, driving speed was registered using a GPS device attached to the cabin. To assist off-line analysis, all measurements and activities performed by the drivers were recorded using an action camera mounted at the rear side of the cabin.

From the unloading of a ship and the subsequent transporting of trailers, a total of 11 complete work cycles were observed. These work cycles were used to make an estimation of the relative duration of clearly distinguishable activities that are typical for RORO work. The most important activity, transport of a trailer (laden or empty) itself, demanded on the average for 41% of the time of a RORO task. Driving solo occurred for 23% of the time, while also 16% of the time the cabin was left in order to, for example, connect the brake hoses.

WBV exposure appeared to be dominated by vibrations in the fore-aft direction for most of the activities distinguished. On a daily basis, the activities that contributed most were driving with a laden trailer (exposure values for the air spring cabin suspension situation were 0.67, 0.36, and 0.49 m/s^2 for the X, Y, and Z axis, respectively) and driving solo (0.58, 0.45, and 0.41 m/s^2 for X, Y, and Z, again with air spring suspension). The frequently occurring turning of the seat resulted in relatively high peaks in the lateral vibration exposure (1.00 m/s^2). The use of the air spring as a cabin suspension resulted in a slightly lower vibration exposure compared to a massive rubber cone. The seat mounted appeared to be not effective in damping horizontal vibrations transmitted from the cabin floor. The largest effect was seen along the for-aft axis when driving with a laden trailer. In that situation, vibrations measured on the seat were more than twice of those measured at the cabin floor.

The RORO work tasks were evaluated using the current European directive 2002/44/EG (evaluating on basis of the RMS and VDV methods), as well as of the ISO directive 2631-5 (2004) for evaluating vibration peaks and shocks (evaluation based on the S_{ed} value) To this end, the relative duration of the activities distinguished, their exposure values measured, and a total

duration of 6 hours (as indicated by the two drivers) or of 8 hours for the RORO tasks per normal working day, were combined. In the situation of the air spring cabin suspension and a 6-hour working day of RORO work, daily vibration exposure, expressed as RMS value, appeared to be highest along the X-axis and amounted 0.46 m/s^2. Hence, it remained below the action value of 0.5 m/s^2. Based on this evaluation method, the work can be interpreted as safe. However, if the evaluation was made using the VDV, a method that more than the RMS value accounts for vibration peaks, the outcome along the X-axis (10.9 $m/s^{1.75}$) exceeds the action value of 9.1 $m/s^{1.75}$, indicating that a health risk is present and action should be taken in near future. If the evaluation was made on basis of the S_{ed}, a method that more than both previous methods accounts for vibration peaks and shocks, the outcome (S_{ed} = 0.50 MPa) indicates a low to moderate probability of adverse health effects if exposed for a full working life (45 years) and year round (240 days/year; see ISO 2631-5, 2004). If the rubber cone cabin suspension was used, all evaluation methods yielded exposure values above the action limits (a_{wx} = 0.51 m/s^2; VDV_x = 12.1 $m/^{s1.75}$) for the 6-hour RORO working day. Also, the S_{ed} value (0.51 MPa) appeared to be slightly higher in that situation. The latter outcomes may be interpreted as follows: the use of the rubber cone cabin suspension system coincides with a slightly higher health risk compared to the air spring cabin damper. The same conclusion (i.e. elevated health risk) was drawn for both cabin suspension systems if a total duration of 8 hours of RORO work per working day is assumed.

In order to restrain discussions on whether the work with the RORO-tractor can be performed safely, it is recommended to implement improvements to reduce the driver's vibration exposure. In particular it is recommended:

1) To reduce the transmissibility of vibrations from cabin floor to seat, especially along the fore-aft axis. This is especially important when driving with laden trailer and when driving solo, tasks that predominantly determine vibration exposure on a RORO tractor.

2) To consider uncoupling of the rotation of the steering wheel and the seat, in order to make the rotation of the seat more smooth. This is since the peaks in vibration exposure due to the frequently occurring rotation of the seat dominate in the outcome S_{ed}. A more smooth seat turning movement is expected to eliminate the vibration peaks and S_{ed} is expected to decrease below values of 0.5 MPa. Of course, this might also be realised by the driver himself by adaptation of his behaviour, but a technical solution is preferred and will probably prevent fast seat turning movements in all cases.

3) To mount the air spring cabin suspension as a standard, since during all (except the stationary activities) it was to some extent reducing vibration exposure.

Keywords: whole body vibration, WBV, exposure reduction, roll-on, roll-off, harbour work, tractor driving, suspension, effectiveness of suspension systems, driving speed, road surface, ISO-2631-1, ISO-2631-5, SEAT, repetitive shocks

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1 Introduction

Roll-on / roll-off (RORO) shipping is one of the ways of transport over the water. In RORO shipping the load together with the wheeled trailer is brought into a RORO vessel (loading) or moved out of it (unloading) via one or more ramps that are part of the vessel. The load is carried either by specific trailers or by the various trailers seen in normal road transport. In the latter case, a specialist tractor (called: RORO tractor) takes over the loaded trailer from the truck in the port of departure and brings it into the ship. In the destination port, the process is carried out the other way around. It may also be that the load is carried by trailers designed specifically for RORO transportation. These trailers are loaded in the port of departure and are unloaded at the destination port for further transportation. Moving these trailers on and from the ship is also done by the RORO tractors. However, a detachable gooseneck as coupling device is needed in that situation.

is a manufacturer of specialist tractors and trucks, among others RORO tractors. The company has a strong international orientation and their vehicles are used in many countries of the world. The company has developed a tractor, RT . In the tractor cabin, the driver is sitting on an air-spring seat. The seat, together with the steering and control sections, can be rotated 180°, so that the driver can maintain his normal working posture when driving in the reverse direction. Steering wheel and seat rotating mechanism are directly coupled. Seat, steering and control unit and turning mechanism are part of the cabin. The latter, in turn, is mounted to the chassis of the tractor with two hinges at the front side of the cabin. At the back end, the cabin rests on one air spring. This spring can also be replaced by a massive rubber block in the form of a cone.

The tasks that need to be carried out with a RORO tractor make that the driver is exposed to whole-body vibrations (WBV) via the seat and cabin floor, and to hand-arm vibration (HAV), mainly via the steering device. The European law prescribes that the operator of a vehicle meant for work is protected as much as possible from exposure to vibrations by applying modern techniques and materials (EU, 2006). The same directive obligates the manufacturer to indicate the level of exposure to vibrations in the user manual as measured according to a harmonized norm, when applicable, or a norm that applies most closely. Relevant in this case are: EN 12096-1997 (Mechanical vibration. Declaration and verification of vibration emission values), EN 1032-2003 (Mechanical vibration. Testing of mobile machinery in order to determine the vibration emission value), and EN 12786-2013 (Safety of machinery. Requirements for the drafting of the vibration clauses of safety standards). Besides, the conditions during the measurements need to be described. For various groups of vehicles, harmonized norms are available. Disadvantage of these harmonized norms is that the operating conditions of the vehicle during the vibration measurements can strongly deviate from the situation in practice during normal use of the vehicle. The latter means that the data that are given in the user manual of a vehicle cannot be used for obtaining a reliable impression of the daily vibration exposure in practice.

An employer of the tractor operator needs to comply with the European vibration directive 2002/44/EG (EU, 2002): the employee may not be exposed to WBV above 0.5 m/s^2 as a root-mean-square (RMS) average value over the working day. When this would be the case, action should be performed to lower the exposure to below this level. If the exposure during a working day exceeds 1.15 m/s^2, further exposure should be stopped immediately, which means in practice that the task cannot be performed further. For HAV, the legal values mentioned above are 2.5 and 5 m/s^2, respectively.

To be able to indicate the WBV exposure level during normal use to their customers, asked ErgoLab Research B.V. to perform a series of measurements of WBV exposure during the use of the RT tractor in RORO practice. Since the duration of loading and unloading of a ship in practice as well as the transportation of trailers in the port area can vary largely, the separate activities have been characterised individually. In addition and based on the information obtained during the measurements, an indication for the daily exposure to WBV is provided. This document describes the details of the equipment, measurements and results.

When measuring exposure to WBV, several ISO-norms are applicable: NEN-ISO 8041-2005 (measuring devices), NEN-ISO 2631-1-1997 (whole-body vibration, general), and NEN-ISO 2631-5-2004 (whole-body vibration, shocks). Exposure measurement and reporting should meet minimal criteria and recommendations. The following items are relevant here:

- vibration measurements should be performed along the three basicentric axes X (fore-aft), Y (laterally) and Z (vertically);
- measurements of sufficient duration should be performed, so that the outcomes are representative for the normal variation in the work; besides, the conditions that can be of influence on the exposure should be covered as much as possible; a minimum of three repetitions per task is recommended;
- vibration signals should be frequency-weighted according to the characteristics given in the norms;
- vibration exposure should be expressed as root-mean-square (RMS) value or vibration-dose-value (VDV);
- the measurements should be preferentially performed with a sufficient amount of operators of varying body mass; ISO recommends to involve at least three persons, having body masses around 50-55 kg, 75 kg, and 95-100 kg;

With respect to the factors of influence on vibration exposure, it is known that driving speed, evenness of the surface, and behaviour of the driver are important factors (see for example: Oude Vrielink 2007)

The measurements aim at making an estimation of the exposure to WBV of drivers of the RORO tractor RT during each of the tasks distinguished below and for a normal working day in practice. The following tasks were discerned:

1. tractor alone, stationary, with engine running idle;
2. tractor alone, driving within the ship and in the port area;
3. tractor coupled to empty trailer, stationary, with engine running idle;
4. tractor coupling, driving and uncoupling of an empty trailer;
5. tractor coupled to loaded trailer, stationary, with engine running idle;
6. tractor coupling, driving and uncoupling of loaded trailer;
7. tractor unloading a RORO ship.

The following questions were aimed to be answered in the present measurements:

- What is the exposure to WBV for the driver during each of the tasks mentioned above?
- What is the differential effect on WBV exposure of applying an air spring as cabin suspension compared to a rubber cone?
- Is the standard seat mounted effective in reducing vibrations transmitted via the cabin floor? Is this effectiveness different when applying both types of cabin suspensions?
- What will be the estimated WBV exposure for a normal working day when using this RT tractor? Will the exposure remain below the action value of the EU norm?
- Will the exposure to shocks for a normal working day remain below the health indications?
- Which activities predominantly contribute to the daily vibration exposure? Can their contribution be quantified?
- What are the differences in WBV exposure between the tractor drivers and when driving at different speeds?

Note that measurements of hand-arm vibration (HAV) have not been performed.

2 Materials, methods and procedure

Exposure measurements were performed on the port location of VCK Logistics (Valreep 13, Amsterdam, The Netherlands). The drivers were two experienced employees of VCK Logistics. All measurements took place at October 3, 2014. The port area consists of several warehouses and paved area in between. The pavement to the largest part consisted of tarmac and concrete.

2.1 Drivers and task duration

Both drivers volunteered for the measurements and signed an informed consent before having started the measurements. Both were experienced men and employees of VCK Logistics. Table 1 summarizes some personal characteristics. Both drivers were free of musculoskeletal pain during the past 12 months.

Table 1: Personal characteristics of the drivers involved.

Driver	Age (years)	Length (m)	Body weight (kg)
1	48	1.86	86
2	39	1.94	116

The drivers had 13-20 years of experience with RORO transport. For one of the drivers, RORO transporting was a full-time job. The other on average did this work for two hours per working day, but this could be up to a full working day during peak periods.
The drivers were asked to estimate their daily working time on a RORO tractor and to indicate their total working day duration. Drivers worked for a full working day (8 hours), of which 5-7 (average: 6) hours were spent on the RORO tractor.

2.2 Tractor and trailers

The exposure measurements were performed with one tractor: RT (see table 2). The cabin was suspended at the rear by either an air spring or a rubber cone. Both suspension systems were tested. The seat mounted, an ISRI 6860/880, was fully adjustable, and was equipped with a vertical air suspension and a mechanical suspension along the fore-aft axis. Pictures of the tractor and seat are given in the Annex C. During all measurements, the tractor was equipped with the same front weight (see table 3).

Table 3 shows the characteristics of the trailers, trailer load and front weight used when driving with the trailer. Pictures of trailers and front weight are given in the Annex C. Note that on request of the commissioner, the specific type of tractor and the brand are made invisible in this Internet version of the report. Brand and type can be obtained on request, however.

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

Make, type	Building year	Wheelbase (m)	Axle track[2] (m)	Mass empty (kg)	Power (kW (hp))	Tyre type[1]	Axle-/cabin suspension[2]	Seat type	Seat suspension, direction[3]
RT	2014	3.30	FA: 2.08 RA: 1.85	12640	210 (285)	FT: GY 315/60 R22.5 GY RT: 315/60 R22.5	FA: leaf springs RA: air springs CF: hinges CR: one air spring or one rubber cone	ISRI 6860/ 880	X: mech Y:- Z: air[a]

[1] GY: Goodyear Marathon LHD II+; FT: front tyre; RT: rear tyre
[2] FA: front axle; RA: rear axle; CF: cabin front; CR: cabin rear
[3] X: frontal; Y: lateral; Z: vertical; -: not present; mech: mechanical
[a] vertical suspension characteristics were adjustable

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

Nr	Make, type	Empty mass (kg)	Loaded mass (kg)	Notes
1	Groenewegen	5400	-	Trailer with three axles; empty
2	Groenewegen	5400	34000	Trailer with three axles; laden
3		313	-	Front weight

2.3 Experimental set-up

2.3.1 Routes, pavement, driving speed, and measurement sequence

All of the measurements have been performed on the port location of VCK Logistics. Figure 1 gives an overview, modified after Google Earth, of the location (left image; 1= point of coupling / disconnecting the trailers; 2= location of roll-on / roll-off ship; the blue lines indicate the routes that were driven) and the actual quality of the tarmac pavement (right image, including some sinks for the rain water). The length of the route a driver took was not constant and varied between 0.7 and 1.6 km.

Drivers were free to choose their driving speed; it was stressed that they should work as safely as they normally would do. The start of the measurements consisted of unloading the RORO-ship for some trailers. Trailers were shunted and uncoupled at various sites of the port area. Thereafter driving solo (without trailer), with empty trailer and with laden trailer were measured. Here, a fixed starting and end point (location #1 in figure 1) was kept. Drivers were instructed to follow a route that was more or less the same for drivers and trailer driving. Solo driving only

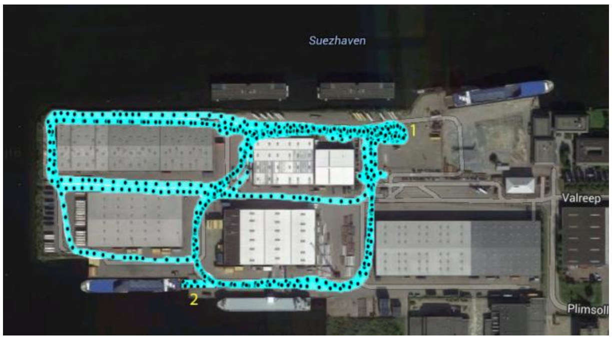

Figure 1: birds eye view of the test track location (left; copy of image obtained from Google Earth) and pavement quality surface (right). In the image on the left, starting point (1) and location of the RORO ship (2) are indicated.

consisted of a shorter route alongside the port edge. The measurements were done firstly with the air spring suspended cabin; thereafter, the same set of measurements was done with the rubber cone cabin suspension. No fixed order of driving was maintained between the drivers. All measurements started with a 2 minutes sampling of the operator sitting at rest on a stationary machine with engine running idle.

2.3.2 Tyre pressure

All tyres were checked before starting the measurements on their pressure: 900 kPa (9.0 bar; 1 bar = 100 kPa) for the front tyres, 880-890 kPa (8.8-8.9 bar) for the rear tyres.

2.4 Measuring devices and procedure

Procedures for the measurement of vibration exposure are 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 parallel, measurements of vibration of the cabin floor were done.
All vibration measurements were performed along the three basicentric axes X (frontal axis), Y (lateral axis) and Z (vertical axis). WBV upon the seat was measured using a Bruel & Kjær (B&K, Naerum, DK) triaxial accelerometer 4322 PE, mounted in rubber-covered steel housing. The pad was fixed on the seat using adhesive tape, in a way that the ischia of the driver were positioned over the middle of the pad. Vibrations of the cabin floor were determined using a B&K triaxial accelerometer 4321, screwed tightly to the floor using a bolt (M8 size) and a steel plate (4 mm thickness; see figure 2, left panel).

A total of 6 signals from the accelerometers were lead into two amplifiers (B&K, Nexus 2692) via shielded wires, where the signals were filtered: (high-pass: 0.1 Hz and low-pass: 1000 Hz for both seat and cabin floor). The signals were then stored on a personal computer (PC; Dell Latitude

Figure 2: illustration of the mounting of the accelerometers at the cabin floor (left) and on the seat (right; hard to see due to the plastic cover).

D610, 2.0 GHz) via a16-bit A/D card (National Instruments, DAQ 6036E with BNC 2090) at a sample frequency of 4096 Hz per channel. Information on the amplification of the signals was stored simultaneously. The signals were on-line frequency-weighted according to ISO-2631-1 (1997), and both the raw and 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) for the frequency weighting.

The complete measuring chain for each channel was calibrated one day before the measurements using the B&K calibrator 4291 (calibration certificate Bruel & Kjaer number C1209213 of December 3, 2012). During the measurements, the amplifiers and the computer were powered by external 12V batteries.

The exact driving speed and position during the measurements was registered with help of a GPS receiver (Garmin GPSmap 62st, Olathe, US), mounted at the front screen of the cabin. Position and speed data were stored in the receiver at a frequency of 1 Hz. Data were transmitted from receiver to personal computer several times over the day. Note that the GPS signal was unreliable when driving in the ship; these track parts were excluded from the analysis of driving speed.

To have a visual check on what happened during the measurements, continuous video registrations were made from the driver and his view to the front. To this end, a small video camera (JVC Action Cam, GC-XA1 BE) was attached to the back screen of the cabin, such that operator and area in front and aside of the machine were recorded. Recording was performed at 30 frames/s. In addition, the start of each vibration measurement was recorded via the sound channel of the camera, so that vibration measurements could be synchronized off-line with the video registrations. Analysis of the video registrations was done with help of LongoMatch software (see http://www.longomatch.org/). The time moments of the following events were indicated: start and stop of the measurement, start and stop of the engine, coupling and uncoupling a trailer, standing stationary, driving over the ramp of the ship, turning of the seat, driving with trailer or solo, and passing surface irregularities. The video registrations made it also possible to indicate at which moments the operator had no contact with the seat. The latter periods as well as those moments of stopping that were not related to normal task performance (such as stopping for the measurement leader to check for proper functioning of the equipment) were excluded from further analysis.

2.5 Data processing

Stored data were processed off-line according to the following steps. Firstly, the video registrations were analysed so that starting and ending moments of the events, indicated in the previous paragraph, were known. Then, for each vibration signal, given the starting and ending moments indicated, a frequency-weighted signal according to ISO-directive 2631-1 (1997) was calculated using LabView and Matlab software. The frequency-weighted signals for both seat and cabin floor 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 $a_w(t_0)$ was calculated for each of the frequency-weighted and k-factor corrected signals, according to formula 1 below (with t0 the moment of observation):

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

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 third step, vibration signals (i.c. raw, frequency-weighted and running RMS signal) for seat and cabin floor (n=6) were displayed together with the driving speed data for a visual inspection of the signal quality. Root-mean-square (RMS) vibration values (a_{wk}, in m/s^2) of a signal with time length T for the 6 frequency-weighted channels were calculated according to

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

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^{th} 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 $m/s^{1.75}$) instead 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^{th} segment for vibration axis k. Action and limit values are 9.1 and 21 $m/s^{1.75}$, respectively.

To evaluate the effectiveness of damping of the driver seat, the SEAT (“seat effective amplitude transmissibility”) value was calculated, as described by Griffin (Paddan and Griffin, 2002). $SEAT_{rmsk}$ is the ratio, expressed as percentage, of the frequency-weighted RMS acceleration value, a_{wk}, on the seat in one of the vibration directions *k*, and the frequency-weighted RMS value at the seat base (or: cabin floor) a_{sbk} in the same direction:

$$SEAT_{rmsk} = \frac{a_w}{a_{sb}} \times 100\% \tag{4}$$

The health effect of exposure to multiple shocks is evaluated applying the ISO directive 2631-5 (2004). The first step is that unweighted accelerations measured on the seat are modelled and transformed into an acceleration response of the human spine. This is done with help of the Matlab routine described in the directive. Thereafter, peaks in the acceleration response are converted into the dose measure D_k (in m/s^2) for each of the acceleration directions k (=X, Y or Z) according to

$$D_k = \left[\sum_i A_{ik}^6 \right]^{1/6} \tag{5}$$

in which A_{ik} is the peak acceleration 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

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

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_{ed} (in MPa) according to

$$S_{ed} = \left[\sum_{k=x,y,z} \left(m_k D_{kd} \right)^6 \right]^{1/6} \tag{7}$$

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).

Table 4: limits for daily compression dose S_{ed} at a variable number of days per year exposure to shocks measured. The values come from 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). Note that the directive assumes exposure during 45 years of working life.

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
moderate: 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

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 should be corrected according to the table 4 below.

Finally, when reporting vibration measurements ISO recommends giving information on the frequency spectra of the measurements. For both the cabin suspension situations, frequency

Table 5: Explanation of the most important outcome variables of the vibration measurements.

a_w	The vibration exposure is expressed in the variable a_w, having the unity m/s^2, which is the weighted RMS acceleration over a certain measurement period. To evaluate the vibration exposure, the highest value of the three axis measured is used. According to the EU law, measures should follow a value of ≥0.5 m/s^2 over an 8-hour working day. The weighing of the acceleration is frequency-dependent and is defined by ISO.
SEAT	Seat Effective Amplitude Transmissibility, or the weighted RMS vibration value measured on the seat as percentage of that measured at the seat base. It is a measure for the effectiveness of the damping of the seat. A value of 100% indicates that vibrations are just transmitted from basis to seat surface. A value of 60% indicates that there is a damping of 40%.
VDV	Vibration Dose Value or vibration exposure calculated as the 4th power of the measured acceleration over a certain measurement period. The VDV is more sensitive to peaks in exposure and its unity is m/s$^{1.75}$. The EU countries have the choice to express their health caution borders as a_w or as VDV. If the VDV is applied, an action value of 9.1 m/s$^{1.75}$ holds, while the limit value is 21 m/s$^{1.75}$.
D	Acceleration dose according to ISO-2631-5 (2004) in m/s^2. It is a help in the evaluation of the probability of adverse health effects as a result of exposure to shocks.
S_{ed}	Equivalent of the daily static compression dose according to ISO-2631-5 (2004), in MPa, as help in the evaluation of the effects of exposure to shocks. If daily exposure occurs year-round (i.e. 240 days / year) and working long long (i.e. 45 years), it is indicated in the directive that the probability of adverse affects for the back is low if the S_{ed} remains below 0.5 MPa. The risk is high if S_{ed} exceeds 0.8 MPa. For 0.5 ≤ Sed ≤ 0.8 MPa, a moderate risk is indicated. Higher borders hold if exposure occurs less frequent.
Time duration	Length of a measurement period (in s), after correction for moments of hold that are not related to normal task performance, and for moments of having no contact with the seat.

spectra of raw unweighted data series measured at the cabin floor for standing stationary with engine running idle, driving solo, driving with empty trailer, and driving with laden trailer have been produced using Fast Fourier Transform (FFT) in Matlab for periods of 30-60 s and a been produced using Fast Fourier Transform (FFT) in Matlab for periods of 30-60 s and a relative constant driving velocity (when driving). These spectra are given in the appendix C.

Table 5 summarizes the major outcome variables of the present vibration measurements.

2.6 Interpretation of measured values to daily work

For the calculation of the daily WBV exposure the law indicates that the vibration axis having the highest value determines the maximal working duration, given an arbitrary working day. The daily exposure in this report is calculated on basis of the time information of tasks to be performed on a regular working day obtained from the drivers, and of the task durations observed during the measurements of unloading the ship.

The overall WBV exposure for a task was calculated from the exposures determined for the individual events (for example: coupling the trailer, driving with trailer, etc) using

$$a_{wk} = \sqrt{\frac{1}{T_0}\sum_{i=1}^{n} a_{wki}^2 T_i} \qquad (8)$$

in which a_{wk} is the weighted vibration exposure of the complete task for the vibration axis k (k = X, Y or Z), a_{wki} is the weighted vibration exposure of each event i, T_i is the duration of each event i, and T_0 is the duration of all events together.

From the drivers a rough indication of the total duration of RORO transport on a regular working day was obtained. Besides, they indicated, again roughly, how this time expenditure was divided over the following tasks: standing stationary with engine running idle, driving without trailer, driving with empty trailer, and driving with laden trailer. In addition, from the measurements performed during unloading the ship and transporting trailers in the port area, information was obtained about the relative duration of each of the above-mentioned tasks. The information from both sources was combined into three working patterns. For these three scenarios, daily exposure to WBV was calculated by combining the task durations with their exposure values, according to

$$a_{wk(eq,day)} = \sqrt{\frac{\sum_{i=1}^{n} a_{wki}^2 T_i}{T_d}} \qquad (9)$$

in which $a_{wk(eq,day)}$ is the daily exposure at a normal working day (i.e. 8 hours), a_{wki} is the exposure calculated for each task i, T_i is the duration of each task i on basis of the scenarios, T_d is the total length of the working day and k is the vibration axis X, Y or Z.

2.7 Presentation of the data and statistics

The results in this report are displayed in tables and in figures as time series, histograms and 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, the horizontal dotted and orange-coloured line indicates the level of the action value for an eight-hour working day.

Given the confined amount of measurements for each task (one machine and two persons), no statistical calculations have been done.

3 Results

3.1 Length of a normal working day for RORO in practice

Table 6: Analysis of a total of 11 work cycles of unloading a ship and transport of a trailer over tarmac pavement in the port area into the task parts (or: events) distinguished (A-H). Both the absolute time per cycle (t, in minutes and seconds) and relative time (as percentage of the cycle time) are given. During event H no exposure occurs. The data are the mean values of 2 drivers.

	Task:	unloading ship		transport of trailer	
	Task part (event):	t (mm:ss.s)	%	t (mm:ss.s)	%
a	Standing stationary, engine idle	00:48.1	9%	00:07.8	2%
b	Turning the seat	00:28.8	6%	00:20.4	5%
c	Make a sharp turn	00:09.6	2%	00:01.1	0%
d	Coupling or uncoupling of a trailer	00:45.6	9%	00:16.0	4%
e	Driving solo	01:58.5	23%	01:27.7	22%
f	Driving with trailer (empty or laden)	02:54.1	34%	03:05.1	47%
g	Driving on ramp ship	00:25.9	5%		
h	Not sitting on seat	01:07.2	13%	01:16.2	19%
	Total task	08:37.8	100%	06:34.3	100%

The drivers reported that roll-on / roll-off tasks with a tractor endured 6 (5-7) hours per normal working day. They reported to perform checking of the goods and maintenance of the vehicles during the remainder of the time. It is assumed that there is no vibration exposure during the latter activities. On basis of a total of 11 work cycles observed during unloading a ship and

Table 7: Time estimation of the duration (in hours and minutes) of task parts (events; A-H) for a normal working day of 6 hours RORO work for just unloading a ship, just transporting trailers in the port area and an linear average of both (average). Like table 6, the data are the mean values of 11 working cycles performed by 2 drivers.

	Task:	unloading ship	average	transport of trailer
	Task part (event):	t (hh:mm)	t (hh:mm)	t (hh:mm)
a	Standing stationary, engine idle	00:33	00:20	00:07
b	Turning the seat	00:20	00:19	00:18
c	Make a sharp turn	00:06	00:03	00:00
d	Coupling or uncoupling of a trailer	00:31	00:23	00:14
e	Driving solo	01:22	01:21	01:20
f	Driving with trailer (empty or laden)[1]	02:01	02:25	02:49
g	Driving on ramp ship	00:18	00:18	00:00
h	Not sitting on seat	00:46	00:58	01:09
	Total task	06:07	06:07	06:07

[1] *One driver indicated only driving laden trailers, the other equal division of both task parts. In this report, 75% is assumed to be driving with laden trailer.*

transporting a laden trailer over tarmac pavement, the duration, both absolute and relative, of clearly distinguishable events (that together build the work cycle) was determined. The outcomes are presented in table 6. On basis of these relative contributions of the events and assuming these remain constant over a working day consisting of approximately 6 hours of RORO work, an estimation of the absolute duration of each event per working day is made for both ship unloading (table 7, left column) and trailer transport over tarmac pavement (table 7, right column), aswell as for a work pattern in between (average work pattern; see table 7, middle column). These data are the time basis for the three scenarios for which daily vibration exposure is calculated.

3.2 Vibration exposure during different tasks

3.2.1 Standing stationary while engine running idle

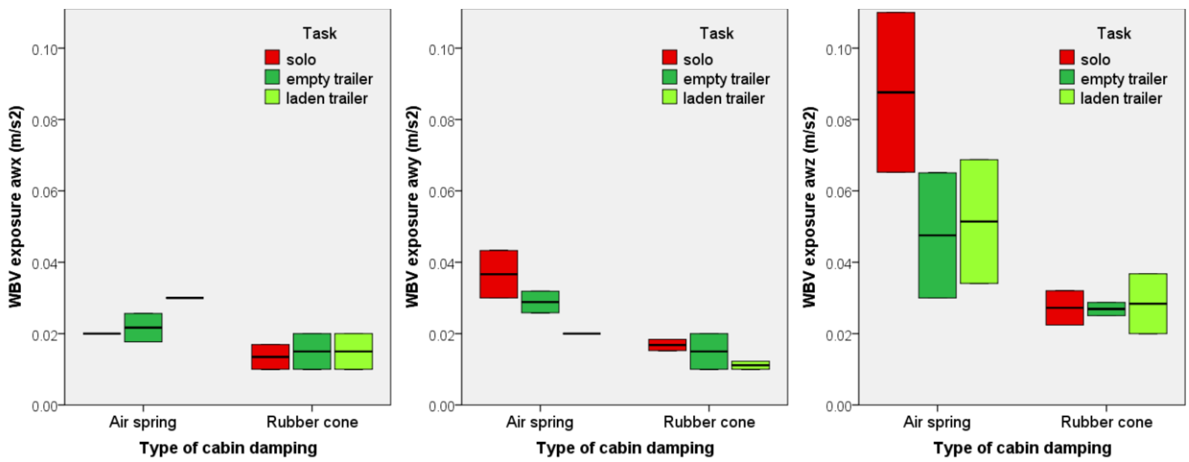

Figure 3: frequency-weighted WBV exposure in the X-direction (left), Y-direction (middle) and Z-direction (right panel) per type of cabin suspension (horizontal axis) for the three stationary tasks distinguished: standing solo, with empty trailer and with laden trailer. The data shown are clustered for both drivers.

In most situations measured, the absolute and relative differences between both drivers appeared small. For this reason, the data over the drivers were pooled. Also the differences between the tasks were small for most of the measurements, as can be seen in figure 3. This holds especially for the rubber cone type of cabin suspension. When the air spring was applied, in most cases the vibration exposure was elevated. The absolute difference, however, appeared small and amounted between 0.005 and 0.06 m/s^2. The median values of the data measured for each of the categories are given in Appendix A. When pooling the data for standing solo, with empty trailer and with laden trailer, the median exposure values for the X-, Y- and Z-direction were 0.03, 0.03, and 0.07 m/s^2 respectively for the air spring cabin suspension, and 0.02, 0.02, and 0.03 m/s^2 respectively for the rubber cone cabin suspension. Frequency spectra of the measurements done at the cabin floor during the stationary situation with engine running idle for one of the drivers are shown in Appendix C.

3.2.2 Driving solo on tarmac (without trailer)

Solo driving was performed as part of the tasks “driving with empty trailer“, ”driving with laden trailer”, and “unloading the ship”. Note that in the latter situation, only the data of driving without gooseneck were included. The vibration exposure of the driver was fairly constant over these tasks: see the table in Appendix A. For this reason, the results obtained for solo driving on even tarmac during the different tasks were pooled. Table 8 summarizes the outcomes. For both types of cabin suspension, the exposure was the highest in the fore-aft direction. Besides, vibration exposure in all directions was elevated if a massive rubber cone was mounted as a cabin suspension. The driving speed was observed to be slightly higher in the latter situation, 21 km/h, compared to 17 km/h in the situation of the air spring mounted. Although a positive relation was seen between WBV exposure in both the X and Z directions (but not in the Y direction) and the driving speed (see figure 4), this relation could only partly explain the differences between the types of cabin suspension. Therefore, it is likely that this difference is the result of the type of cabin suspension: applying the air spring will result in a lower WBV exposure along all vibration axes during solo driving compared to a massive rubber cone.

Table 8: Whole-body vibration exposure as measured on the seat of the RORO tractor RT during driving solo on even tarmac in the fore-aft (X), sideward (Y) and vertical (Z) direction. The values given are median values over both drivers; for each driver data of solo driving obtained during different tasks were pooled.

	Vibration exposure direction:	X	Y	Z
	Cabin suspension:	(m/s^2)	(m/s^2)	(m/s^2)
1	Air spring	0.58	0.45	0.41
2	Rubber cone (massive)	0.77	0.53	0.53

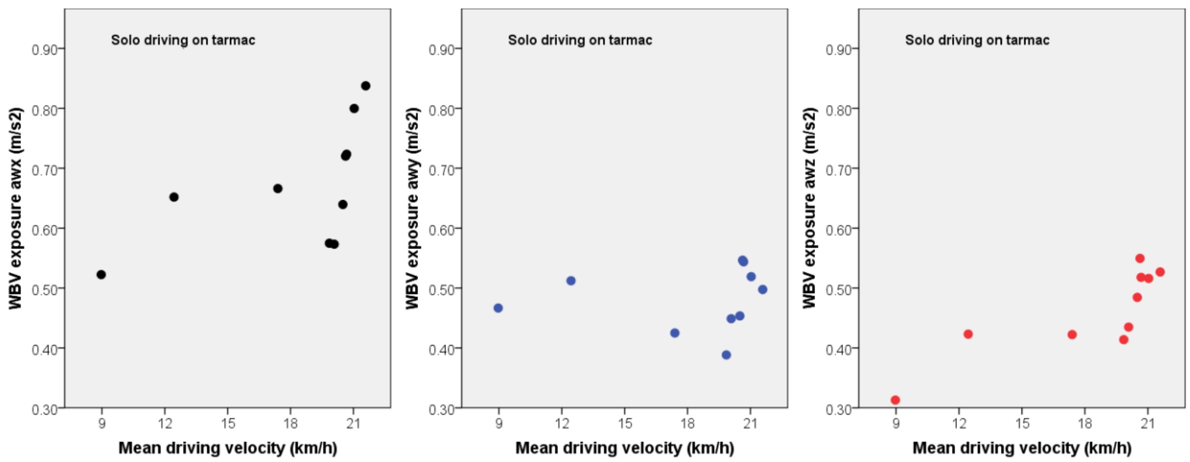

Figure 4: frequency-weighted WBV exposure in the X-direction (left), Y-direction (middle) and Z-direction (right panel) as function of the driving speed (horizontal axis) for solo driving on even tarmac. The data shown are clustered for both drivers.

The seat appeared not very effective in reducing the vibrations that were transmitted from the cabin floor: see figure 5. Along both horizontal axes, the vibration on the seat was amplified compared to the cabin floor for both types of cabin suspension (SEAT along the X-axis amounted 141 % and 169%, and for Y 128% and 141% for air spring and rubber cone, respectively). In the vertical direction, these values were 99% and 86%, respectively. This means that only in the situation of driving solo with the massive rubber cone mounted as cabin suspension, the seat demonstrated some reduction of the vibrations of the cabin floor.

Frequency spectra of the measurements done at the cabin floor during solo driving are shown in Appendix C for one of the drivers.

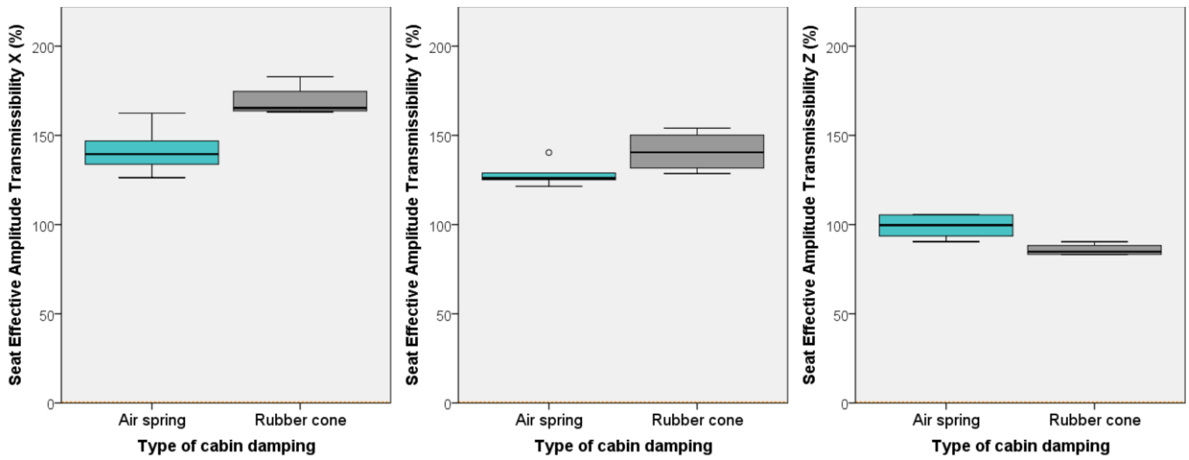

Figure 5: Seat effective amplitude transmissibility (SEAT) in the X-direction (left), Y-direction (middle) and Z-direction (right panel) as function of the type of cabin suspension (horizontal axis) for solo driving on even tarmac. The data shown are clustered for both drivers.

3.2.3 Driving with empty trailer

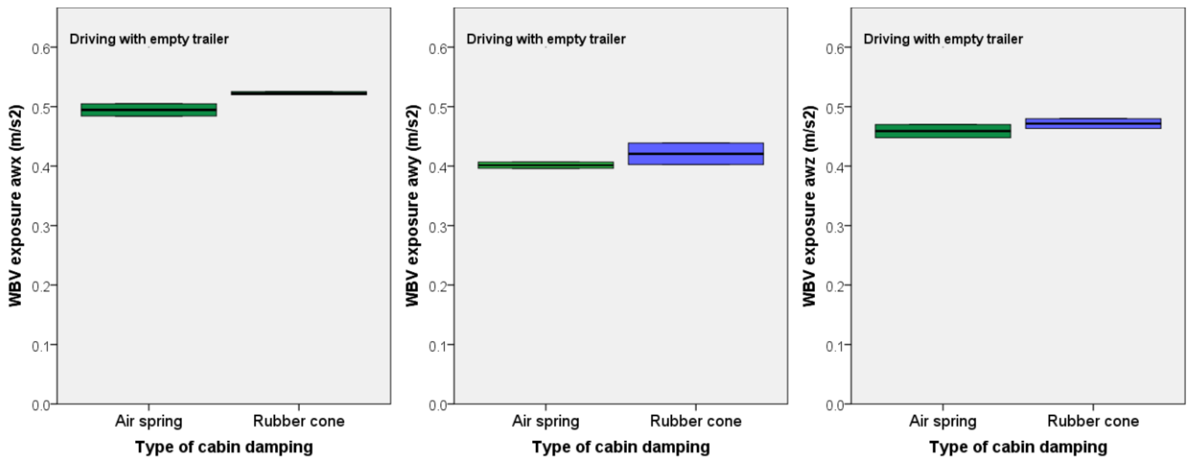

Figure 6: frequency-weighted WBV exposure in the X-direction (left), Y-direction (middle) and Z-direction (right panel) as function of the type of cabin suspension (horizontal axis) for driving on even tarmac with empty trailer. The data shown are clustered for both drivers.

Figure 6 shows the WBV exposure on the seat when driving with empty trailer on even tarmac. Although in all vibration directions the situation with the air spring cabin suspension resulted into a marginally lower exposure (median values in X: 0.49 and 0.53 m/s^2, in Y: 0.41 and 0.42 m/s^2, in Z: 0.46 and 0.47 m/s^2 for air spring and rubber cone, respectively), it is unclear whether this is the direct result of the suspension type. The reason for this is that the average driving speed was somewhat elevated when the rubber cone was mounted: 25.0 km/h versus 20.5 with air spring. The difference in driving speed may well explain the difference in exposure found. The driving speed of both drivers was comparable in both situations. Like for driving solo, the highest vibration exposure on the seat was seen along the X-axis. Specification of the outcome data is given in a table in Appendix A.

Seat effective amplitude transmissibility showed a comparable behaviour compared to driving solo: the seat amplified the vibrations of the cabin floor in the horizontal plane (SEAT values were 167 and 190% for X and 131 and 140% for Y, for air spring and rubber cone cabin suspension, respectively), and did some damping in the vertical direction (SEAT values for Z were 99 and 88% for air spring and rubber cone cabin suspension, respectively).

Frequency spectra of vibrations at the cabin floor for driving with empty trailer are given in Appendix C.

3.2.4 Driving with laden trailer

Driving with laden trailer resulted into a higher exposure to WBV in the fore-aft direction compared to an empty trailer: see figure 7. And again, this axis appeared to dominate vibration exposure on the seat. The differences between both types of cabin suspension were small. Median exposure in the fore-aft direction was 0.67 m/s^2 for both types of cabin suspension. In sideward and vertical directions, the values were 0.36 and 0.38 m/s^2, and 0.49 and 0.48 m/s^2 for air spring and rubber cone, respectively. The average driving velocity was slightly higher in the

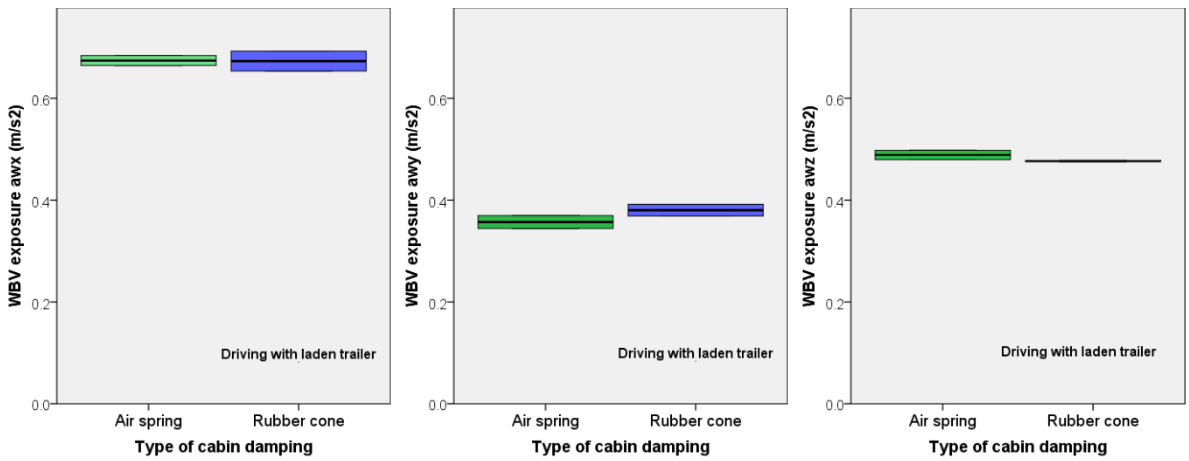

Figure 7: frequency-weighted WBV exposure in the X-direction (left), Y-direction (middle) and Z-direction (right panel) as function of the type of cabin suspension (horizontal axis) for driving on even tarmac with laden trailer. The data shown are clustered for both drivers.

rubber cone suspension situation: 22.7 versus 19.9 km/h. A summary of the data measured and some frequency spectra can be found in the Appendices A and C.

Figure 8 shows the SEAT values measured for both cabin suspension types. SEAT values for the Y and Z axes were only slightly higher compared to the ones measured during driving with empty trailer: 138 and 149 % for Y, and 106 and 94% for Z for air spring and rubber cone cabin suspension, respectively. In contrast, SEAT values in the fore-aft direction were considerably higher

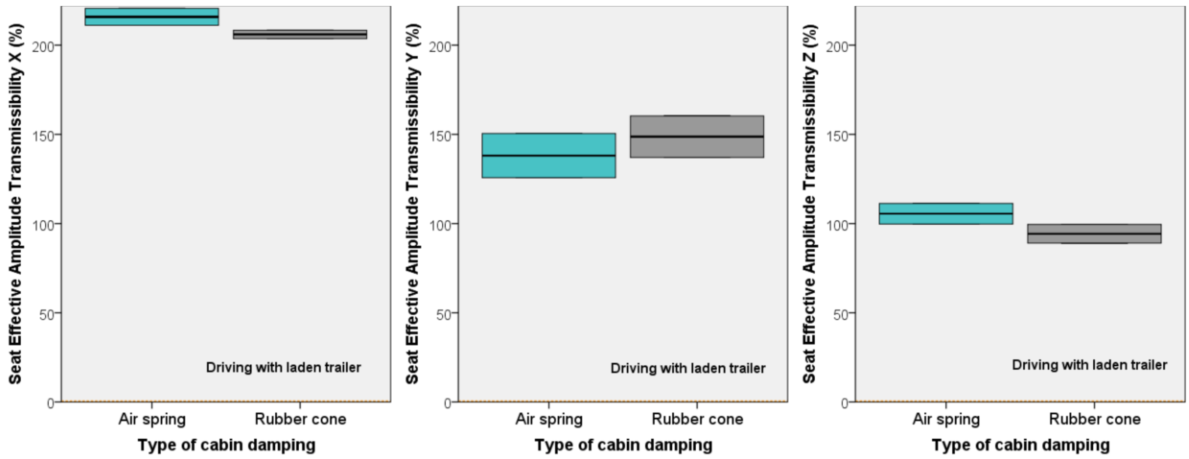

Figure 8: Seat effective amplitude transmissibility (SEAT) in the X-direction (left), Y-direction (middle) and Z-direction (right panel) as function of the type of cabin suspension (horizontal axis) for driving on even tarmac with laden trailer. The data shown are clustered for both drivers.

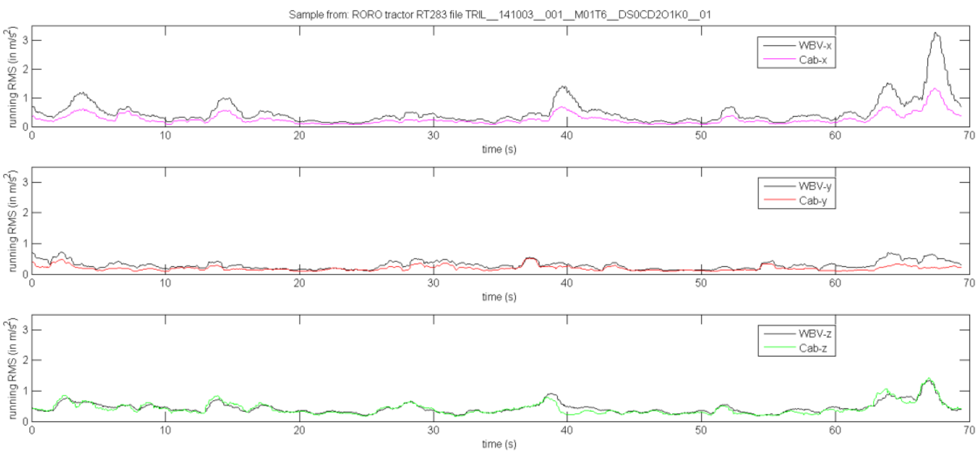

Figure 9: Running RMS of the weighted acceleration data (in m/s^2) along the three axes X (upper panel), Y (middle) and Z (lower panel), measured at the cabin floor (Cab) and on the seat (WBV) for one operator during driving the RORO tractor with a laden trailer. The data shown comprise a period of approximately 70s. The average driving speed for the pattern shown was 26 km/h.

in both situations: 216 and 206% for air spring and rubber cone, respectively. These values mean that the vibrations of the cabin floor along the X-axis are doubled when driving with a laden trailer. In figure 9, this phenomenon is illustrated with help of a running RMS signal registered when driving with laden trailer. The signals measured both at the cabin floor and on the seat for one of the drivers are depicted as a time series. It can be seen that the vertical vibration magnitude most of the time is identical when measured at the cabin floor compared to on the seat (figure 9, lower panel). Vibrations in sideward direction frequently appear to have a larger magnitude on the seat compared to the cabin floor. This is most evident at the vibration peaks: see figure 9, middle panel. The latter phenomenon can be seen most clearly along the X-axis of vibration (figure 9, upper panel). Along this axis, vibrations at the seat most of the time have a higher magnitude compared to that of the cabin floor. It must be stated that the seat was equipped with a mechanical spring in the fore-aft direction, which was unlocked. It is not known whether a comparable effect would have been obtained if driving with the spring blocked, so as if there was no horizontal suspension system present.

3.2.5 Other tasks

Table 9 shows the measurement results of some activities that will occur during RORO work, but which demand for a limited amount of time, compared to the driving activities themselves. More detailed data on the measured values are given in the Appendix A. As expected, turning the seat

Table 9: Whole-body vibration exposure as measured on the seat of the RORO tractor RT during various the tasks and conditions indicated in the fore-aft (X), sideward (Y) and vertical (Z) direction. The values given are mean values over both drivers; for each driver data obtained during different tasks were pooled.

Task	Vibration exposure direction: / Cabin suspension:	X (m/s^2)	Y (m/s^2)	Z (m/s^2)
Turning the seat	Air spring	0.36	1.00	0.24
	Rubber cone (massive)	0.31	0.93	0.22
Make a sharp turn	Air spring	0.78	0.55	0.27
	Rubber cone (massive)	0.58	0.41	0.27
Trailer coupling / uncoupling	Air spring	0.36	0.21	0.20
	Rubber cone (massive)	0.39	0.20	0.21
Ramp driving	solo	1.00	0.41	0.53
	with laden trailer	0.43	0.34	0.43

will result into a vibration exposure mainly in the sideward direction. No effect of type of cabin suspension was seen. Making a sharp turn was measured only for two turns in the case of the air spring cabin suspension situation. This duration is too short to give a highly reliable impression of the exposure in that situation. For this reason, the data on the air spring situation in the table above should be interpreted with care. Coupling and uncoupling of a trailer paralleled rather low vibration exposure, with the highest values, as expected, along the X-axis. Finally, driving the ramp on and off the ship was tested only with the air spring cabin suspension. The situation driving solo for both drivers resulted into an elevated exposure along all vibration axes, but most pronounced in the fore-aft direction, compared to driving with laden trailer. Although driving solo was performed at a slightly higher speed (7 km/h versus 5 km/h with laden trailer), this cannot completely explain the difference between both in the fore-aft direction.

3.2.6 Unloading a ship

Due to practical reasons, ship unloading was measured for only a limited number (seven) of cycles. Ship unloading involved both road trailers (n=2) and specific roll trailers (n=5). The latter demands for a gooseneck being mounted. One cycle consisted of driving solo over the tarmac surface to the ramp of the boat, and entering one of its floors. Within the boat, a trailer was coupled. Thereafter, this trailer was transported to the tarmac-paved area close to the berth and detached. Different floor conditions within the boat compared to the tarmac surface were observed. Besides, to enter the various floors, the tractor had to climb or descend slopes that were provided with a rough surface to prevent sliding. Although the driving speed could not be measured within the boat since no GPS signal was detected there, it was observed from the video registrations that the speed within the boat was lower compared to that on the tarmac area. It will be clear that all of these factors can influence the vibration exposure of the driver.
Table 10 summarizes the outcomes when comparing (a) driving solo on tarmac with and without gooseneck, (b) driving solo – both with and without gooseneck – on tarmac and on the boat floor, and (c) driving with a laden trailer, both road trailer and roll trailer, on tarmac and on the boat floor. Differences between the drivers appeared not systematic. Therefore, the data presented are mean values over both drivers. Driving with a gooseneck mounted was observed to have a slight reducing effect on the vibration exposure. The effect can be well explained considering the mass of the gooseneck. Increased mass of a vehicle in general tends to decrease vibration exposure. However, considering the duration of the measurements of only slightly more than three minutes, this conclusion must be drawn with caution. Definitive conclusions would demand for additional measurements. During driving solo on the boat floor, a moderately higher vibration exposure was seen along the X-axis mainly. Although – again – the measuring time still was very modest (approximately 5-7 minutes), the difference may well be explained by the nature of the boat floor, which was to a certain extent unequal. This effect was not found when comparing tarmac and boat floor for driving with laden trailer: exposures were almost identical. It must be stated that driving with trailer within the boat was done at very modest velocity, and this might have kept the vibration exposure low despite the unfavourable floor conditions.

Table 10: Comparison of the whole-body vibration exposure as measured on the seat of the RORO tractor RT during varying conditions of performing a task, expressed in the fore-aft (X), sideward (Y) and vertical (Z) direction. The values given are mean values over both drivers. The total duration of the measurements is also indicated.

	Vibration exposure direction: Task	Condition:	X (m/s²)	Y (m/s²)	Z (m/s²)	Measurement duration (s)
a	Driving solo on tarmac	without gooseneck	0.62	0.41	0.42	188
		with gooseneck	0.50	0.37	0.26	201
b	Driving solo (with and without gooseneck)	on tarmac	0.56	0.39	0.34	389
		on the boat floor	0.72	0.34	0.45	287
c	Driving with laden trailer	on tarmac	0.36	0.42	0.35	428
		on the boat floor	0.38	0.34	0.38	661

3.3 Interpretation towards a working day

The three scenarios for a daily work pattern as depicted in table 7 – unloading a ship, transport of a trailer and the average scenario in between – were used to calculate daily vibration exposure. In all of the scenarios, driving with trailer was assumed to occur for 25% of the time with empty trailer and for 75% of the time with laden trailer. Furthermore, driving on the ramp of the ship was assumed to occur solo for 50% of the time, and for 50% with laden trailer. For each event, mean values over both drivers, as can be found in Appendix A, were used as input for the calculations of daily exposure. The outcomes are displayed in the figures 10 to 12 and show both the situation with air spring cabin suspension and that with rubber cone suspension. It must be stated that event "driving on the ramp" was measured only in the case of the air spring suspension mounted. To be able to calculate daily exposure values for the rubber cone suspension situation, the exposure values measured for this event in the air spring situation were used. Daily vibration exposures have been calculated for the work patterns described in table 7, which assume that RORO activities are performed for 6 hours per working day. This implies that a normal working day will include a total of slightly more than 5 hours of different activities that have whole-body vibration exposure, while during the remainder of the day no exposure is assumed. In addition to this, a "worst case" scenario was calculated, which meant that the RORO activities themselves endured for the full 8-hour working day (instead of the 6 hours of table 7). The relative duration of the individual activities was kept the same compared to that in table 7.

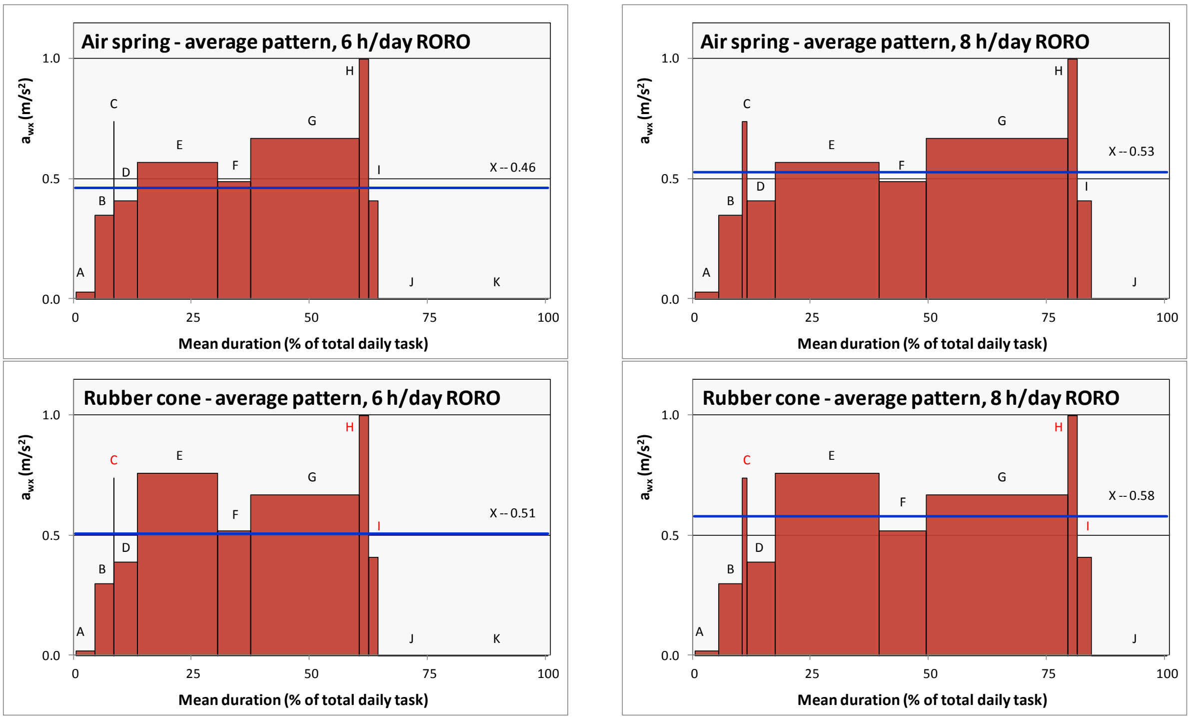

Figure 10: Calculation of the daily exposure to WBV a_w (in m/s^2; blue horizontal line; the value and dominant axis are indicated above the line at right) and the exposure values of the events distinguished (A-K; see below) for an average working day pattern (see table 7, middle column). The duration of the events is shown relative to a full working day (horizontal axis). Panels show RORO tasks performed for 6 hours (left) and 8 hours (right) per working day. Both upper panels show the outcomes for using an air spring cabin suspension; the lower ones for the rubber cone cabin suspension. Explanation of the event letters: A: sitting on a stationary machine, engine running idle; B: turning the seat; C: making a sharp turn; D: coupling or uncoupling of a trailer; E: driving solo; F: Driving with empty trailer; G: driving with laden trailer; H: driving solo on ramp; I: driving on ramp with laden trailer; J: not sitting on the seat during RORO work; K: other tasks, not with a RORO tractor. The red-coloured letters C, H and I indicate that their exposure values have been taken from the air spring situation.

Figure 10 illustrates that an average working day pattern of RORO activities for 6 hours per working day and using an air spring cabin suspension will result in a daily WBV exposure slightly below the action value of the European vibration directive: 0.46 m/s^2 RMS. The dominant vibration axis appeared to be the X-axis (fore-aft). Daily exposure values for both other vibration directions are 0.35 m/s^2 (Y) and 0.33 m/s^2 (Z; see Appendix A, final table). The activity "driving with a laden trailer" (G in the figure 10) contributed most dominant to the daily exposure value: it determined 28% of the total exposure. If, however, it was assumed that the RORO activities endure the full 8 hours of a working day, the daily exposure will exceed the action value, and actions should be taken to lower the WBV exposure. Since driving with laden trailer contributes most dominant, and it has been shown clearly that the vibration exposure on the seat is higher compared to the cabin floor, it is advised to improve the effectiveness of the seat damping along the fore-aft axis. Using a massive rubber cone as cabin suspension will result into an elevated daily exposure vibration, such that an average daily work pattern for both 6 and 8 hours of RORO activities will exceed the action value. Average vibration exposure values for the 6 hour work pattern were 0.51, 0.37 and 0.36 for X, Y, and Z, respectively. Again, driving with laden trailer contributes most to the daily exposure: 22%. This was slightly more than the 20% contribution of driving solo.

Figure 11 summarizes the daily WBV exposure calculation for the trailer transport working pattern (see table 7, right column). In this scenario, making sharp turns and driving over the ramp of a ship are excluded from the calculations. Despite this, the estimations of daily vibration exposure appear rather comparable with the scenario described above for the average working pattern. The contribution of driving with laden trailer increased to 36% and 28% of the daily exposure measure in the air spring and rubber cone cabin suspension situation, respectively.
For the working pattern “unloading a ship” the evaluation of the daily WBV vibration exposure is depicted in figure 12. Again, the outcomes for the different scenarios are highly comparable with those for the average working pattern shown in figure 10. The contribution of driving with laden trailer was 24% and 18% of the daily exposure measure for air spring and rubber cone cabin suspension, respectively.

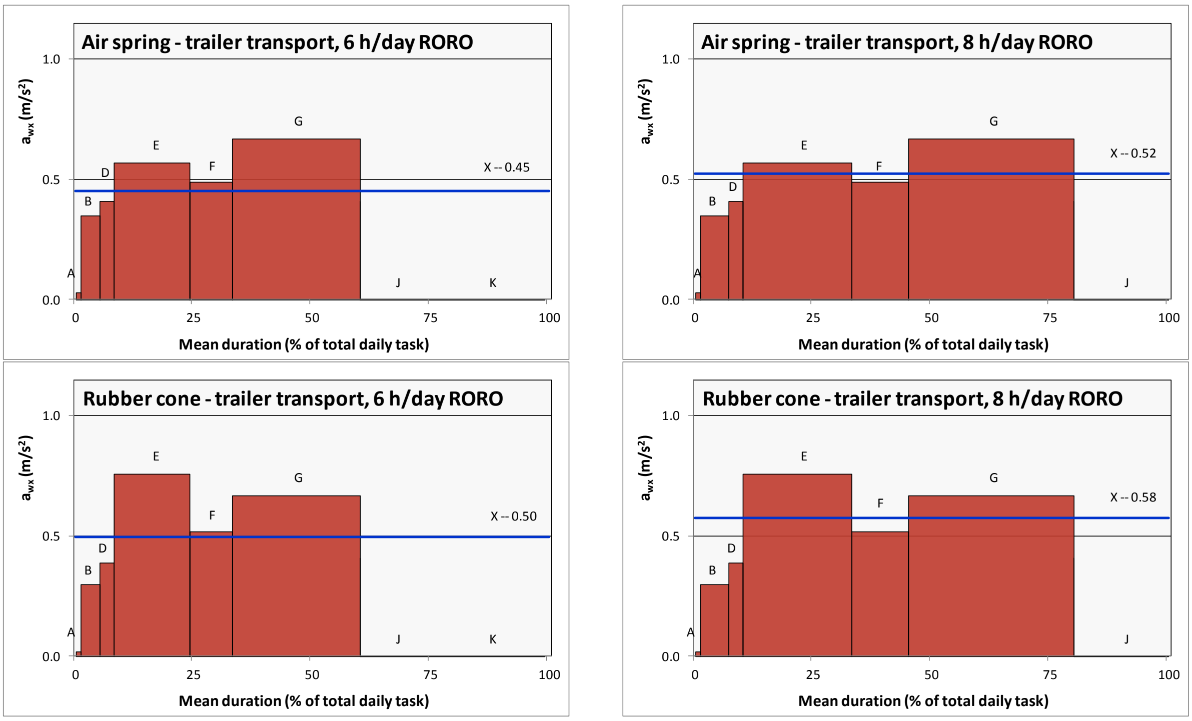

Figure 11: Calculation of the daily exposure to WBV a_w (in m/s^2; blue horizontal line; the value and dominant axis are indicated above the line at right) and the exposure values of the events distinguished (A-K; see below) for a trailer transport working day pattern (see table 7, right column). The duration of the events is shown relative to a full working day (horizontal axis). Panels show RORO tasks performed for 6 hours (left) and 8 hours (right) per working day. Both upper panels show the outcomes for using an air spring cabin suspension; the lower ones for the rubber cone cabin suspension. Explanation of the event letters: A: sitting on a stationary machine, engine running idle; B: turning the seat; D: coupling or uncoupling of a trailer; E: driving solo; F: Driving with empty trailer; G: driving with laden trailer; J: not sitting on the seat during RORO work; K: other tasks, not with a RORO tractor.

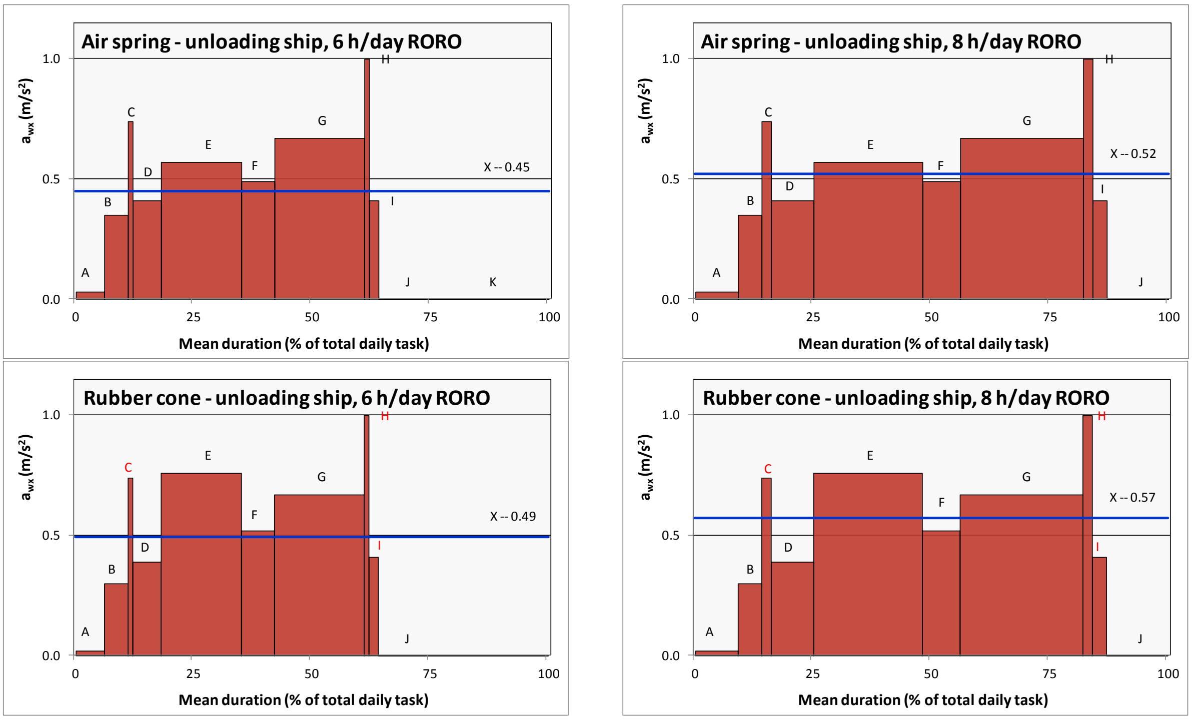

Figure 12: Calculation of the daily exposure to WBV a_w (in m/s^2; blue horizontal line; the value and dominant axis are indicated above the line at right) and the exposure values of the events distinguished (A-K; see below) for the unloading ship working pattern (see table 7, left column). The duration of the events is shown relative to a full working day (horizontal axis). Panels show RORO tasks performed for 6 hours (left) and 8 hours (right) per working day. Both upper panels show the outcomes for using an air spring cabin suspension; the lower ones for the rubber cone cabin suspension. Explanation of the event letters: A: sitting on a stationary machine, engine running idle; B: turning the seat; C: making a sharp turn; D: coupling or uncoupling of a trailer; E: driving solo; F: Driving with empty trailer; G: driving with laden trailer; H: driving solo on ramp; I: driving on ramp with laden trailer; J: not sitting on the seat during RORO work; K: other tasks, not with a RORO tractor. The red-coloured letters C, H and I indicate that their exposure values have been taken from the air spring situation.

The average working pattern (table 7, middle column) for a 6-hour RORO activities working day is also evaluated on vibration peaks and shocks, using the vibration dose values VDV and the S_{ed} evaluation tools. The calculation is done under the assumption that the exposure of driving on the tractor endures slightly more than 5 hours, while a full working day endures 8 hours (i.e. t_d = 28800 s). In practice, working days of longer and shorter duration may occur. Furthermore, it was assumed that the work is done all year long, so around 240 days/year.

Both VDV and S_{ed} appeared higher if the rubber cone was applied as cabin suspension.

VDV was highest along the fore-aft axis, having values of 10.92 m/s$^{1.75}$ and 12.10 m/s$^{1.75}$ for air spring and rubber cone, respectively. Since these values both exceed the action value of 9.1 m/s$^{1.75}$, it is advised to reduce exposure to more intense vibrations in the fore-aft direction. Again, driving with laden trailer and driving solo contributed most. Compared to the X-axis, VDV for the Y-axis was slightly lower: 10.78 and 10.40 $m/s^{1.75}$ (air spring and rubber cone). Also these values exceed the action value of 9.1 $m/s^{1.75}$. The event "turning the seat" is the main contributor to this exposure value by far. The rotational speed of the seat is determined by the speed of rotating the steering wheel by the driver and their coupling is immediate. It might be an idea to implement an indirect coupling here, so that at least the start and stop of the seat rotation become more smooth. VDV values for the vertical vibration remain well below the action limit: 6.7 and 7.0 $m/s^{1.75}$ for air spring and rubber cone.

Also the evaluation of the S_{ed} as a measure of the exposure to vibration peaks and shocks shows that there is a moderate probability of adverse health effects[2]: values were 0.50[3] and 0.51 MPa for air spring and rubber cone, respectively. The main contributor to this exposure to shocks appeared to be the "turning the seat" activity. This indicates that the vibration peaks as a result of the rotation of the seat should be taken serious and are advised to be reduced. Of course, here is also a behavioural aspect present, like in driving speed, acceleration rate, etc., but a technical solution would prevent vibration peaks to occur in all cases.

A summary of the outcomes of the calculations of VDV and S_{ed} is given in the final table of Appendix A.

[2] *The ISO-2631-5 (2004) directive indicates that the estimation of the probability of adverse health effects are based on in vitro studies of the bone mineral density decay with increasing age and vibrational load, and the limits assume exposure during a full working life of 45 years. The borders that are indicated in the directive (see also: table 4 of the present report) have not been validated in epidemiologic research and, therefore, should not be explained too stricly. However, there are indications that the values given in the ISO-2631-5 (2004) directive tend to underestimate the health risk of the lumbar spine. This was concluded by Bovenzi et al., 2014 (see reference list) on basis of their analysis of 537 occupational drivers.*

[3] *Note that this value is just at the border between low and moderate probability of adverse health effects. Besides, the directive is not very clear whether the value of 0.5 MPa belongs to the low or moderate probability category. In order to protect employees at best and also seen in the light of the previous comment, in the present report the value of 0.5 MPa is considered to be a moderate health risk.*

4 Conclusions and recommendations

From the present measurements, the following can be concluded:

- The fore-aft axis is dominant in whole-body vibration exposure of the driver of a RT RORO tractor during normal work tasks. The activities that most importantly contribute to the WBV exposure are driving with laden trailer and solo driving.
- The turning of the seat results into peaks in the vibration exposure in the lateral direction.
- The seat mounted is not at all effective in reducing vibrations in the horizontal plane and only to a limited extent in reducing the vertical vibrations. The lack of effectiveness in the fore-aft direction was most obvious when driving with a laden trailer.
- Vibration exposure along all of the vibration axes appears to be slightly lower when an air spring was mounted as cabin suspension, compared to a massive rubber cone.
- If applying an estimated daily activities pattern based on the current set of activities, the vibration exposure levels were such that only if RORO work is done for approximately 6 hours per day and an air spring cabin suspension is mounted, the daily exposure evaluated by the root-mean-square method indicates that the work can be performed without health risks. However, if the work is evaluated using evaluation methods that also include the effect of vibration exposure peaks, VDV and S_{ed}, it should be mentioned that a low to moderate probability of adverse health effects is present. If the RORO work is done for more than 6 hours per working day, the probability of adverse health effects will increase.

In order to reduce vibration exposure the following is recommended:

- The transmissibility of vibrations from cabin floor to seat should be reduced, especially along the fore-aft axis. This is especially important when driving with laden trailer and driving solo, since these activities dominate vibration exposure on a RORO tractor.
- Since the frequently occurring rotation of the seat is the main cause of the peaks in vibration exposure, it is advised considering uncoupling of rotation of the steering wheel and the seat, in order to make the rotation of the seat more smooth.
- The air spring cabin suspension is advised to be mounted as a standard. Note that this should be re-evaluated if a different type of seat suspension will be applied.

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Appendix A – Measurement values of WBV exposure during different tasks of the RORO tractor, and for a simulated work day

Terms used:

reference axis : axis of the vibration measurement
cabin suspension : type of cabin suspension: 1=air spring, 2=massive rubber cone
task : task performed: 1=stationary solo, 3=stationary empty trailer, 4=driving empty trailer, 5= stationary laden trailer, 6=driving laden trailer, 8=unloading a ship
t_m : total time measured in s
average speed : average driving speed in km/hour
meas. (n) : number of measurements
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 value 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

Sitting on RORO tractor RT___ standing stationary with engine running idle

reference axis	cabin suspension	task	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						0.02	0.08	0.129				
y	1	1	169	0	4	0.04	0.15	0.34	0.01			
z						0.09	0.32	0.42				
x						0.03	0.11	0.31				
y	1	3	172	0	5	0.03	0.15	0.30	0.01			
z						0.05	0.19	0.30				
x						0.03	0.11	0.18				
y	1	5	151	0	5	0.02	0.08	0.21	0.01			
z						0.05	0.19	0.27				
x						0.02	0.05	0.083				
y	2	1	84	0	9	0.02	0.08	0.18	0.01			
z						0.03	0.11	0.18				
x						0.02	0.05	0.10				
y	2	3	86	0	7	0.02	0.05	0.19	0.01			
z						0.03	0.09	0.12				
x						0.02	0.05	0.10				
y	2	5	86	0	6	0.01	0.05	0.17	0.01			
z						0.03	0.09	0.13				
x						0.03	0.14	0.33				
y	1	all	492	0	14	0.03	0.18	0.41	0.02			
z						0.07	0.34	0.44				
x						0.02	0.07	0.14				
y	2	all	256	0	22	0.02	0.09	0.22	0.01			
z						0.03	0.14	0.21				

Solo driving on even tarmac with a RORO tractor RT (without goose neck)

reference axis	cabin suspension	task	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						0.58	3.69	6.867				
y	1	4	334	15	10	0.46	2.40	5.36	0.21			
z						0.40	2.51	4.92				
x						0.61	3.69	7.71				
y	1	6	341	16	8	0.48	2.61	5.10	0.20			
z						0.43	2.52	5.34				
x						0.57	3.83	7.65				
y	1	8	287	19	14	0.41	2.14	4.66	0.20			
z						0.39	2.45	5.70				
x						0.76	4.87	9.619				
y	2	4	367	21	10	0.53	2.89	6.37	0.46			
z						0.52	2.92	5.23				
x						0.78	5.08	10.04				
y	2	6	360	21	10	0.53	2.80	6.40	0.25			
z						0.54	3.16	6.70				
x						0.58	5.00	9.86				
y	1	all	961	18	32	0.45	3.19	6.20	0.25			
z						0.41	3.38	6.56				
x						0.77	5.93	11.10				
y	2	all	727	21	20	0.53	3.39	7.17	0.27			
z						0.53	3.62	7.02				

Driving on even tarmac with a RORO tractor RT with empty road trailer

reference axis	cabin suspension	task	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						0.49	3.81	6.88				
y	1		752	21	15	0.41	2.69	5.51	0.21			
z						0.46	3.03	5.40				
x						0.53	4.12	8.33				
y	2		580	25	11	0.42	2.61	5.51	0.21			
z						0.47	2.84	5.06				

Driving on even tarmac with a RORO tractor RT with laden road trailer

reference axis	cabin suspension	task	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						0.67	5.78	11.21				
y	1		917	20	18	0.36	2.45	4.26	0.21			
z						0.49	3.34	5.86				
x						0.67	5.65	12.04				
y	2		647	23	13	0.38	2.45	4.54	0.20			
z						0.48	3.01	5.13				

Turning the chair when sitting on RORO tractor RT	standing stationary with engine running idle (solo, empty and laden trailer)											
reference axis	cabin suspension	task	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						0.36	2.03	4.05				
y	1	all	259	0	60	1.00	7.27	11.04	0.39			
z						0.24	1.99	2.41				
x						0.31	1.54	2.96				
y	2	all	166	0	34	0.93	6.21	10.10	0.35			
z						0.22	1.36	2.26				

Make a sharp turn on even tarmac with a RORO tractor RT												
reference axis	cabin suspension	task	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						0.78	2.74	4.79				
y	1		23	3	3	0.55	2.21	2.66	0.05			
z						0.27	0.90	1.47				
x						0.58	2.53	4.61				
y	2		97	3	6	0.41	1.54	3.11	0.11			
z						0.27	1.06	1.68				

Coupling and uncoupling of a trailer with a RORO tractor RT												
reference axis	cabin suspension	task	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						0.36	3.14	5.51				
y	1	all	285	1	27	0.21	1.39	3.02	0.11			
z						0.20	1.28	2.20				
x						0.39	1.85	3.05				
y	2	all	102	1	13	0.20	0.83	1.83	0.07			
z						0.21	1.02	1.70				

Driving on a ramp solo of with laden trailer with a RORO tractor RT												
reference axis	Trailer / solo	Trailer type	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						1.00	3.54	6.92				
y	Solo	all	56	7	8	0.41	1.51	2.65	0.12			
z						0.53	1.72	3.00				
x						0.43	1.96	4.60				
y	Trailer	all	123	5	8	0.34	1.36	2.45	0.13			
z						0.43	1.85	3.87				

Estimated daily exposure on RORO tractor RT	on basis of the average working pattern (see table 7 in the main text on p. 23)										
reference axis	cabin suspension	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					0.46					10.92	
y	1	3869		185	0.35				28800	10.78	0.50
z					0.34					6.70	
x					0.51					12.10	
y	2	2753		135	0.37				28800	10.40	0.51
z					0.36					7.00	

NOTE : cabin suspension 1 = air spring, 2 = rubber cone. Calculations are based on extrapolation of the present measurements to an average daily working pattern (see table 7). In this pattern, a driver is sitting on the chair of the tractor for slightly more than 5 h/day. Driving on the ramp of the ship is only measured with the air spring cabin suspension (=1); these data have also been used for calculating daily exposure in the situation of the rubber cone cabin suspension.

Appendix B – The machinery used

RT with front weight mounted

RT during roll-on / roll-off

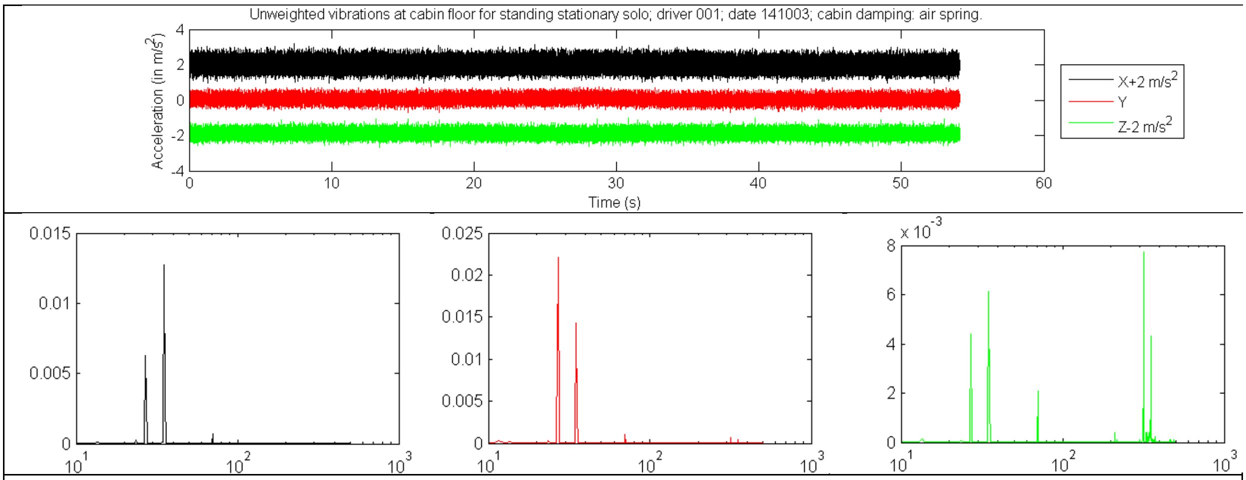
ISRI 6860 / 880 seat

RT with detachable gooseneck

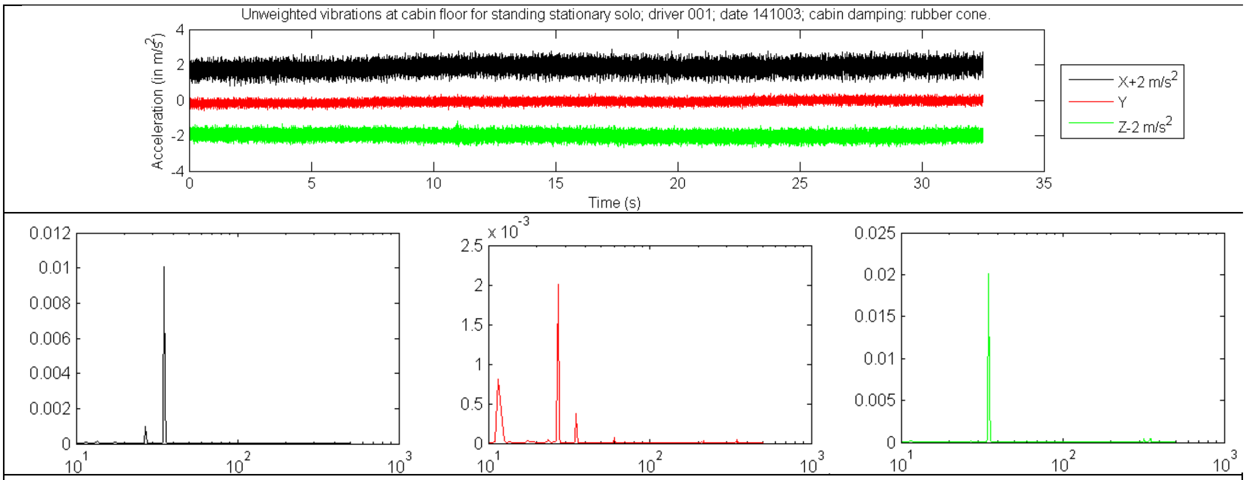
Empty Groenewegen trailer

Laden Groenewegen trailer

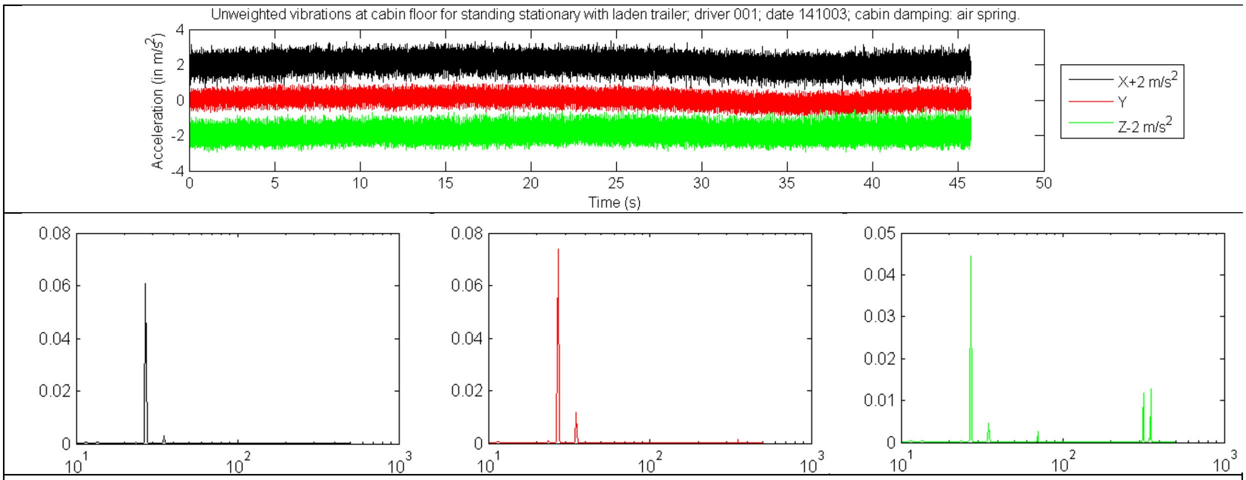
Appendix C – Frequency spectra



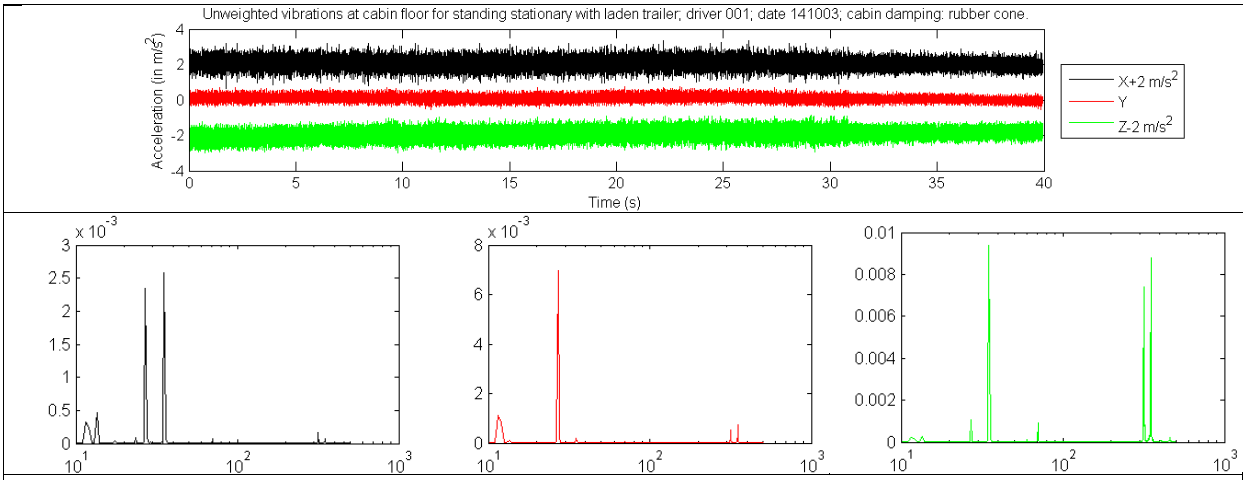
Time series (upper panel) and frequency plots (X, Y, Z) for cabin floor measurements; tractor standing solo stationary with engine running idle; air spring cabin suspension



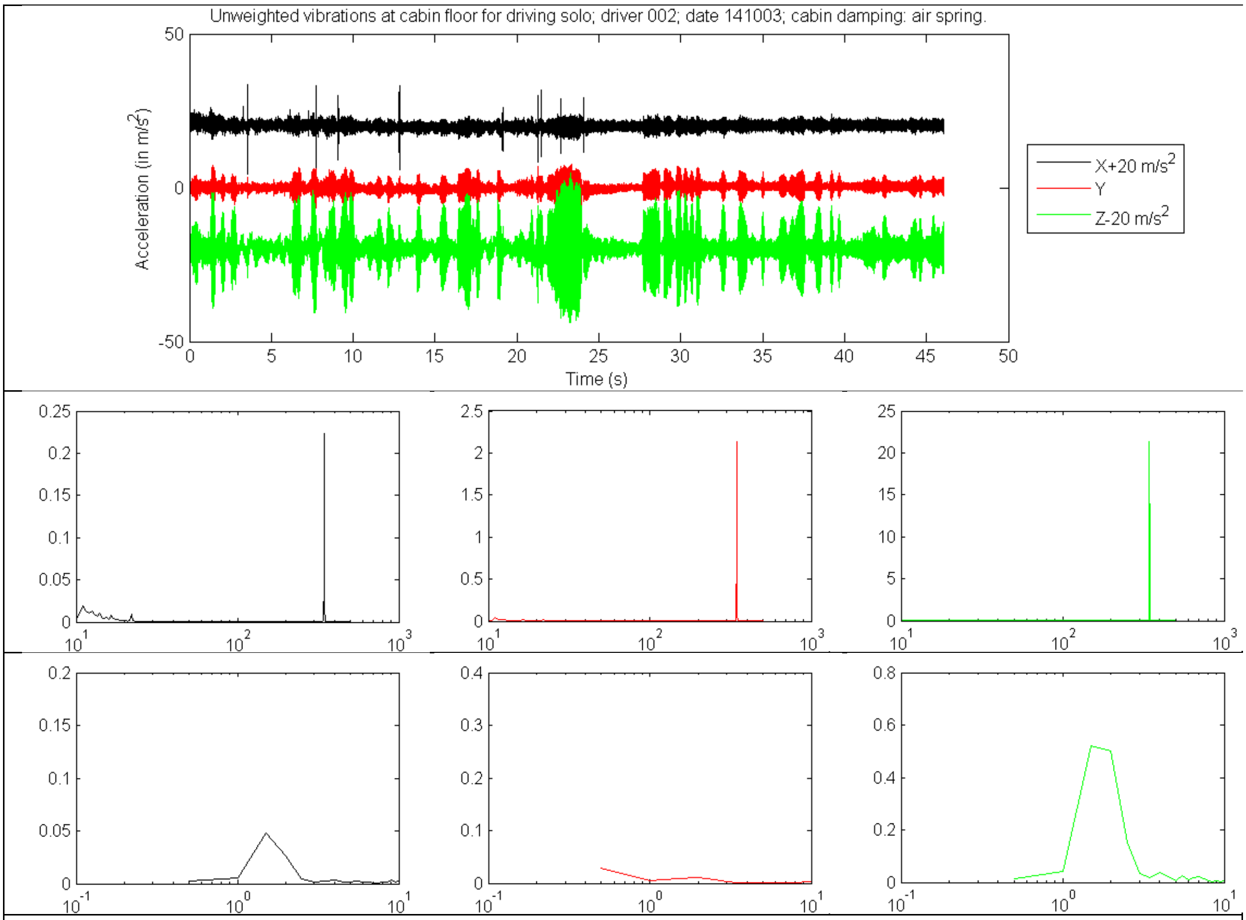
Time series (upper panel) and frequency plots (X, Y, Z) for cabin floor measurements; tractor standing solo stationary with engine running idle; rubber cone cabin suspension



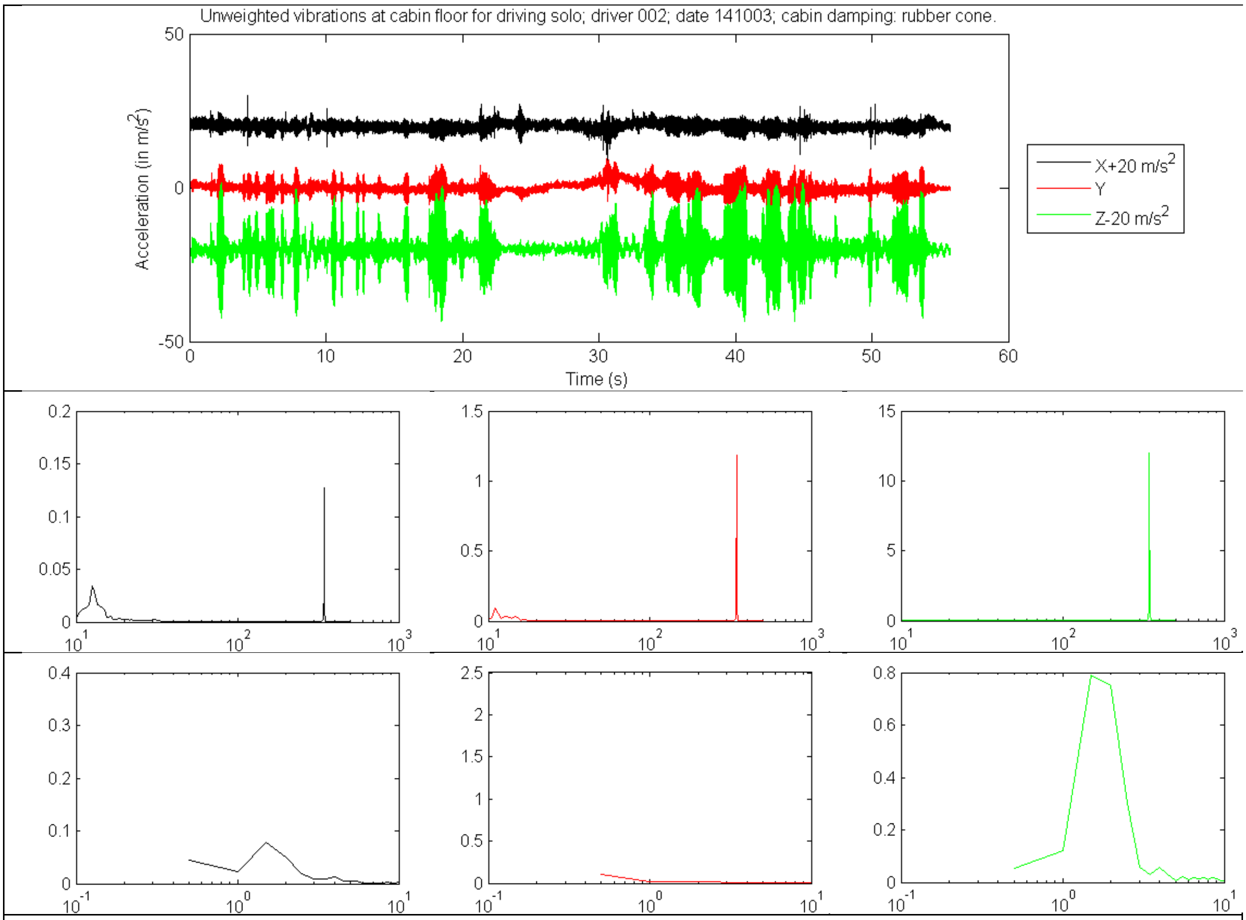
Time series (upper panel) and frequency plots (X, Y, Z) for cabin floor measurements; tractor standing stationary with laden trailer with engine running idle; air spring cabin suspension



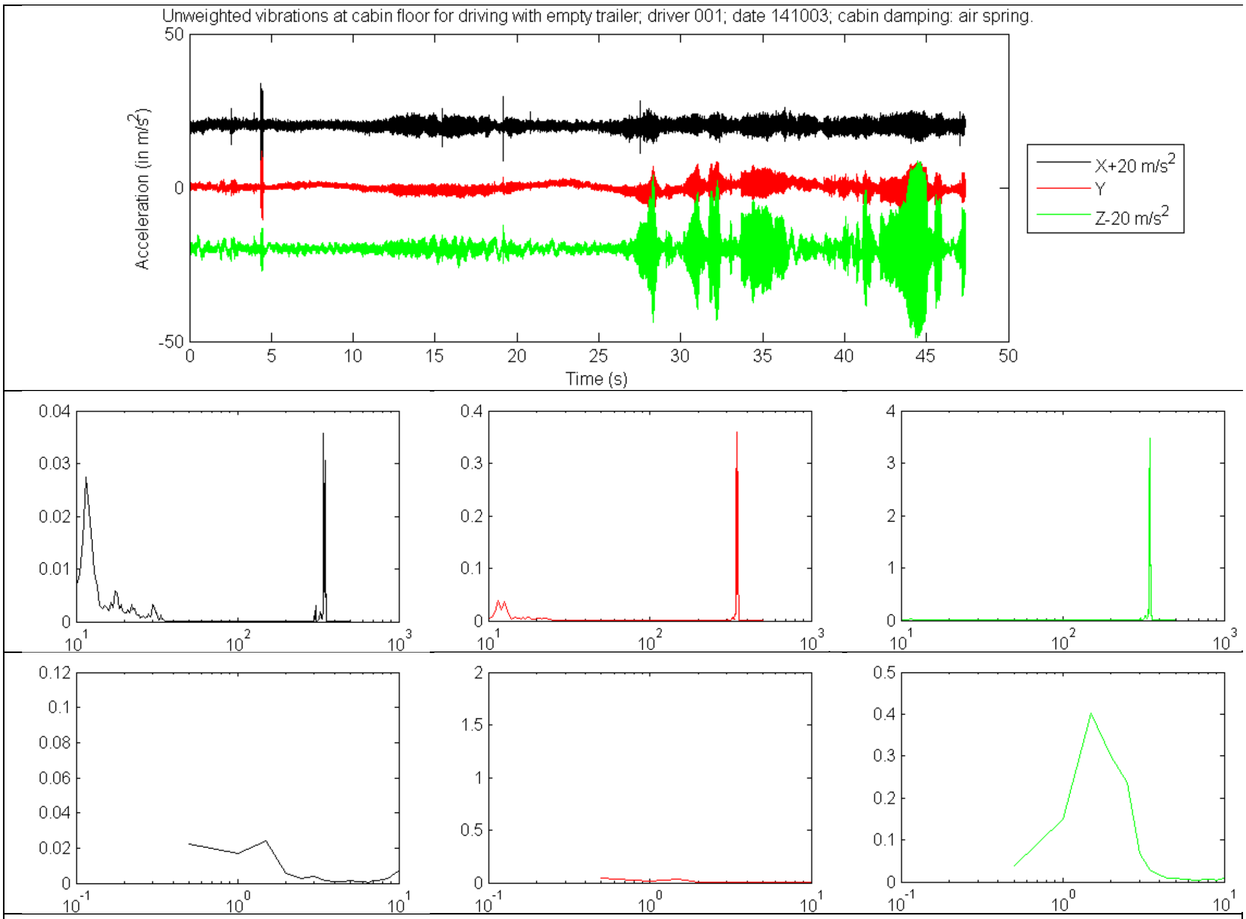
Time series (upper panel) and frequency plots (X, Y, Z) for cabin floor measurements; tractor standing stationary with laden trailer with engine running idle; rubber cone cabin suspension



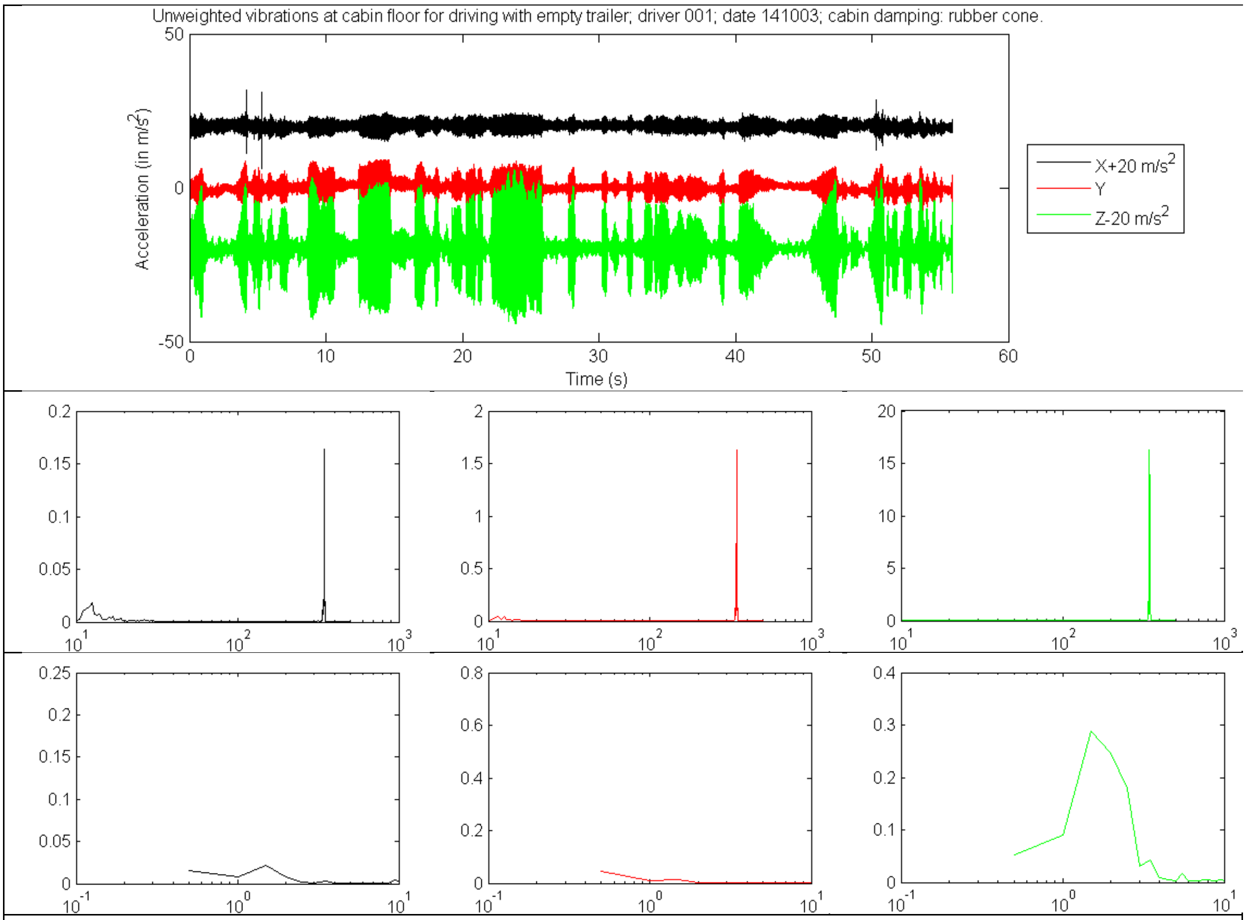
Time series (upper panel) and frequency plots (X, Y, Z; note the different scales) for cabin floor measurements; tractor driving solo; air spring cabin suspension



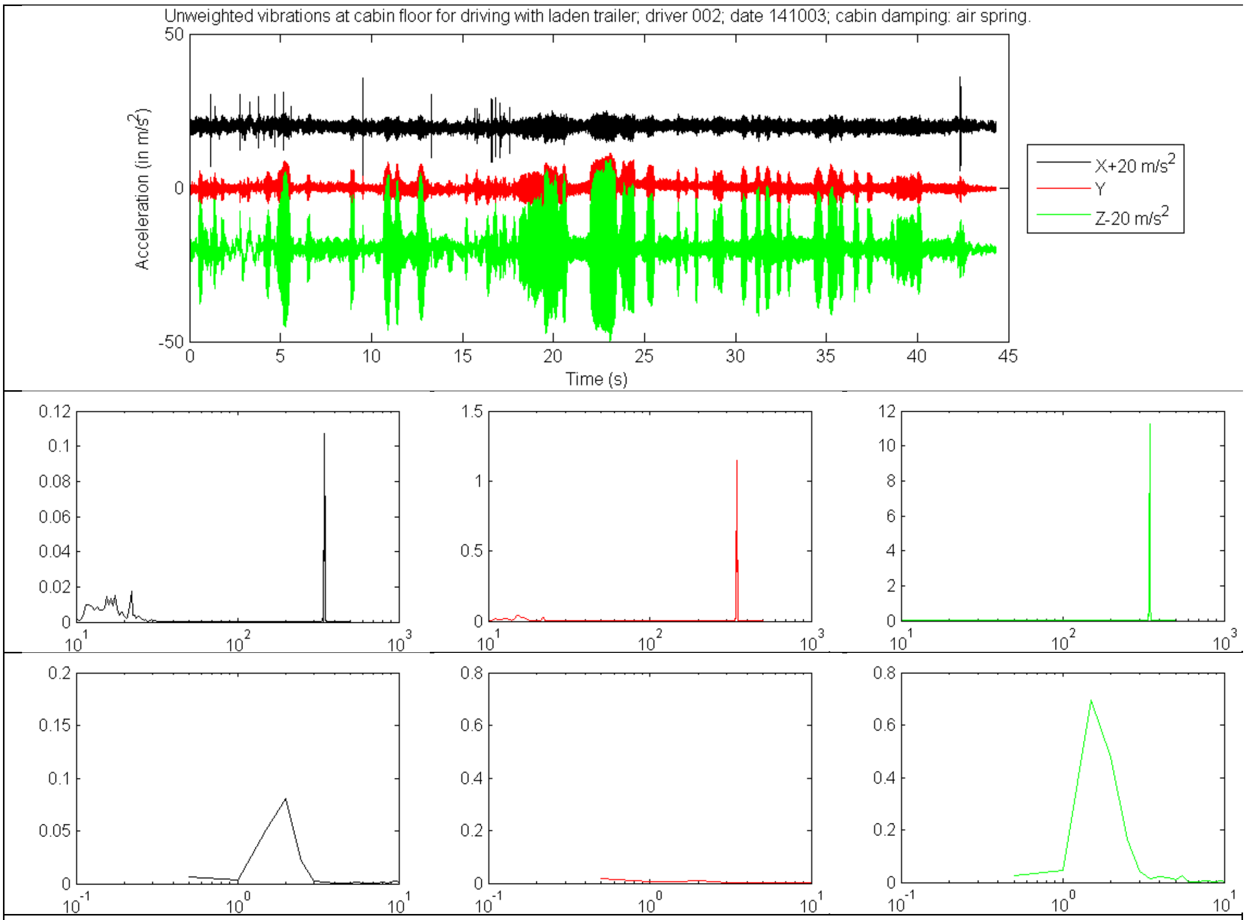
Time series (upper panel) and frequency plots (X, Y, Z; note the different scales) for cabin floor measurements; tractor driving solo; rubber cone cabin suspension



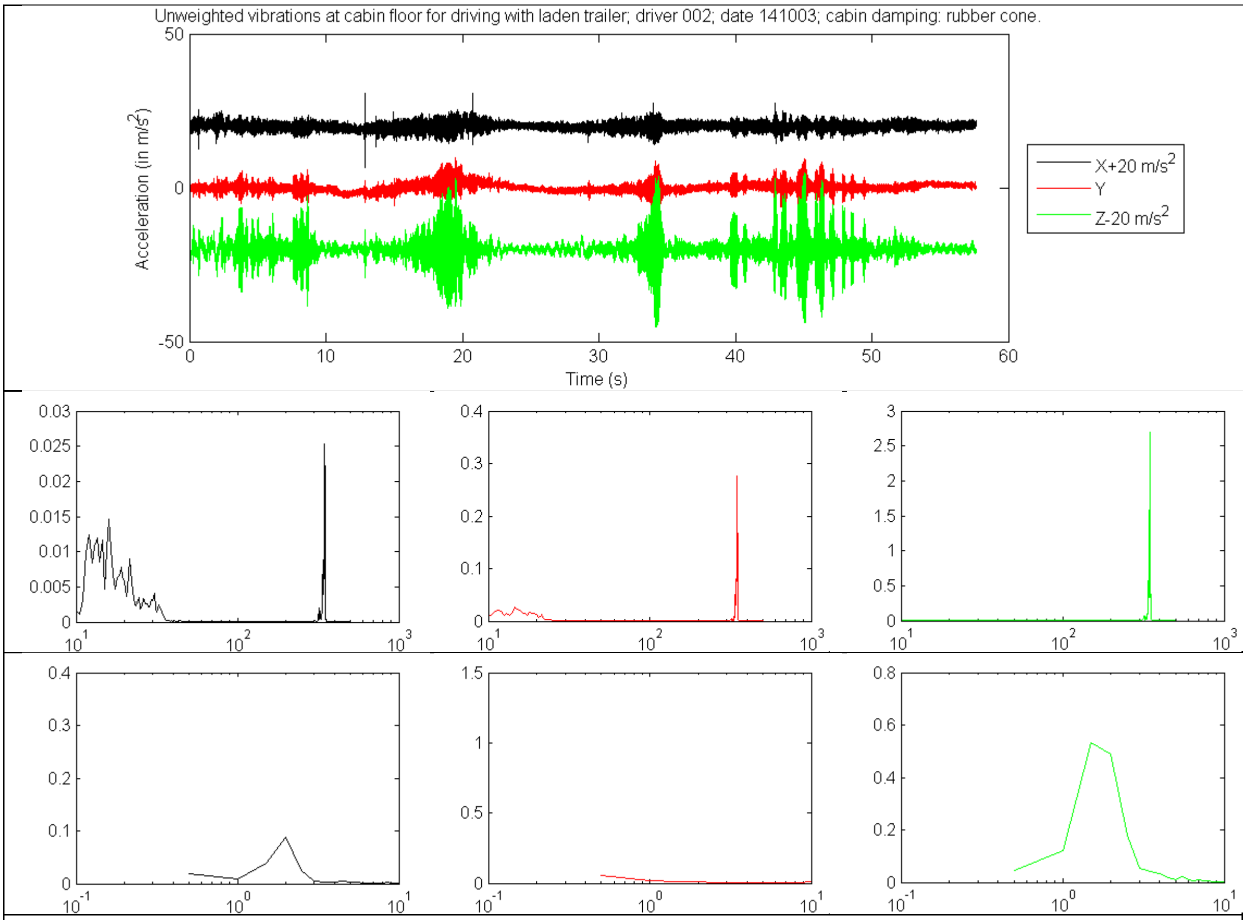
Time series (upper panel) and frequency plots (X, Y, Z; note the different scales) for cabin floor measurements; tractor driving with empty trailer; air spring cabin suspension



Time series (upper panel) and frequency plots (X, Y, Z; note the different scales) for cabin floor measurements; tractor driving with empty trailer; rubber cone cabin suspension



Time series (upper panel) and frequency plots (X, Y, Z; note the different scales) for cabin floor measurements; tractor driving with laden trailer; air spring cabin suspension



Time series (upper panel) and frequency plots (X, Y, Z; note the different scales) for cabin floor measurements; tractor driving with laden trailer; rubber cone cabin suspension