ErgoLab Research

knowledge works better !

profi MAGAZIN FÜR PROFESSIONELLE AGRARTECHNIK

TRACTORS profi AND FARM MACHINERY

TREKKER

Final report tractor suspension test 2012

Comparison of high-power agricultural tractors: effect on whole-body vibration exposure during a standardized test in practice

Vergelijking van hoog-vermogen agrarische tractoren: effect op de blootstelling aan trillingen tijdens een gestandaardiseerde test in de praktijk

Huub H.E. Oude Vrielink

Report 2012-0601

Final report tractor suspension test 2012

Comparison of high-power agricultural tractors: effect on whole-body vibration exposure during a standardized test in practice

Vergelijking van hoog-vermogen agrarische tractoren: effect op de blootstelling aan trillingen tijdens een gestandaardiseerde test in de praktijk

Huub H.E. Oude Vrielink

Report 2012-0601

Colophon

About ErgoLab Research B.V. ‘Knowledge works better’

ErgoLab Research was established in 2006 out of Wageningen University & Research Centre (Wageningen UR). ErgoLab Research aims to transfer and apply specialist knowledge and skills in the area of work and health to working people, government, educational institutions and society in a understandable way, by testing, training, consultancy, measurements & research and coaching. Know-how and skills have been developed in more than 24 years of experience in fundamental and applied research. The area that is covered is broad and consists of labour and labour conditions, engineering and technology, physiology, health behaviour, and physical load, sports and health.

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.:

- Measurement of the daily exposure to whole-body vibration during internal transportation of sand-lime brick using forklift trucks (2012)
- Exposure to whole-body vibration and effectiveness of chair damping in high-power agricultural tractors having different damping systems in practice (2009)
- Analysis of the exposure to whole-body and hand-arm vibrations using agricultural tractors (2007)

Title	Comparison of high-power agricultural tractors: effect on whole-body vibration exposure during a standardized test in practice
Author(s)	Huub H.E. Oude Vrielink
Report number	2012-0601
ISBN-number	
Date of publication	July 2012
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

To test the effectiveness of active cabin suspension on vibration exposure of the driver, five modern agricultural tractors were tested with and without pulling a loaded trailer at two different speed patterns (15 km/h constant, and 20-30 km/h variable) on an unequal but paved track with help of two drivers of different body weight. On four of the tractors, an active cabin suspension system was mounted; the fifth tractor, which had a passive mechanical cabin suspension, served as control. Besides, driving behaviour in practice was measured for three different seasonal tasks (transportation of mast, soil, and silage) during one working day of five different contract workers with help of a GPS device.

Vibration was measured on the seat in accordance with ISO (2631-1, 1997, 2631-5, 2004) along the 3 standard axes. In addition, vibration of the tractor cabin at the chair base was measured to determine the effectiveness of damping of the chair. Vibration signals were displayed and stored digitally on a laptop computer. Processing of the data occurred off-line and included only the straight parts of the track.

Each tractor was driven two times by the two drivers. The variation between repetitions and drivers appeared small, in comparison to the effect of trailer and speed, so that these data were pooled.

Because the test track appeared to be more damaged and unequal compared to a similar test performed in 2009, the test results cannot be fully compared: vibration exposure at present is likely to be considerably higher.

The active cabin suspension systems on the tractors appeared to be effective in reducing vertical vibration exposure of the driver. However, the horizontal vibration dominated the exposure: for some tractors at low speed this occurred along the lateral axis, but most often it was the longitudinal (forward-backward) axis. Trailer pulling and increased driving speed enhanced this longitudinal vibration exposure, more than that along the lateral axis. Vertical vibration exposure increased only with speed.

It is unknown whether the present exposure values obtained on the rough test track are representative for the situation in normal practice. If, however, this is considered to be the case, and the exposure measurements are combined with the driving behaviour of typical contract workers tasks, then the vertical vibration exposure remains under or near the action value for a whole working day for all of the tractors with active cabin suspension. In contrast, none of these remained below the action value when evaluating the forward-afterward vibration exposure. Hence, these horizontal vibrations limit the daily maximal working time. Three of the tractors, all having an active cabin suspension system, exceeded the action value modestly to moderately. One of the tractors with active cabin suspension did not perform better than the tractor without active suspension in this respect.

The one tractor that demonstrated the best performance in the forward-backward and vertical directions showed a relatively large instability over the lateral axis. Although this axis was not dominating vibration exposure in most cases, it contributed considerably to an increased sensitivity for multiple shocks.

Finally, the chairs mounted in the actively suspended cabins appeared effective in further reducing the vertical vibrations. However, they did not reduce, sometimes even enhance, the vibrations in the horizontal plane, especially along the forward-backward axis. In an attempt to further improve vibration damping, attention should be paid to the effectiveness of damping of the chair in the horizontal plane.

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, tractor work.

Content

Preface

This document reports the testing by ErgoLab Research of five modern agricultural tractors on vibration exposure and comfort of the driver. The test was a logical follow-up of the testing performed in 2009, and again the initiative of the farm machinery magazines Trekker, being a division of Reed Business, and Profi International. And again, a strive for objective data on tractor make and configuration options for the exposure in practice of the driver to whole-body vibrations was the direct reason. ErgoLab Research, performing independent research and consultancy and aiming to gather and transfer specialist knowledge, was asked to perform the measurements and to present the outcomes firmly and clear.

The following persons and companies are kindly acknowledged:

- the machinery magazines Trekker and Profi Magazine 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 driving their rounds, and the drivers Toon, Jan-Paul, Hans, Gert-Jan, and Kevin for volunteering the gps measurements;
- the following agricultural contractors that voluntarily participated in the gps measurements: Derks Agra (Nijmegen), Gerritsen (Heelsum) and Rauw & Zn. (Achterberg);
- the suppliers and manufacturers of the machinery.

1 Introduction

There is an important tendency among manufacturers of agricultural tractors to make their machinery more comfortable and safe for the driver during normal use in practice. With respect to a reduction of whole-body vibration exposure, a large variety of damping systems have been developed and applied. One may think of front and rear axle damping systems, separate systems to fully or partly damp the driver cabin, and various options in seat damping. The materials and techniques applied can be passive mechanical damping using metal springs, dampers, or rubber blocks, but also air suspension, in combination with pneumatic systems. Finally, also active control of accelerations and damping characteristics are applied.

Whether these systems are equally effective in control of accelerations and reduction of vibration exposure during conditions as found in practice is unclear. Therefore, in 2009 Trekker and Profi Magazine organized a test with 10 agricultural tractors of different make and having different suspension systems. The outcomes on whole-body vibration exposure during driving at different speeds and with different loads over an unequal but paved trajectory were meant to serve their international readership. The main outcomes (see: Oude Vrielink, 2009) were that

- the horizontal forward-backward vibration axis appeared to be dominant during driving, limiting the working time given the values specified by the EU;
- trailer pulling and faster driving, independently, resulted in a strongly increased exposure to these longitudinal vibrations;
- the difference in exposure between the various tractors was considerable;
- damping of cabin and / or axles resulted in a substantially lower vibration exposure;
- if the outcomes of the test were 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.

Since 2009, some manufacturers have developed more sophisticated cabin suspension systems and applied them in their tractors. In the present research, the effect of the application of four of these modern systems is evaluated. To be able to compare the outcomes with those of the 2009 test, the same track, drivers, driving speeds, and trailer type and load have been used. Since changes in the track surface may have happened since then and driving behaviour of both drivers may have changed, an extra tractor, identical to one of those tested in 2009 and without active cabin suspension, is tested again to facilitate the comparison of outcomes between the present data and the previous study. In addition, to better interpret the outcomes towards the normal working days of agricultural contractors, sampling of the driving behaviour of some of the latter during a typical working day is included in the present study.

The present research aimed to compare whole-body vibration exposure and effectiveness of seat damping between different agricultural tractors, four provided with an active cabin suspension system and one with a passive mechanical system, during empty driving and transportation of a heavy trailer on a paved local track. The comparison was performed at two different driving speeds: (1) a slow round driving constantly 15 km/h, except for the bends, and (2) a fast round driving the straight parts at speeds between 20 and 30 km/h.

The following questions were aimed to be answered:

1. Does the application of an active cabin suspension system in an agricultural tractor result in a meaningful reduction of the vibration exposure for the driver in comparison with a tractor not having mounted an active cabin suspension?

2. To what extent do the modern suspended agricultural tractors differ in respect to vibration exposure? Is the difference meaningful? Are the differences retained during transport of a heavy trailer compared to empty driving? What is the effect of driving speed?

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

4. What is the consequence of the outcomes for the maximal driving time per working day in reference to the European vibration directive, combining the outcomes of the vibration exposure measurements and the driving behaviour of agricultural contractors in practice?

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 (location Doetinchem, The Netherlands). The track was situated at an experimental farm location of Wageningen University & Researchcentre, Runderweg 8 in Lelystad, The Netherlands.

Driving behaviour, i.e. the distribution of driving speeds, number of driving hours per day and ratio between driving and not driving, was measured for three different seasonal tasks (transportation of mast, soil, and silage) during one working day of five different drivers. The drivers were employed by three different agricultural contractors in the east Rhine region of The Netherlands. Driving behaviour was assessed using a gps device (Garmin GPS 60, Olathe, US), which was mounted on the tractor shortly before the driver started working. The device sampled position and actual speed each five seconds.

2.1 Drivers

All of the drivers volunteered for the measurements and signed an informed consent before having started the measurements.

Two experienced drivers performed the exposure measurements. Both were men and employees of magazine Trekker. They were experienced in driving tractors. Table 1 summarizes some personal characteristics. One of the drivers reported he had some pain in the shoulders during the past 12 months. The pain was still there during the test. However, as appeared on inquiry, the pain did not lead to a different driving behaviour. He reported no complaints of other body regions. The other driver was free of complaints.

Table 1: Personal characteristics of the drivers involved.

Driver	Age (years)	Length (m)	Body weight (kg)
1	36	1.74	75
2	52	1.72	83

Drivers that volunteered in the driving behaviour measurements were all men and between 22 and 48 years of age (average: 32 years). All were very experienced in performing tractor driving. Four of them were employees; one was subcontracted for the task.

2.2 Tractors and trailer

The exposure measurements were performed with 5 tractors of different makes: see table 2. Of these, four tractors (2-5) had an actively suspended cabin. Tractor one, with a passive mechanically suspended cabin, was involved for comparison of the present data with those of the test in 2009. In all tractors, the same type of seat was mounted. Only for tractor 4, the seat was also suspended laterally. Tractors 3 and 5 were supplied with a seat that had adjustable vertical damping characteristics. 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. Pictures of the machinery and seats 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	Claas Axion 810 Cmatic	2011	8540	125 (170)	FT: 600/65 R28 Tre RT: 650/65 R42 Tre	FA: hydropneumatic (1) CF: springs + dampers CR: springs + dampers	MSG 95A / 731	X: mech Y: - Z: air[a]
2	Massey Ferguson 7620 Dyna-VT	2012	8440	147 (200)	FT: 540/65 R30 Tre; RT: 650/65 R42 Tre	FA: hydropneumatic (1) CF: rubber mountings CR: cylinders + accumulators	MSG 95AL / 741	X: mech Y: - Z: air[a]
3	Valtra T162 Versu	2012	7600	136 (185)	FT: 600/65 R28 Tre RT: 650/65 R42 Tre	FA: air suspension CF: rubber mountings CR: air cylinders (2)	MSG 95A / 731	X: mech Y: - Z: air[b]
4	John Deere 6210 R Autopower	2012	8160	154 (210)	FT: 540/65 R30 Tre; RT: 650/65 R42 Tre	FA: hydropneumatic (3) CF: rotating bearings CR: cylinders (2) + accumulators (4)	MSG 95AL / 741	X: mech Y: mech Z: air[a]
5	Claas Axion 850 Hexashift	2012	9340	171 (233)	FT: 600/65 R28 Tre RT: 650/65 R42 Tre	FA: hydropneumatic (1) CF: springs + dampers CR: air cylinders (Z-Activ)	MSG 95AL / 741	X: mech Y: - Z: air[b]

[1] Tre: Trelleborg TM 800; FT: front tyre; RT: rear tyre
[2] FA: front axle (number of positions); CF: cabin front; CR: cabin rear
[3] all seats were Grammer, type Maximo Professional, having vertical low-frequency air suspension
[4] X: frontal; Y: lateral; Z: vertical; -: not present; mech: mechanical
[a] vertical damping characteristics not adjustable
[b] 5 positions adjustable vertical damping characteristics

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	7400	27600	Trailer with two axles; loaded material: soil; pressure on drawbar: 3860 kg
2	John Deere	900	-	Front weight

The following tractors were driven by the contract workers: New Holland T7030, John Deere 6930, John Deere 6920S, and Fendt (types not specified).

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 heavily damaged at several points. Figure 1 gives an overview, depicted from Google Earth, of the track (left image) and the actual quality of the concrete road (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 test 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 driving direction as indicated. Driving occurred at two speed patterns: (1) driving slowly, which consisted of driving at 15 km/h all of the straight parts of the track, (2) driving at high speed, which consisted of driving at 25, 20, 30 and 20 km/h over the 1st, 2nd, 3rd, and 4th straight part of the track, respectively. Bends were taken at variable lower speeds. After having completed a round at both speed patterns, both rounds were repeated once. This set of four measurements was done with loaded trailer first, where after the rounds were driven without trailer. The loaded experiments were completed for both drivers, where after the second (unloaded) situation was tested. The order of testing was from tractor 1 to tractor 5.

2.3.2 Tyres

The suppliers were asked to mount a standard type of tyres for all tractors: see table 2. 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 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 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, DK) triaxial accelerometer 4322 PE, mounted in a rigid pad. The pad was fixed on the seat using adhesive tape (see figure 2, right 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, left panel).

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

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: 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 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 a 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 of the computer during the measurements, it could be registered which action (out of a set of predefined activities: straight drive, bend, 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 vibration data. Registration of this actual activity was done to speed up the analysis of the data afterwards, that is 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 on the tractor. Position and speed 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. Data segments of the straight parts of the track and of the bends were selected separately. For the straight parts, the criterion was that the driving speed was at or very near (± 1 km/h) the target speed. Hence, the bends parts comprised of both the deceleration and acceleration phase, aswell as the bend itself. When driving some of the tractors, certain holes in the track were so deep that the driver lost contact with the seat surface during fast driving. These moments were not only indicated by the driver during driving, these were also clearly recognizable in the vibration registrations: instantaneous z-values peaked to over 100 m/s^2. To be able to compare their vibration exposure, these holes were excluded from the calculation for all tractors (see figure 3) in this experimental situation only (i.e. fast speed; the effect was more pronounced in the empty driving situation). In the text of the Results-section, separate information per tractor is given on the severeness of the effect of these holes. 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

$$a_{wki} = \sqrt{\frac{1}{T} \cdot \int_0^T a_{wk}^2(t) \cdot d(t)} \qquad (2)$$

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 $m/s^{1.75}$) in stead of the rms value mentioned above. VDV is calculated according to

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

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.

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

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

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

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

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 effectiveness of damping of the driver seat, the SEAT ("seat effective amplitude transmissibility") value was calculated, as described by Griffin (Paddan and Griffin, 2002). $SEAT_{rms}$ 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 modelled 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 acceleration of the ith 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

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

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 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).

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 seasonal work, the transport task with a tractor will normally endure the full working day. However, the driving task itself is only part of total work time. To have an idea about the real driving time, driving speeds were sampled from five different contract workers which performed three different seasonal tasks: transporting mast, soil, and silage. Driving occurred mainly on paved (asphalt) roads and the distance of driving was variable. For all tasks, speeds below 6 km/h were considered to contribute only limitedly to vibration exposure. Although this border is quite arbitrary, it was based on the speed distributions of all tasks, which demonstrated a minimum value around 6 km/h. Besides, on basis of earlier findings (see e.g. Oude Vrielink, 2007), it is really to be expected that these slow speeds hardly contribute to the vibration exposure. Besides this, driving speeds were categorized into two classes: 7-17 km/h and >18 km/h. The total time driven in each of the three classes distinguished was calculated per contract worker.

Another point is that the number of days per year that the tractor is used may vary. The current legislation holds for every working day, and does not take into consideration that exposure may depend on the season.

For the interpretation of the WBV exposure values measured towards daily rms exposure, the exposure measured for the slow speed round is used for the 7-17 km/h category, while that of the fast speed round is used for the >18 km/h category. The exposure for the category 0-6 is assumed zero. Daily exposure is calculated according to equation 4 (see earlier). 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 box plots. A box plot 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). 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 two typical patterns for driving at high speed for a full round, with and without trailer. Shown are WBV running rms values for the three axes and the concomitant actual driving speed. The arrows indicate the track parts causing the driver to loose contact with the chair for some tractors. These parts were excluded from the calculation of the average rms values for all tractors at each round driven in the situation driving at fast speed. Bends can be easily identified from the velocity registration. In comparison to the 2009 measurements (figure 3 in Oude Vrielink, 2009), the more pronounced peaks for the X- and Z- axis are evident.

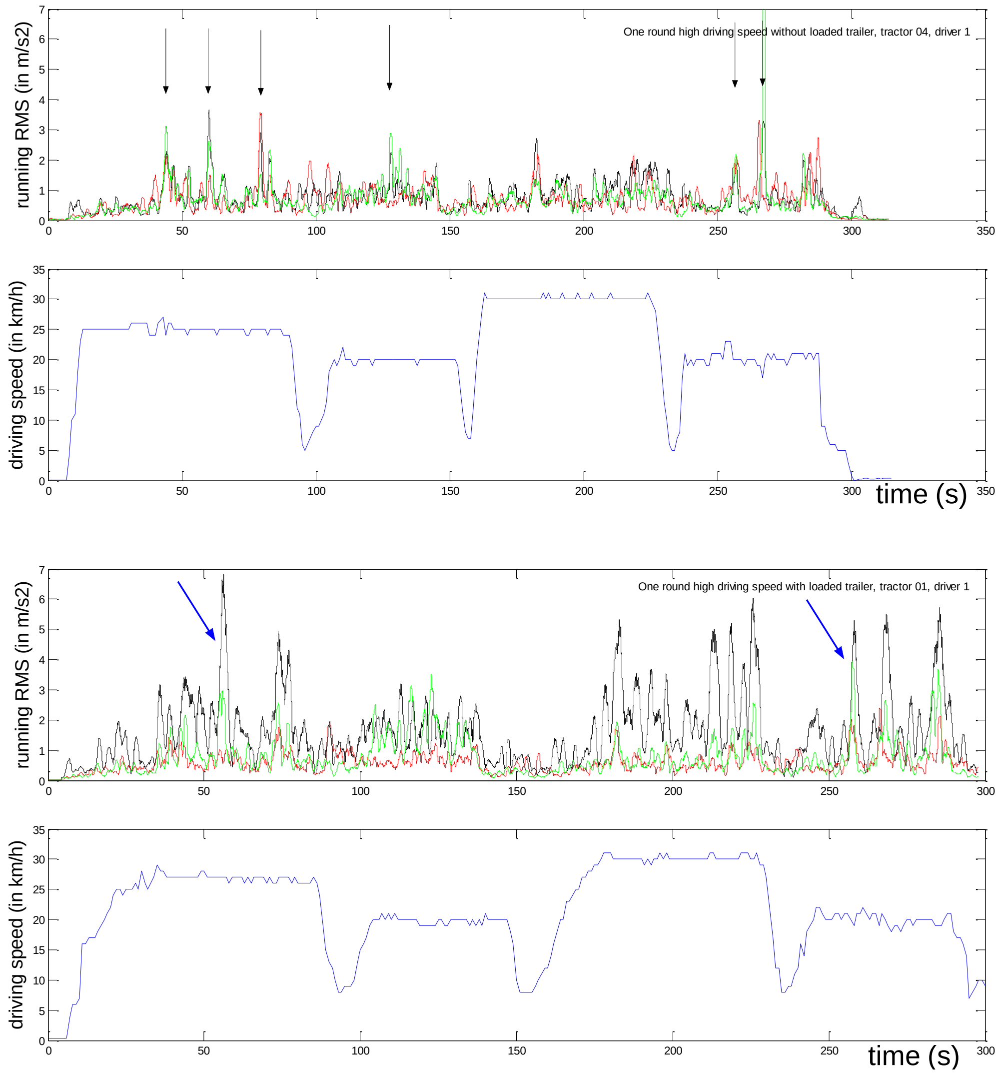


Figure 3: running rms signals for WBV in the X-direction (black line), Y-direction (red), and Z-direction (green), and concomitant driving speed (blue line) for tractor 4 driving empty (upper panels) and tractor 1 pulling a loaded trailer by the same driver for a full fast test round. The arrows indicate the peaks in exposure that have been excluded (see Materials section: Data processing).

3.2 Effect of driver and repetition

In figure 4, the exposures a_w per tractor for the three axes and for both drivers are displayed. The data shown are clustered for repetition, driving speed, and load (driving empty or loaded trailer). From the figures, some different findings can be deduced: (1) WBV exposure in the for-aft direction dominates for all tractors, (2) the spread in vibration exposure is highest for the for-aft direction as well, while lowest laterally (3) the median values and the range seem well-comparable for both drivers. The difference between the drivers for the Z-axis were smallest and not significant (median values over tractors of 0.59 m/s^2 and 0.62 m/s^2 for drivers 1 and 2, respectively; $p=0.26$). For the Y-axis, these values were 0.75 and 0.85 m/s^2. Driver 2 scored a slight but systematic higher value ($p<0.001$). For the X-axis, driver 1 exposure appeared to be systematically higher ($p < 0.001$). However, also this difference still appeared small compared to the range (median value over all tractors was 0.93 m/s^2 for driver 1 compared to 0.78 m/s^2 for driver 2). The spread in range predominantly mirrors the effect of driving speed and trailer pulling. Because of the relatively small differences, the data in the next analysis are pooled for drivers.

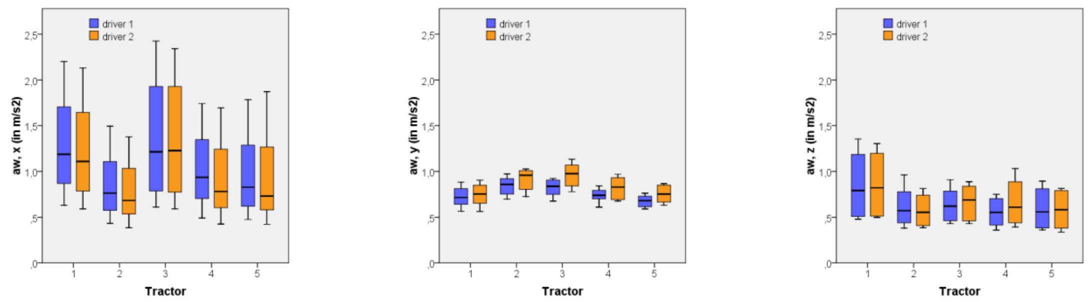


Figure 4: frequency-weighted WBV exposure in the X-direction (left), Y-direction (middle) and Z-direction (right panel) per tractor (horizontal axis) for each of the drivers. The data shown are clustered for repetitions, driving with and without trailer, and driving at high and low speed rounds. Data come from the straight parts only.

Figure 5 shows the effect of repetition on the vibration values a_w for the three axes for each tractor. The data are clustered for drivers, driving speed, and load. Both the median values and ranges of both repetitions are well-comparable. The differences appeared to be non-systematic and not significant. Hence, the data for the repetitions were clustered.

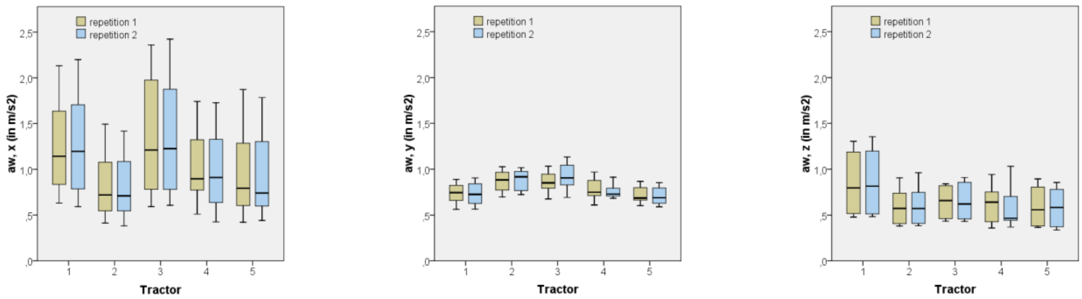


Figure 5: frequency-weighted WBV exposure in the X-direction (left), Y-direction (middle) and Z-direction (right panel) per tractor (horizontal axis) for driving the first and second round (=repetition). The data shown are clustered for drivers, driving with and without trailer, and driving high and low speed rounds. Data come from the straight parts only.

3.3 Driving speed realised

Figure 6 displays the driving speed realised per tractor, on average per round but taking into account the straight parts only. During the low speed round, tractor 3 was driven fastest (median value: 16.0 km/h), while tractor 4 was slowest (median: 15.1 km/h). During the high speed round, tractor 2 was fastest (25.4 km/h median), while tractor 5 was driven slowest (24.2 km/h median). In the appendix A, the average driving speed for each tractor is given. Compared to the 2009 measurements (Oude Vrielink, 2009) the average speed during the fast speed round is elevated. The reason for this is the inclusion of straight parts ánd bends in the previous research, while in the present figures only the straight parts are involved.

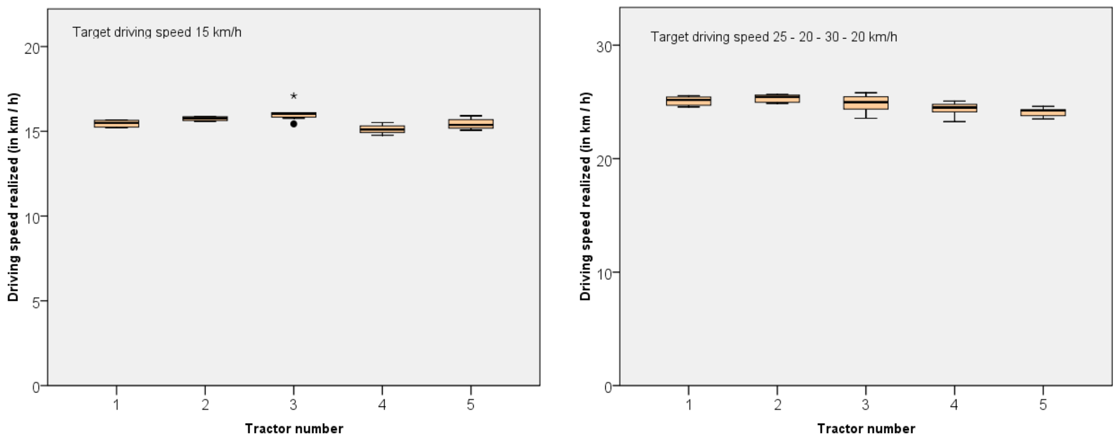


Figure 6: average driving speed realised for each round per tractor for the straight parts only. The left panel shows the mean driving speed realised when driving at a target speed of 15 km/h. On the right, the same is shown for the higher target driving speed of 20, 25, and 30 km/h. The data displayed are clustered for both drivers, repetitions, and driving with and without trailer.

3.4 Difference between empty driving and pulling a loaded trailer

The effect of driving speed, empty or with loaded trailer, is shown in figure 7, pooled for all tractors. For each vibration axis the exposure increases with increasing driving speed ($p<0.001$ (unloaded) and $p<0.001$ (loaded) for each of the vibration axes).

The effect of exclusion of the deepest potholes in the fast driving situation hampers a strict direct comparison between empty driving and pulling a loaded trailer (see figure 3 and section 3.5). This is because in the former situation more potholes were excluded. On basis of the 2009 measurements (Oude Vrielink, 2009), it was expected that trailer pulling would result in an increased WBV exposure in the fore-aft direction, and the opposite to be occurring for both other vibration axes. In the present results, the effect of excluding the vibrations caused by the potholes in the empty drive situation is that the vibration values during empty driving are somewhat reduced. Therefore, the difference in the fore-aft direction in the figure below will be exaggerated compared to the 2009 measurements, while this difference for both other axes will be underestimated (see figure 7). For the frontal axis, trailer pulling resulted in a median increase of the a_{wx} from 0.49 m/s^2 to 0.90 m/s^2 at slow speed ($p<0.001$) and from 0.86 m/s^2 to 1.78 m/s^2 ($p<0.001$) at the high velocity round. In the lateral (Y) direction, a slight decrease was seen when empty driving was compared with trailer pulling at both speeds: median values over all tractors of 0.74 m/s^2 and 0.68 m/s^2 ($p=0.001$), for low speed empty and loaded driving, respectively, and 0.91 m/s^2 and 0.86 m/s^2 ($p<0.001$) for high speed empty and loaded driving, respectively. In the vertical direction Z, effects of trailer pulling compared to empty driving were minimal at both speeds. At slow speed, there was a slight but insignificant decrease ($p=0.1$) if pulling a trailer was compared to empty driving: median values were 0.45 m/s^2 and 0.40 m/s^2, respectively. At high speed, the effect of trailer pulling was small un not significant ($p=0.06$), and median values were 0.83 m/s^2 and 0.81 m/s^2 for empty and loaded driving, respectively. Note that the values measured for tractor 1 at high driving speed appear as "stray values". These data, hence, are excluded from the median value. The effect of trailer pulling at high driving speed will be more pronounced if these data are also included in the median value for empty driving.

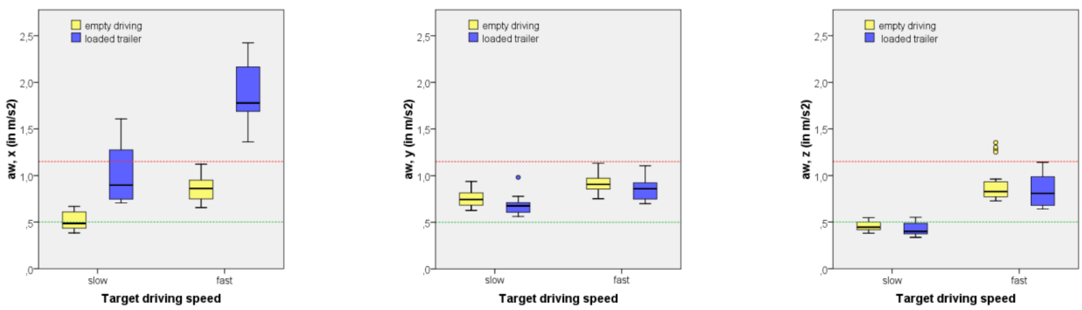


Figure 7: frequency-weighted WBV exposure in the X-direction (left), Y-direction (middle) and Z-direction (right) for driving at slow (15 km/h) and fast target speed (25-20-30-20 km/h). Per driving speed category, the data are subdivided into empty driving (yellow boxes) and pulling a loaded trailer (blue boxes). The data displayed are clustered for tractors, drivers and repetitions. Only straight driving is included. The horizontal lines indicate the action value (in green) and limit value (red) for a whole working day. Note 1: the cluster of stray values for fast empty driving: these data come from tractor # 1. Note 2: fast driving excludes data for the potholes.

3.5 Differences between tractors and their seat damping

It should be noted first that driving with some of the tractors at high speed over the track at some moments resulted in losing contact between driver and seat. During pulling a trailer, this happened only for tractor 1 for driver 2 at the moments indicated by the arrows in figure 3 (lower part). For empty driving, losing contact with the seat happened most often for tractors 1 and 3 for both drivers: see arrows in figure 3, upper part. For tractor 2, this happened only when passing the two deepest holes, these were those indicated in the lower part of figure 3. Tractors 4 and 5 behaved in between and demonstrated losing contact consequently for 4 out of 6 potholes. No clear difference between both latter tractors was seen.

Figure 8 shows the vibration measurement results for the five tractors. From the figure, it appears that the dominant vibration axis depends on driving speed and load pulling, much more than on tractor type. During empty driving the Y-axis dominates at slow speed, and for some tractors at high speed as well. The effect of pulling a trailer on the Y- and Z-axis vibrations appears limited. In contrast, the vibration exposure in the X-axis (for-aft direction) increases heavily at both driving speeds. In that situation (figure 8, upper right), tractors 2, 4, and 5 showed the lowest vibration exposure, tractor 2 overall showing the best performance. Still, the vibration exposure during fast driving appeared above the limit value. Even when driving at slow speed, tractors 1 and 3 exposed above this limit value. Note that the vibration values reported for the tractor 1 in the present test are higher compared to the 2009 test (Oude Vrielink, 2009). Two explanations can be given for this. (1) The present results comprise of only the straight parts at the target velocity, while the 2009 results comprised of the full round, so including bends, deceleration and acceleration parts. The on average higher velocity for the present results may explain in part the higher vibration values. (2) The quality of the paved track most likely did not resemble the quality three years ago, since no meaningful repairs had been realised since then. This point is supported by the presently observed phenomenon of loosing contact with the seat for tractor 1 (empty driving): this did not occur during the 2009 test for the same tractor type tested, nor for any of the others.
The effect of increased speed on vibration exposure remained limited sideward. It was most pronounced in the for-aft direction, especially when pulling a loaded trailer. This effect, expressed as absolute value, seems to be more or less comparable for all tractors tested.

Figure 9 shows the unweighted and weighted chair base accelerations in comparison with those measured on the seat. Note that the figure displays the high speed round data only. Like in the 2009 test, it appeared that the unweighted accelerations measured at the chair base, containing vibrations between 0.5 Hz and 2000 Hz, were the highest for the Z-axis: see figure 9, left panels. The accelerations of the chair base of tractor 1 seem to be a bit elevated for this axis compared to the others. This holds also for tractor 3 for the Y-axis. Tractor 2 performed the best and is among the lowest values for both the empty and loaded drive in all vibration axes.

The middle panels of this figure 9, seen vertically, demonstrate the effect of frequency-weighing. For a proper comparison, note that the weighted signals for the X- and Y-axes have been multiplied with the k-factor 1.4, as prescribed in ISO-2631-1 (1997). The weighing filter functions so that the vibration frequencies that are considered most harmful to the human body are allowed to pass predominantly. After the weighing procedure, the difference between the tractors tested is eliminated: there appears to be no clear distinction between the tractors for all axes.

The right panels of figure 9 show the weighted seat accelerations during high velocity driving. For most tractors, except for tractor 1, the values on the seat for the Z-axis seem to be somewhat lowered. For the Y-axis, the values seem comparable, while for the X-axis the vibrations on the seat seem elevated compared to the seat base. This is especially true for the loaded trailer situation.

The previous is reflected in the $SEAT_{rms}$ value, displayed in figure 10. For the X-axis (left panel) the median values for all tractors are over 100%, indicating an amplification of the horizontal vibrations on and by the seat. Tractors 2, 4, and 5 showed the best performance. For the Y-axis, data spread around 100%, indicating no clear damping effect of the chair. Only for tractor 2 the values in all situations were clearly above 100%. It should be remembered that only on tractor 4 a seat was mounted that had lateral vibration suspension. The difference with the other seats is not very obvious. For the Z-axis, the $SEAT_{rms}$ values for the four tractors 2-5 remain well below 100%, indicating the chair is effective in further reducing the accelerations of the cabin. Only for tractor 1, an increase in vibration exposure on the seat was seen.

In an attempt to explain better the observed differences in vibration exposure between the tractors, a Fast Fourier frequency analysis was done on the measurements at the seat base for the straight part that was driven at 30 km/h. The duration of the registrations analysed ranged between 50 and 65 seconds. The registrations and the frequency patterns are shown in the Annex D. Shown are the registrations for only driver 1 for empty driving and pulling a trailer. Those of driver 2 appeared almost a copy (and for that reason, they are not displayed). The registrations show the time series data for the X- (in black), Y- (in red) and the green Z-axis (upper panel; note that the offset of the X- and Z-signals was changed for the sake of clarity of display). There under appear the frequency patterns for the three axes (in corresponding colours) and divided into two frequency scales of 0.1 – 10 Hz (low frequency; lower panels) and 10 – 1000 Hz (high frequency; middle panels). The figures are screen dumps of those produced with help of Matlab. An analysis in a descriptive sense revealed the following:

- *Trailer pulling:* pulling a trailer resulted in a reduction of the frequency spectrum, mainly in the low-frequency part, and mainly for the X- and Z- vibration axis. This appeared true for all of the tractors tested. No clear effect was seen for the Y-axis.

- *Tractor comparison in the low-frequency range:* the low-range frequency content of the Z-axis during empty driving was comparable for all of the tractors. For the X-axis, tractors 2 and 5 displayed a somewhat lower frequency content compared to the others. Tractors 2 and 5 were comparable, and tractors 1, 3 and 4, in turn, were also. When pulling a trailer, tractors 1, 2, 3, and 4 demonstrated frequency responses that were fully comparable. Tractor 5, however, showed a tendency towards higher frequencies in this low frequency range for both the X- and Z-axis.

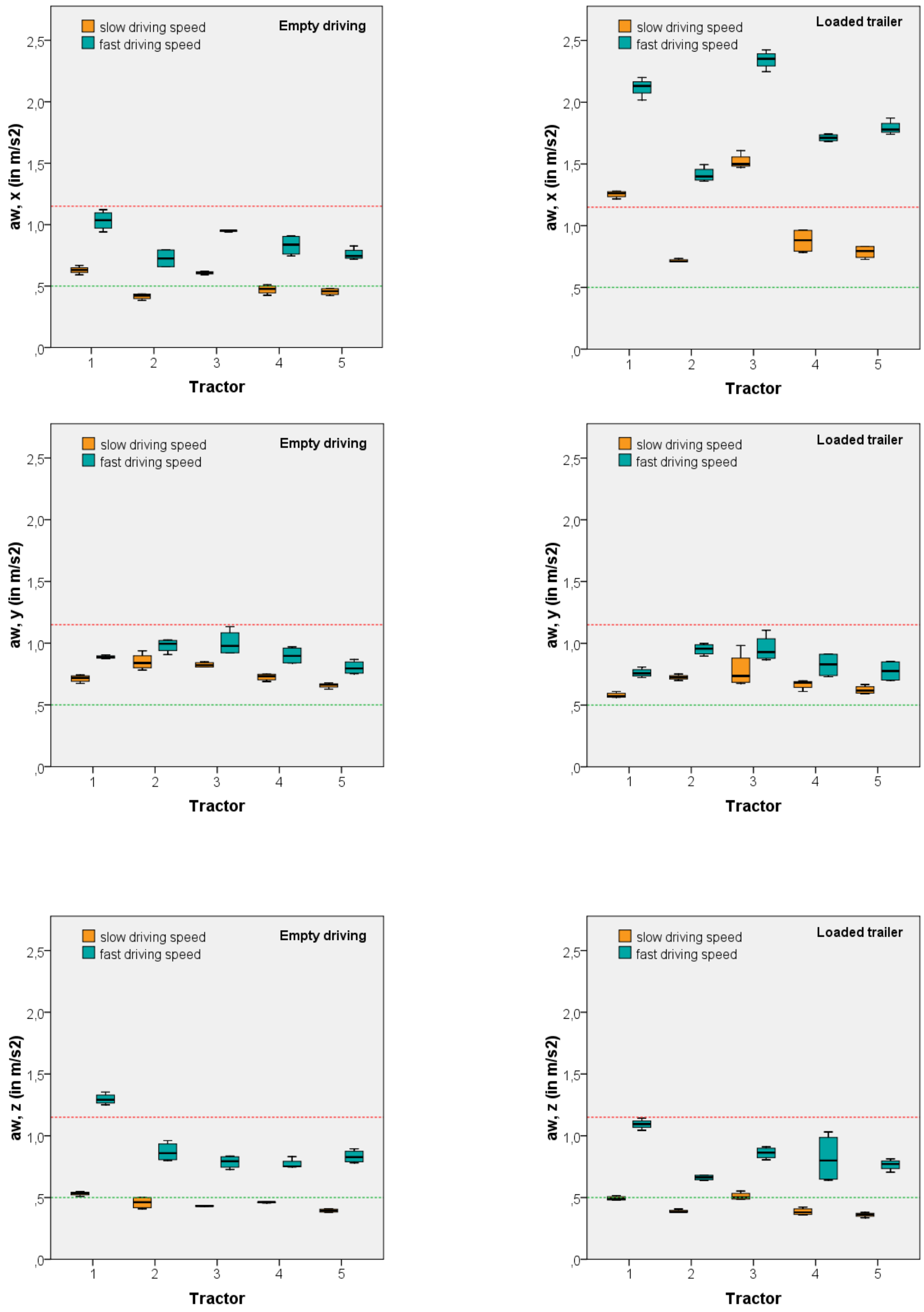


Figure 8: frequency-weighted WBV exposure in the X-direction (upper panels), Y-direction (middle panels) and Z-direction (lower panels) per tractor (horizontal axis) for empty driving (left column) and driving with a loaded trailer (right column). For each tractor, the data are subdivided into the slow (15 km/h; orange boxes) and fast target speed (25-20-30-20 km/h; blue boxes). The data displayed are clustered for drivers and repetitions. The horizontal dashed lines indicate the action value (in green) and limit value (red) for a whole working day. Note that fast driving excludes data for the most severe potholes. Data come from the straight parts only.

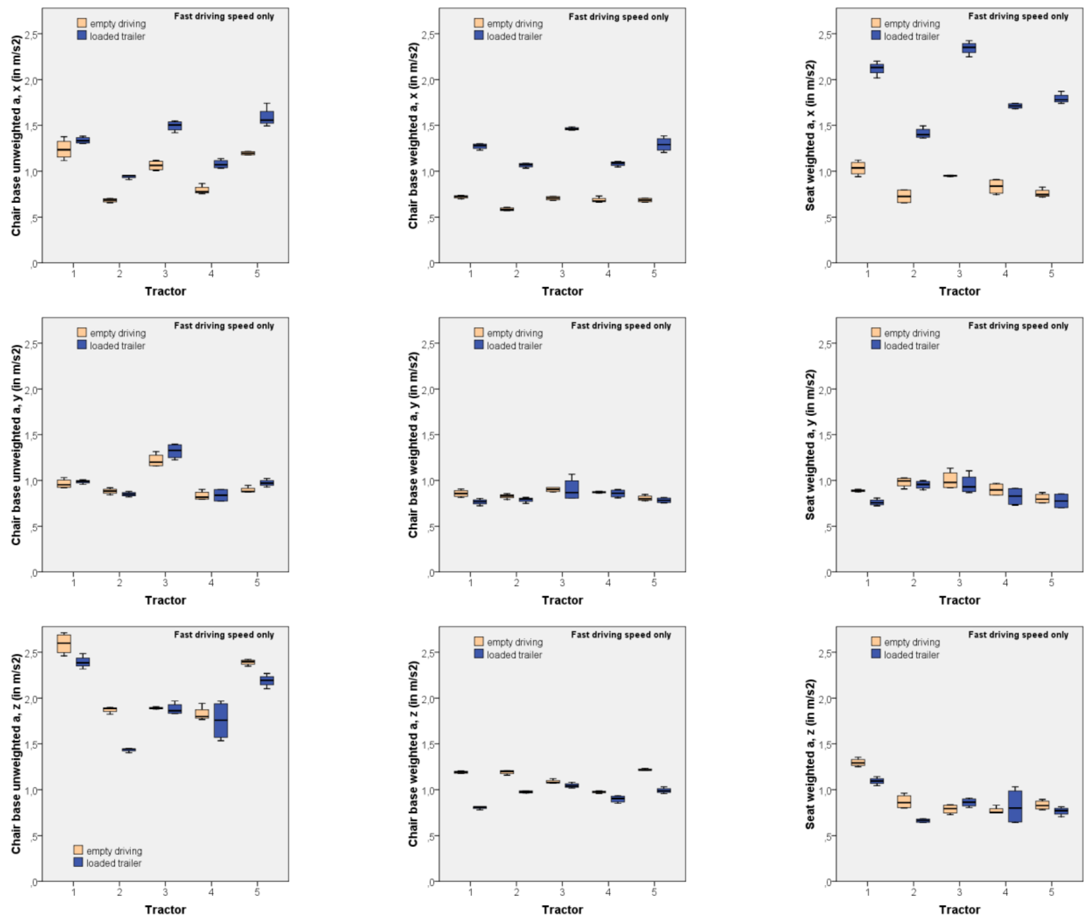


Figure 9: unweighted chair base acceleration (left column), weighted chair base acceleration (middle column) and weighted seat acceleration (right column) in the X-direction (upper), Y-direction (middle) and Z-direction (lower panels) per tractor (horizontal axis) for empty driving and driving with loaded trailer. The data displayed are clustered for both drivers and repetitions, and display high speed driving only. When comparing the middle and left columns, note that the weighted signals for the X- and Y-axes have been multiplied with the k-factor 1.4.

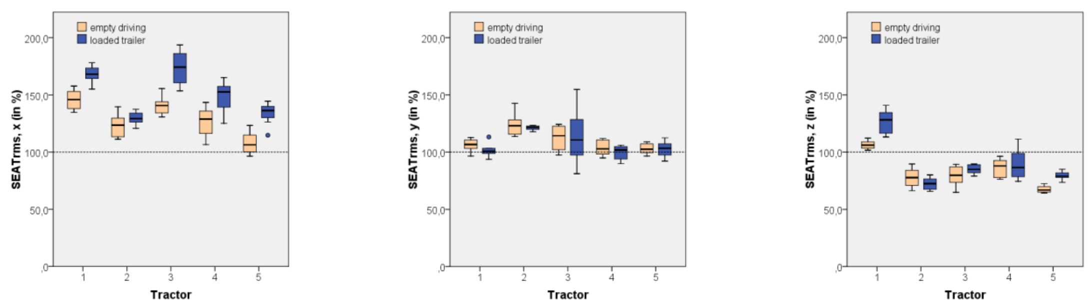


Figure 10: seat effective amplitude transmissibility ($SEAT_{rms}$) for the X-axis (left), Y-axis (middle) and Z-axis (right panel) per tractor (horizontal axis) and for driving with and without trailer. The data displayed are clustered for drivers, repetitions, and driving speed. Data come from the straight parts only.

- *Tractor comparison in the high-frequency range:* the Z-axis of tractor 1 while driving empty shows a relatively high contribution of vibrations near 400 Hz. Peaks in this range are also found for the other tractors, however, of far lower relative height. Tractor 2 has a striking flat spectrum in this range. For both other vibration axes the spectra seem comparable for the tractors. When pulling a trailer, the peaks in the high frequency part of the spectra for tractors 1 and 5 are obvious. Both latter demonstrate peaks comparable in height; the peak for tractor 5 is slighty lower than 300 Hz while that of tractor 1 remains near 400 Hz.

These spectra can explain part of the differences between the tractors observed in figure 9. If we focus, for example, on the lower left panel, the high unweighted vibration level for tractor 1 compared to tractor 2 (empty and loaded) is most likely explained by the peak in the high vibration range. Since the low-frequency range for both tractors was comparable, the result of frequency filtering prescribed by ISO-2631 (in which high frequencies are predominantly filtered out) is that vibrations after frequency-weighing are comparable for both tractors (figure 9, middle-low). On the other hand, since the frequency spectra of both tractors in the low range seem very similar, this cannot explain why the vibration measurement on the seat is lower for tractor 2 compared to tractor 1. Two remarks must be made here to explain the difference. (1) The spectra shown are derived from only the highest speed segment of the track. The vibration measurements also include three other segments driven at lower speeds, and their frequency spectra have not been analyzed. (2) The type of chair (see table 2) for both tractors is different. It might be that the chair in tractor 2 in general is better in damping the low frequencies that are transmitted via the cabin floor.

3.6 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.

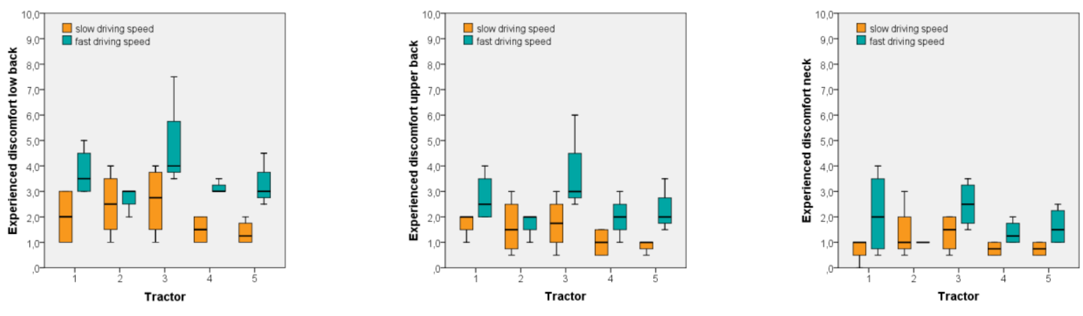


Figure 11: subjective score of local discomfort experienced at the low back (left), upper back (middle), and neck (right) per tractor (horizontal axis) after completing one round driving with loaded trailer. The data displayed are clustered for drivers and driving with or without trailer.

The pattern for the body regions seems comparable, especially during the low speed round. On average, the discomfort scores for the low back are highest. After having driven fast, tractor 2 scores lowest on discomfort, closely followed by tractors 5 and 4. Tractors 3 and 1 seem to score somewhat more uncomfortable.

3.7 Interpretation towards a working day

In the Annex A, the rms, VDV and spinal compression data are given per tractor, averaged for empty driving and pulling a loaded trailer, for both speed categories separately 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.

In Annex E, the driving speed distributions of the five contract workers in practice are displayed. The table 5 below summarizes the number of hours and the percentage of time driven in each speed category for the five different tasks.

Table 5: Total task duration (in hours) and distribution over three speed categories (0-6 km/h, 7-17 km/h, >17 km/h) of contract work in practice. The distribution over the categories is given in absolute hours and relative as percentage of the total work time.

Task	Total task (h)	Cat 0-6 (h; %)	Cat 7-17 (h; %)	Cat 18+ (h; %)
Transport of mast - 1	7.1	4.1 (58%)	0.6 (8%)	2.4 (33%)
Transport of mast - 2	8.9	4.8 (54%)	1.0 (11%)	3.1 (35%)
Transport of soil	9.1	7.5 (83%)	0.6 (6%)	1.0 (11%)
Transport of silage - 1	8.5	2.1 (25%)	2.0 (23%)	4.4 (52%)
Transport of silage - 2	14.0	5.9 (42%)	5.2 (37%)	2.9 (20%)

The outcomes of the soil transport were rather exceptional: the driver indicated afterwards he had to wait for almost a whole day before he could become active. This task and the calculated outcomes should not be taken too seriously, therefore. Although it needs no clarification that this approach is rather rough, the durations driven in each category have been used to make an estimation of the daily vibration exposure, assuming that the values measured during the present test also hold for the situation in practice. These results are shown in tables 6 and 7. Shown in table 6 are the values for those vibration axes that were highest (the EU standard 2002/44/EU requires for a safe use without further action that a_w at any axis remains below the action limit for a whole working day). In all cases but one, this was the X-axis (fore-aft). In addition, the estimated vertical vibration values (Z-axis) are also given: see table 7.

Table 6: Estimation of the daily vibration exposure, given the measurement outcomes of the test and assuming them representative for the exposure in practice, for three types of contract work performed by five different drivers in practice. The dominant vibration axis is all cases was the fore-aft direction (X), except for one: the Y-axis (indicated). The background colours indicate a value lower than the action value (green), between action and limit value (orange) and above the limit value (red). Besides, the lower range of passing the action value, i.e. a value between 0.5 and 0.7, is indicated in pale orange.

Task / Tractor	Transport of mast - 1	Transport of mast - 2	Transport of soil	Transport of silage - 1	Transport of silage - 2
1 – Claas Axion 810	0.96	0.99	0.58	1.23	0.92
2 – Massey Ferguson 7620 Dyna-VT	0.65	0.62	0.39	0.83	0.64 (Y)
3 – Valtra T162	0.99	1.02	0.60	1.28	0.98
4 – John Deere 6210R	0.78	0.80	0.46	0.98	0.71
5 – Claas Axion 850	0.76	0.78	0.45	0.96	0.69

Table 7: Estimation of the daily vibration exposure in the vertical direction (Z-axis), given the measurement outcomes of the test and assuming them representative for the exposure in practice, for three types of contract work performed by five different drivers in practice. The background colours indicate a value lower than the action value (green), between action and limit value (orange) and above the limit value (red). Besides, the lower range of passing the action value, i.e. a value between 0.5 and 0.7, is indicated in pale orange.

Task / Tractor	Transport of mast - 1	Transport of mast - 2	Transport of soil	Transport of silage - 1	Transport of silage - 2
1 – Claas Axion 810	0.71	0.73	0.42	0.90	0.63
2 – Massey Ferguson 7620 Dyna-VT	0.45	0.46	0.27	0.57	0.42
3 – Valtra T162	0.51	0.52	0.30	0.65	0.48
4 – John Deere 6210R	0.47	0.48	0.28	0.59	0.44
5 – Claas Axion 850	0.47	0.48	0.28	0.60	0.43

One may argue the results of the present vibration measurements can not be used for calculation of the consequences in practice. This because the test track was badly damaged while the contract workers indicated they were driving on well-maintained public roads for the major part of the driving time. Hence, it is possible that the tables are more likely to present some worst case scenario than a normal average. From the data presented in table 6, therefore, one may not conclude that each of the tractors tested will be unsafe with regard to vibration exposure if driven in practice. The data of this table can be used to compare the tractors themselves. Tractors 1 and 3 shown the worst performance, also illustrated by exceeding the limit value for one of the tasks. It appears that tractor 3 performs even worse in the frontal plane compared to tractor 1. Tractor 2 has the best performance and remains for a great part in the low-range above the action value. The tractors 4 and 5 score in between the above mentioned extremes. The difference between both appears very limited.

Considering the vertical vibration exposure estimation (table 7), even during this bad scenario most of the cabin-damped tractors keep the vibration exposure beneath or around the action value. The differences between the tractors 2, 4, and 5 are very small. And also the difference with tractor 3 is limited. Only tractor 1, having no active cabin suspension, attracts attention in a negative sense.

With regard to the evaluation of the exposure to multiple shocks, S_{ed} (see appendix A), a quite different picture can be seen. Here, tractors 4 and 5 show the best performance and, assuming the track and speeds are representative for normal transport work and that this work is performed for 120 days per year (see table 4), both tractors keep the daily compression dose S_{ed} under 0.6 MPa, indicating the risk injury because of exposure to shocks is low. Although the difference between these tractors is small, the tractor 5 gives the highest protection against shock exposure.
In contrast, the performance of tractor 2 is comparable to that of tractor 3. The main cause of this is that the S_{ed} is most sensitive to shocks occurring laterally and tractor 2 and 3 demonstrate the highest exposure values for lateral (Y-axis) vibration. The values measured are such that only at high speed driving there is a risk present for health damage as a result of exposure to multiple shocks. Only for tractor 1 in that case, the risk is high.

4 Conclusions and recommendations

From the present measurements, it is concluded that

- The active cabin suspension systems on tractors are effective in reducing vertical vibration exposure of the driver. Even if the results of the present measurements on the rough test track are extrapolated to contract work patterns in practice, the vertical vibration exposure is under or near the action value for a whole working day.
- However, the horizontal forward-backward vibrations dominate during driving a tractor, whether or not equipped with an active cabin suspension system. Trailer pulling enhances this forward-backward vibration exposure. These horizontal vibrations limit the daily maximal working time with respect to vibration exposure.
- One may question the use of the present data for calculating the daily maximal working times in practice, because the test track was quite badly damaged. If this is still done, however, none of the tractors remained below the action value when some typical contract work patterns were evaluated. Three of the tractors having an active cabin suspension system, exceeded only modestly to moderately the action value.
- The tractor that demonstrated the best performance in the forward-backward and vertical directions showed a greater instability along the lateral axis. Although this axis was not limiting vibration exposure in most cases, it contributed considerably to an increased sensitivity for multiple shocks.
- The chairs mounted in the actively suspended cabins were effective in further reducing the vertical vibrations. However, they did not reduce, or even enhance, the vibrations in the horizontal plane, especially along the forward-backward axis. In an attempt to further improve vibration damping, attention should be paid to the effectiveness of damping of the chair in the horizontal plane.

- Furthermore, it is hard to compare the present results with those obtained from the 2009 test. The main reason is the test track that appeared to be more damaged and unequal compared to some years ago. This is confirmed not only by the present observation of the driver losing contact with the chair, which was not the case in 2009. It can also be concluded by comparing the measurement results of tractor 1 (present) and tractor 6 (2009), which were of similar type. This comparison reveals a strongly elevated vibration exposure at present for the forward-backward and the vertical axis, most pronounce when pulling the trailer. The difference cannot be explained taking into account that the 2009 results also include the bends.

References

Borg, G. A. V., 1982. Psychophysical bases of perceived exertion. Med Sci Sports Exerc. 14, 377-381

EU, 2002. Richtlijn 2002/44/EG van het Europees Parlement en de Raad van 25 juni 2002 betreffende de minimumvoorschriften inzake gezondheid en veiligheid met betrekking tot de blootstelling van werknemers aan de risico's van fysische agentia (trillingen) (zestiende bijzondere richtlijn in de zin van artikel 16, lid 1, van Richtlijn 89/391/EEG) - Gezamenlijke verklaring van het Europees Parlement en de Raad. Publicatieblad van de Europese Gemeenschappen. L 177 (6.7.2002), 13-19

ISO-2631-1, 1997. Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration - Part 1: General Requirements. ISO, Geneva, pp. 31.

ISO-2631-5, 2004. Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration - Part 5: Method for evaluation of vibration containing multiple shocks. ISO, Geneva, pp. 20.

ISO-8041, 2005. Human response to vibration - measuring instrumentation. ISO, Geneva, pp. 90.

Oude Vrielink, H. H. E., 2007. Analysis of the exposure to whole-body and hand-arm vibrations using agricultural tractors. Report 2007-02 (in Dutch; Englisch summary). ErgoLab Research BV & Wageningen UR, Bennekom/Wageningen, report 2007-02, ISBN: 978-90-8585-154-7, 75 pp.

Oude Vrielink, H. H. E., 2009. Exposure to whole-body vibration and effectiveness of chair damping in high-power agricultural tractors having different damping systems in practice. ErgoLab Research B.V., Bennekom, report 2009-10-1, 46 pp.

Paddan, G. S. and Griffin, M. J., 2002. Effect of seating on exposures to whole-body vibration in vehicles. Journal of Sound and Vibration. 253, 215-241

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, only straight parts, 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					0.947	7.38	10.59			18.28	
y	low speed	3023	15.6	8	0.640	5.66	6.86	0.25	28800	14.01	0.46
z					0.517	4.42	5.84			10.95	
x					1.586	10.31	14.69			29.75	
y	high speed	1630	25.4	8	0.833	6.23	8.76	0.55	28800	18.00	1.12
z					1.199	10.57	17.05			30.54	
x					1.170	8.27	11.19			21.99	
y	accumulated	4653	20.1	16	0.735	5.69	6.92	0.33	28800	15.18	0.64
z					0.802	6.89	9.74			18.99	

Tractor 2: uneven track driving, only straight parts, 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					0.570	5.05	7.92			12.64	
y	low speed	2935	15.8	8	0.770	6.62	9.56	0.34	28800	16.59	0.62
z					0.407	3.41	4.95			8.57	
x					1.082	7.26	10.64			21.04	
y	high speed	1616	25.4	8	0.965	6.85	11.64	0.42	28800	19.86	0.86
z					0.743	6.37	10.59			18.57	
x					0.715	5.57	8.44			14.71	
y	accumulated	4551	20.4	16	0.907	6.85	9.98	0.37	28800	19.20	0.73
z					0.572	5.02	8.08			13.59	

Tractor 3: uneven track driving, only straight parts, 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					1.050	8.16	10.67			20.41	
y	low speed	2865	16.1	8	0.825	7.15	8.51	0.34	28800	17.97	0.62
z					0.467	4.39	7.48			10.98	
x					1.625	10.45	13.62			30.26	
y	high speed	1630	25.0	8	0.980	6.94	10.14	0.38	28800	20.11	0.78
z					0.845	8.05	8.48			23.33	
x					1.219	8.65	11.37			22.90	
y	accumulated	4496	20.2	16	0.884	7.13	9.24	0.36	28800	18.81	0.70
z					0.633	6.09	8.43			16.82	

Tractor 4: uneven track driving, only straight parts, 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					0.647	5.74	8.39			14.17	
y	low speed	3082	15.2	8	0.703	6.22	7.47	0.29	28800	15.36	0.53
z					0.434	4.45	7.30			11.03	
x					1.296	8.80	12.09			25.35	
y	high speed	1659	24.4	8	0.876	6.14	8.35	0.36	28800	17.82	0.73
z					0.771	5.62	10.50			16.23	
x					0.849	6.57	9.05			17.41	
y	accumulated	4741	19.6	16	0.736	6.16	7.57	0.31	28800	16.08	0.57
z					0.556	5.03	9.05			13.46	

Tractor 5: uneven track driving, only straight parts, 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					0.610	5.12	7.76			12.77	
y	low speed	2987	15.3	8	0.647	5.60	6.83	0.24	28800	13.97	0.44
z					0.373	3.16	4.21			7.89	
x					1.277	8.84	12.29			25.11	
y	high speed	1680	24.2	8	0.803	5.95	8.04	0.31	28800	17.20	0.64
z					0.793	6.65	7.47			19.33	
x					0.767	5.68	8.17			15.16	
y	accumulated	4667	19.8	16	0.686	5.64	7.49	0.28	28800	14.98	0.54
z					0.570	4.98	5.93			13.55	

Annex B – 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).

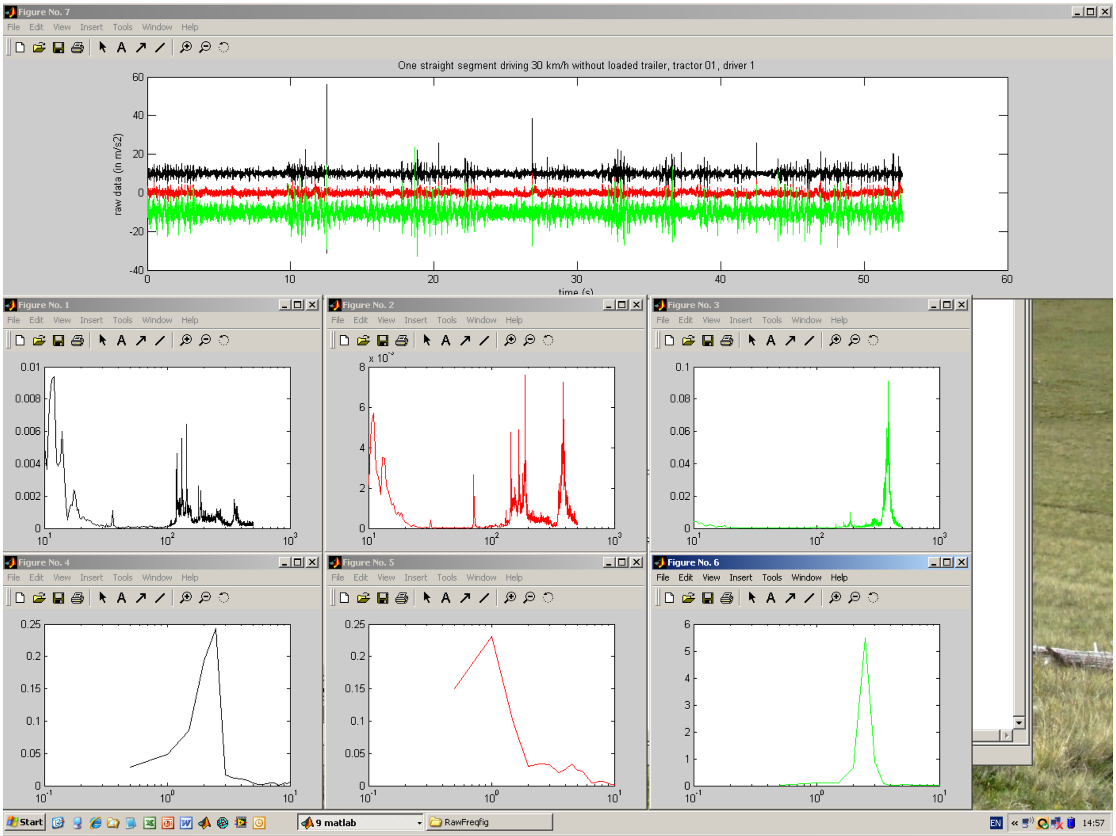
Score experienced local discomfort	
Anchor expression	*Value*
Nothing at all	0
Very, very weak (just noticable)	0,5
Very weak	1
Weak (light)	2
Moderate	3
Somewhat strong	4
Strong (heavy)	5
	6
Very strong	7
	8
	9
Very, very strong (almost maximal)	10
Maximal	*

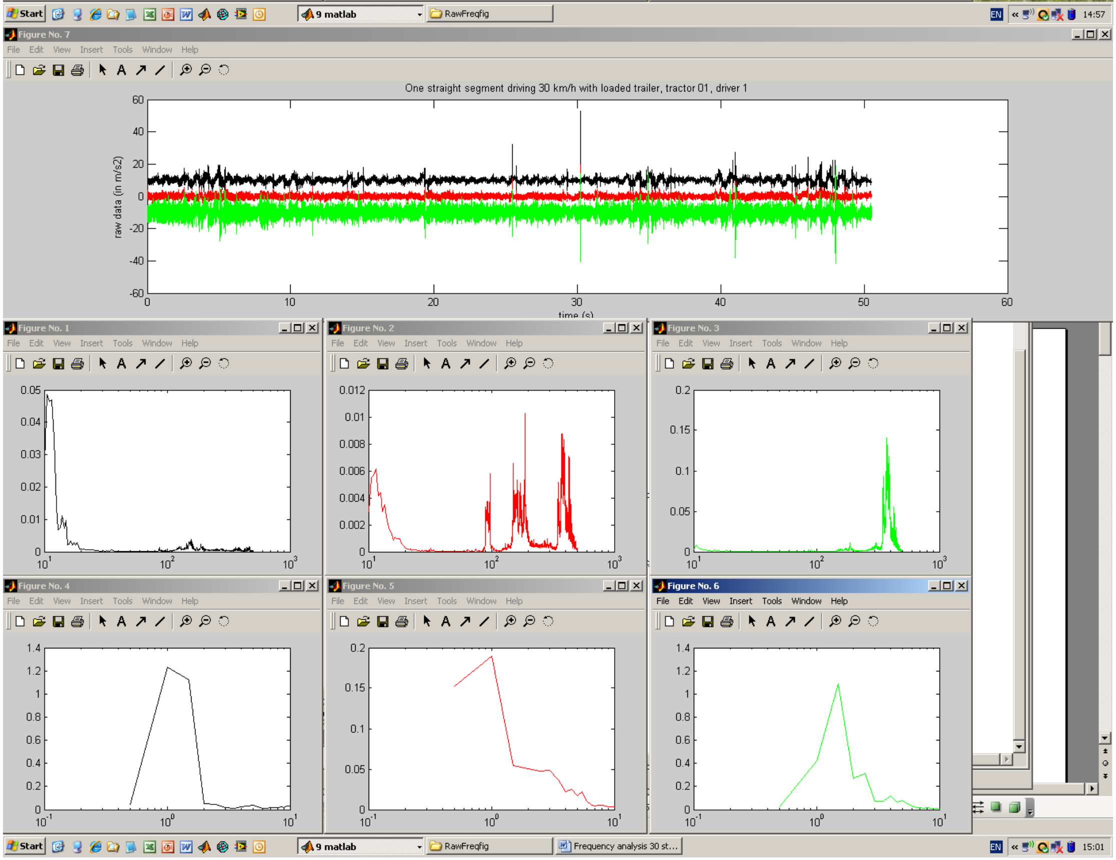
Annex C – The machinery used

	
1. Claas Axion 810	2. Massey Ferguson 7620 Dyna VT
	
3. Valtra T 162	4. John Deere 6210 R
	
5. Claas Axion 850	Grammer seat MSG95AL/741 12V (Maximo Professional)

	
Trailer: Joskin Trans-SPACE 700023, BC150	Front weight: John Deere
	
Front tyre: Trelleborg TM 800	Rear tyre: Trelleborg TM 800

Annex D – Frequency spectra driving 30 km/h straight





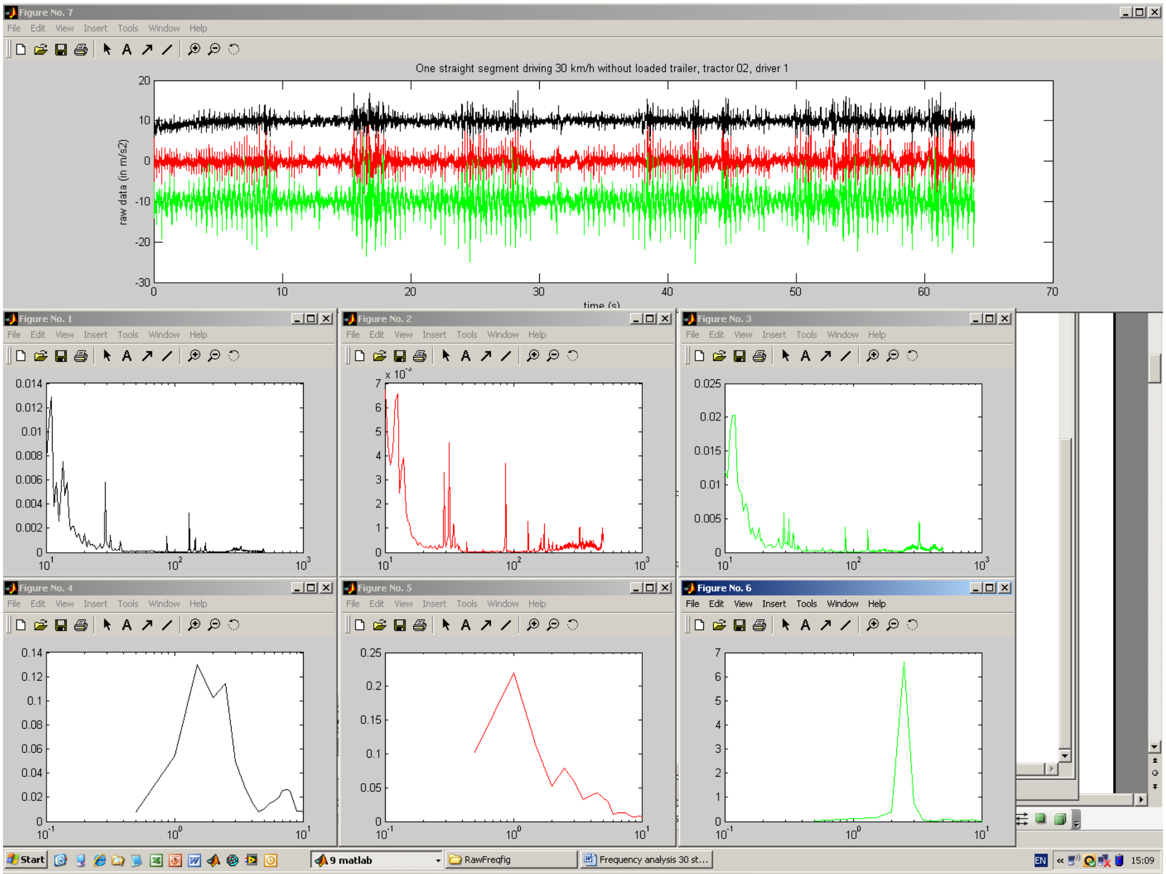


Figure No. 7
One straight segment driving 30 km/h without loaded trailer, tractor 02, driver 1
raw data (in m/s2)
time (s)
Figure No. 1
Figure No. 2
Figure No. 3
Figure No. 4
Figure No. 5
Figure No. 6

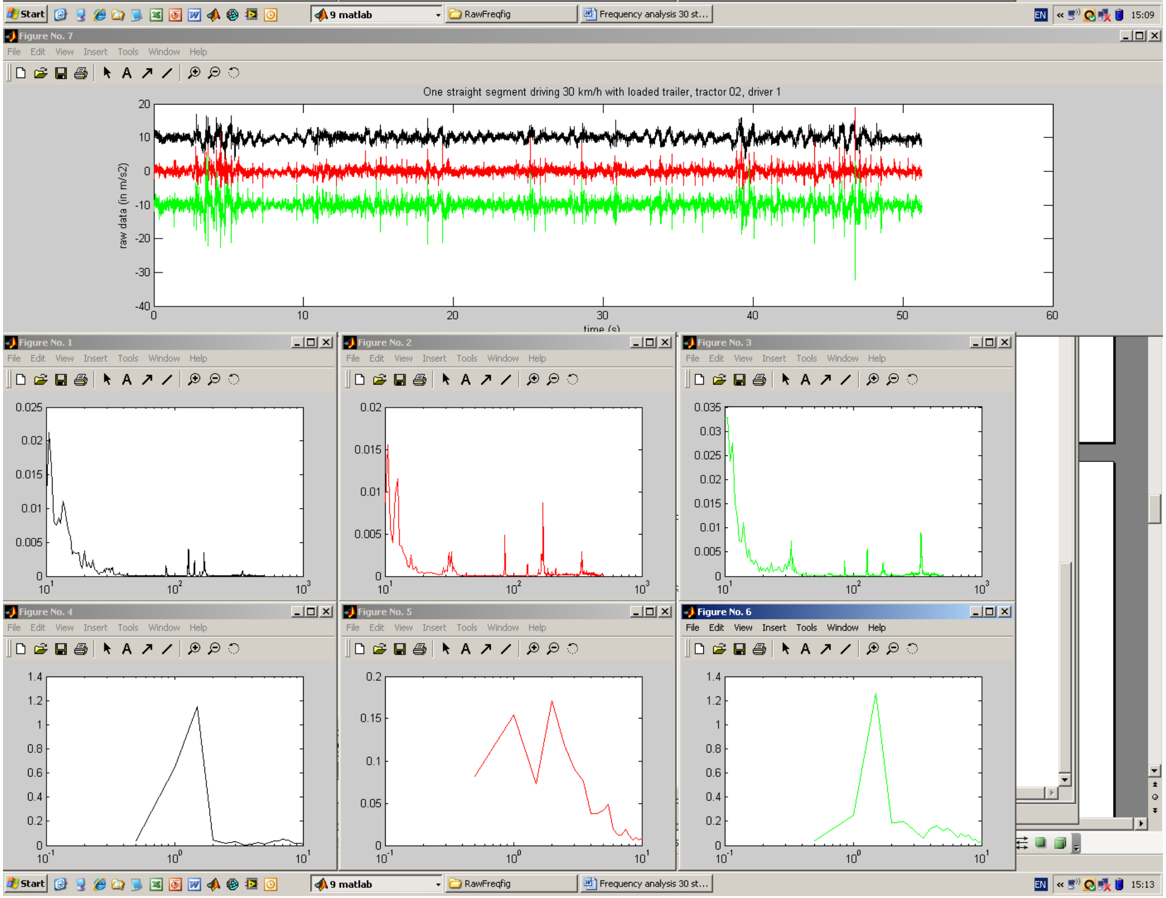


Figure No. 7
One straight segment driving 30 km/h with loaded trailer, tractor 02, driver 1
raw data (in m/s2)
time (s)
Figure No. 1
Figure No. 2
Figure No. 3
Figure No. 4
Figure No. 5
Figure No. 6

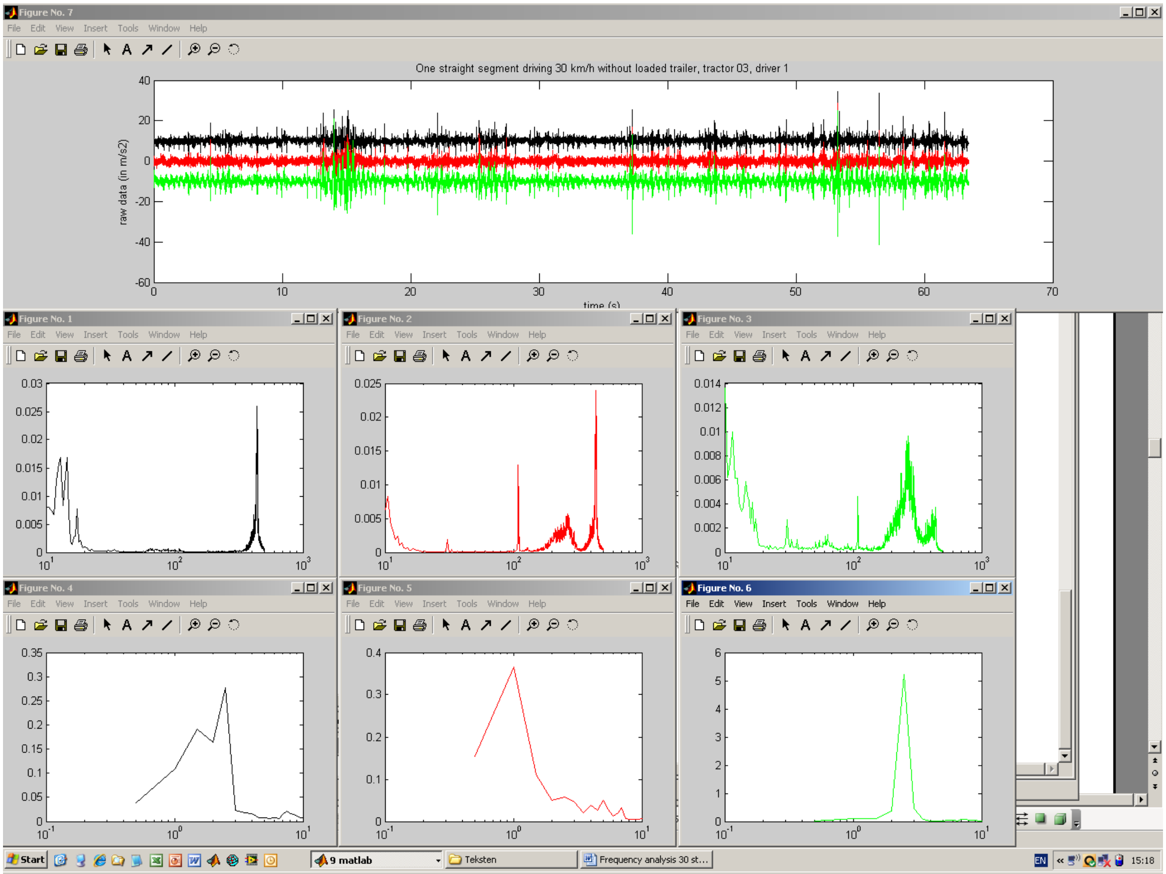


Figure No. 7
One straight segment driving 30 km/h without loaded trailer, tractor 03, driver 1
raw data (in m/s2)
time (s)
Figure No. 1
Figure No. 2
Figure No. 3
Figure No. 4
Figure No. 5
Figure No. 6
9 matlab
Teksten
Frequency analysis 30 st...
15:18

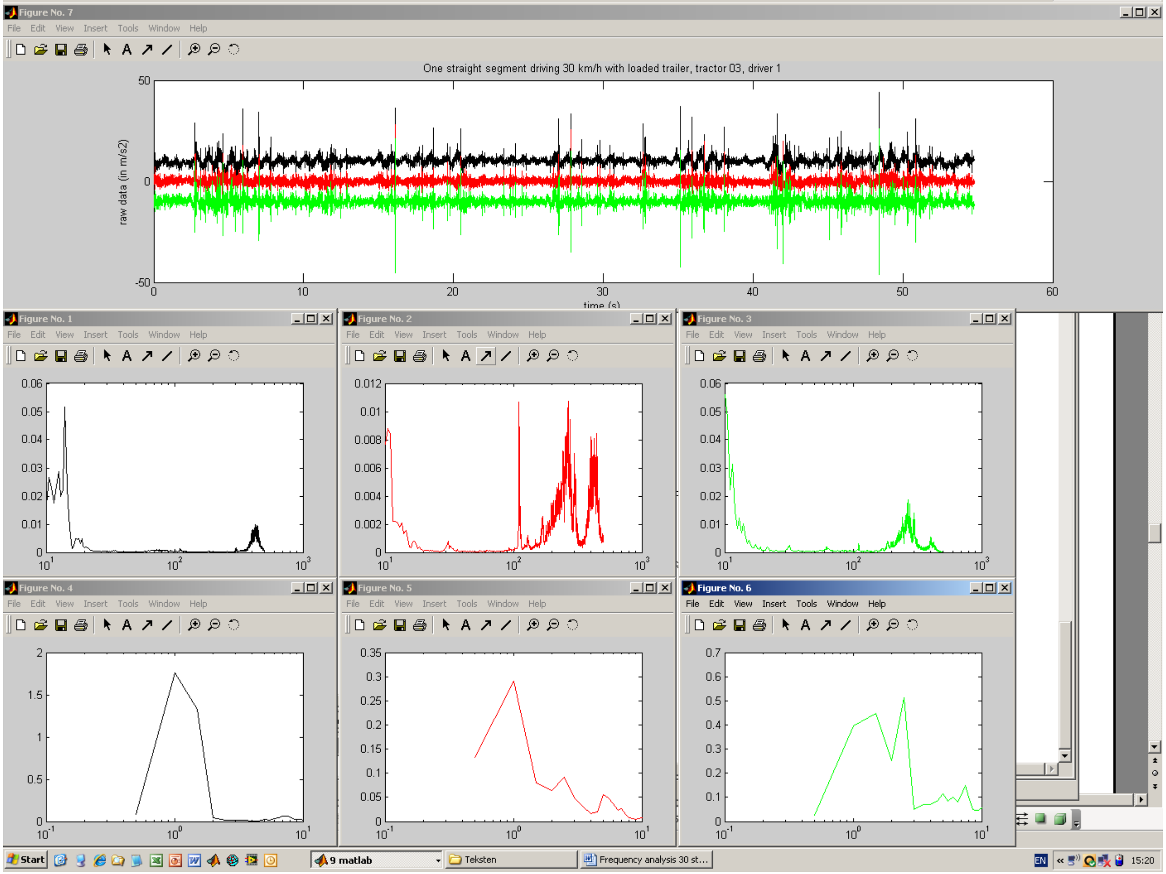
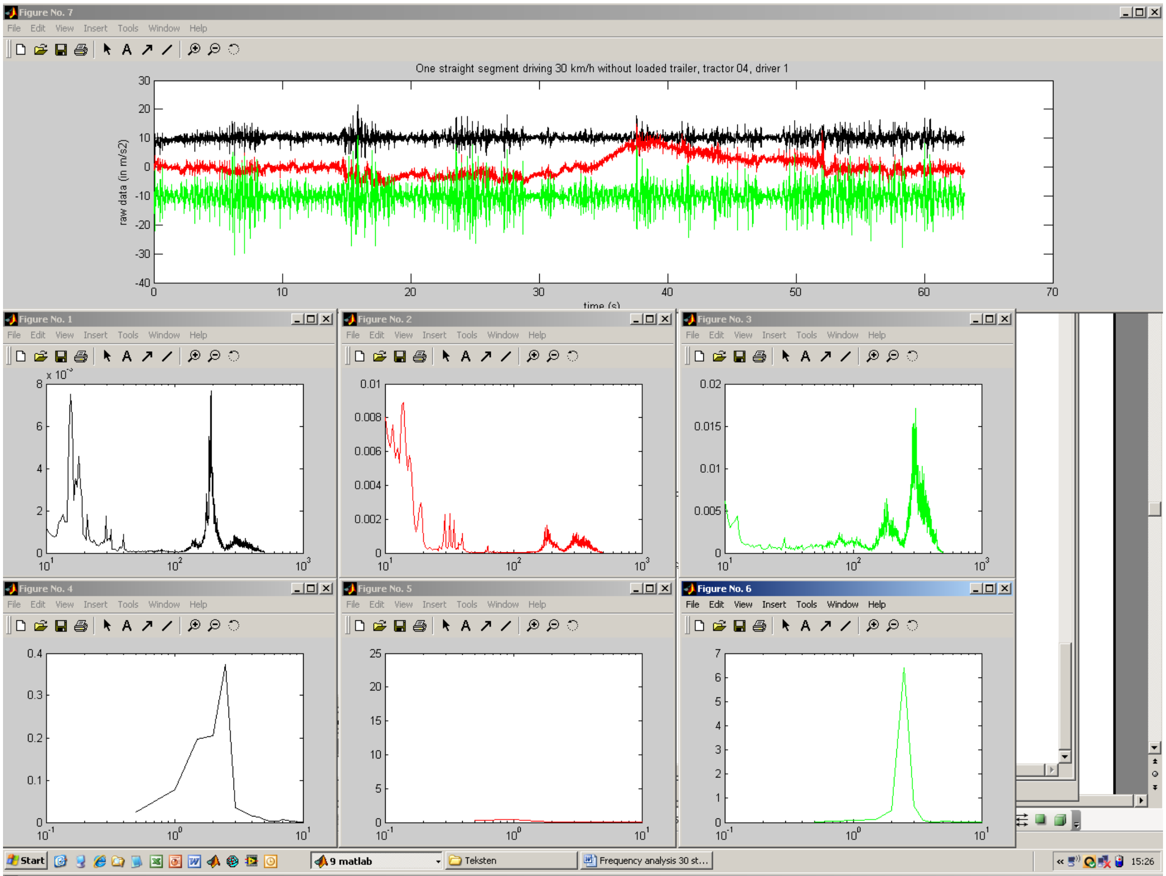
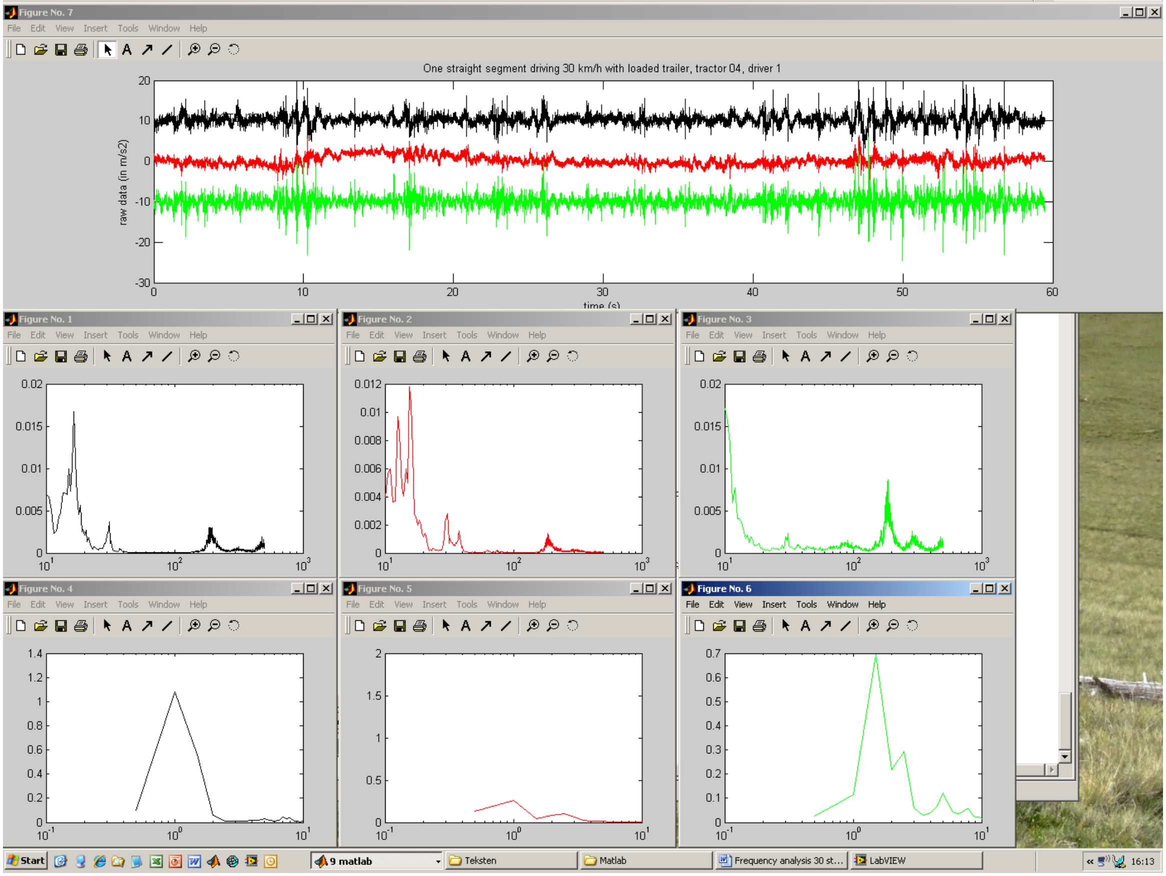
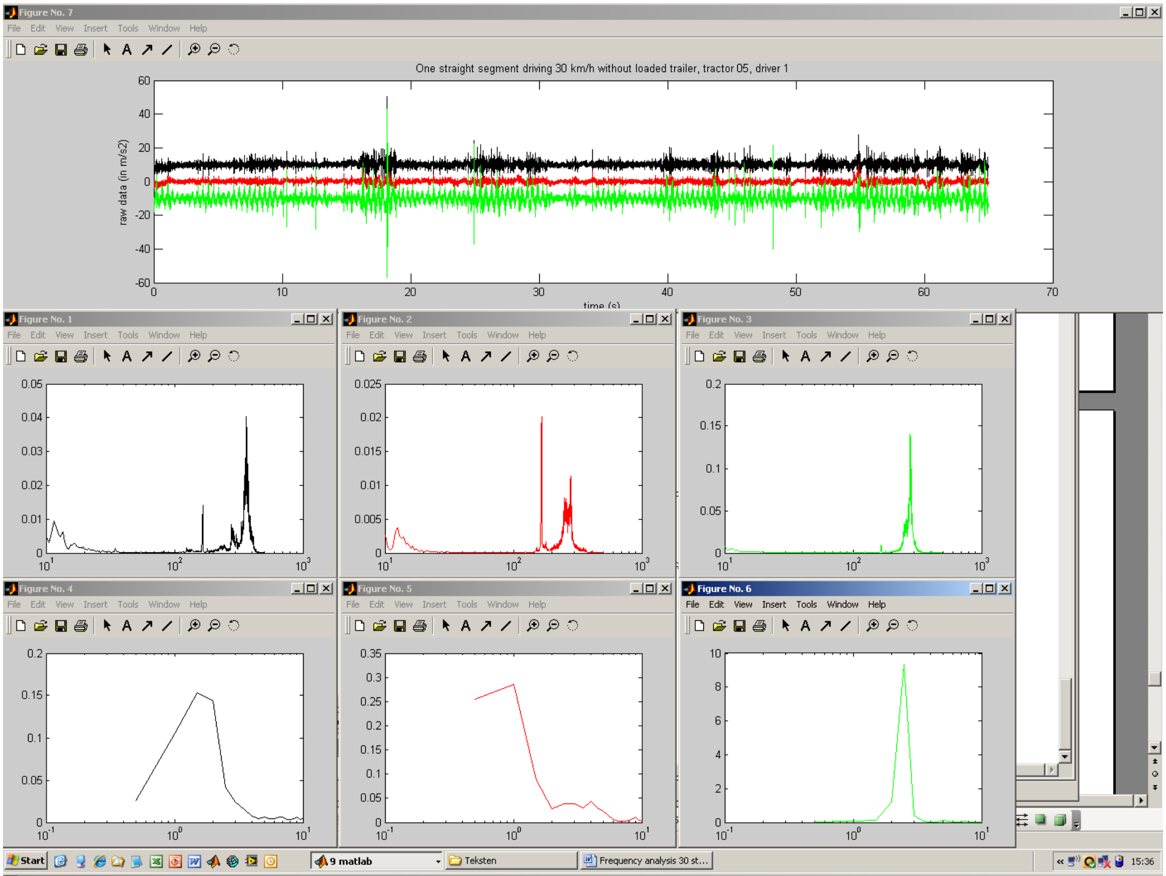
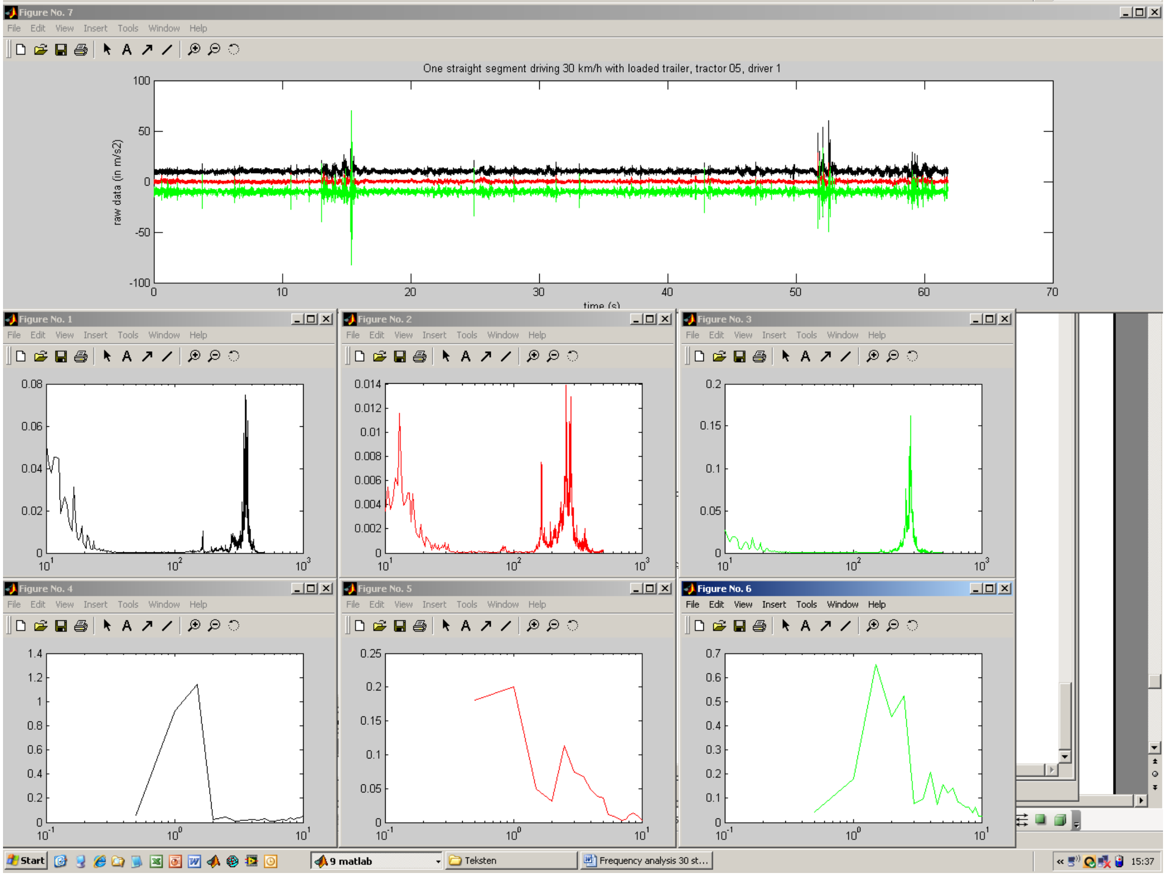


Figure No. 7
One straight segment driving 30 km/h with loaded trailer, tractor 03, driver 1
raw data (in m/s2)
time (s)
Figure No. 1
Figure No. 2
Figure No. 3
Figure No. 4
Figure No. 5
Figure No. 6
9 matlab
Teksten
Frequency analysis 30 st...
15:20

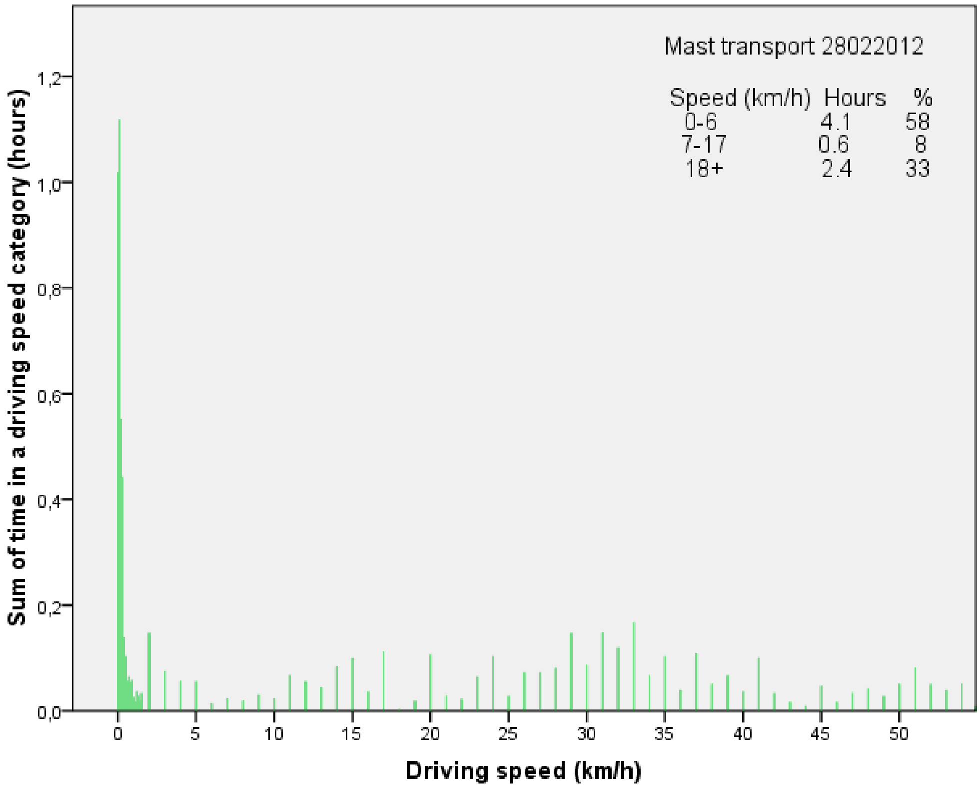

One straight segment driving 30 km/h without loaded trailer, tractor 04, driver 1
raw data (in m/s2)
time (s)

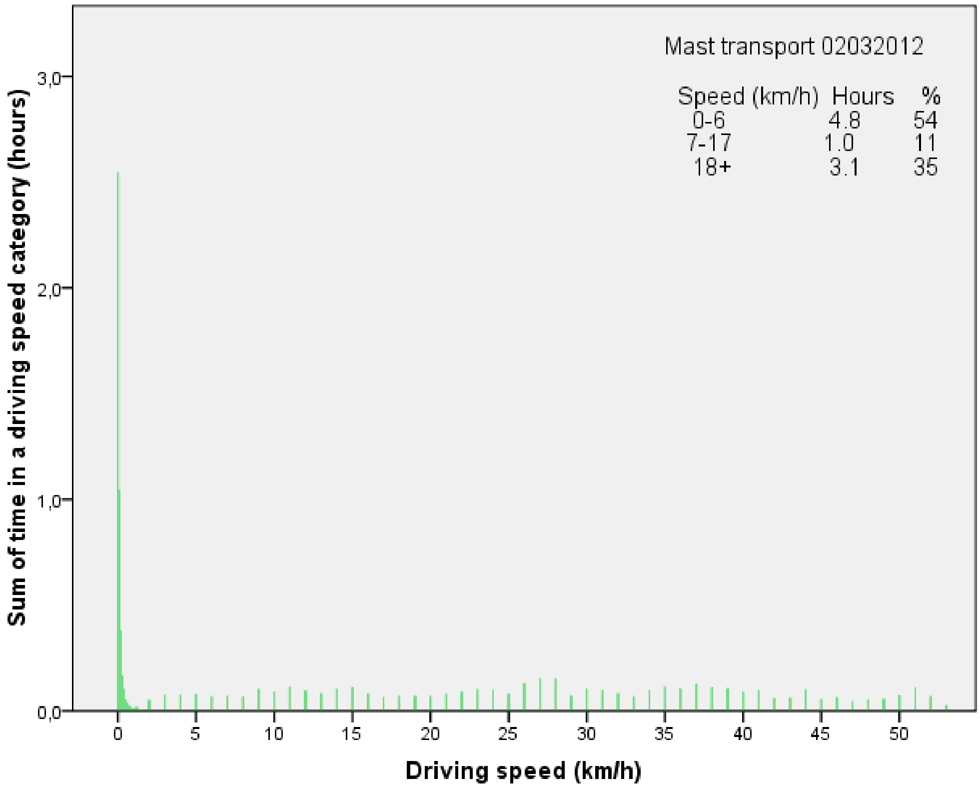

One straight segment driving 30 km/h with loaded trailer, tractor 04, driver 1
raw data (in m/s2)
time (s)

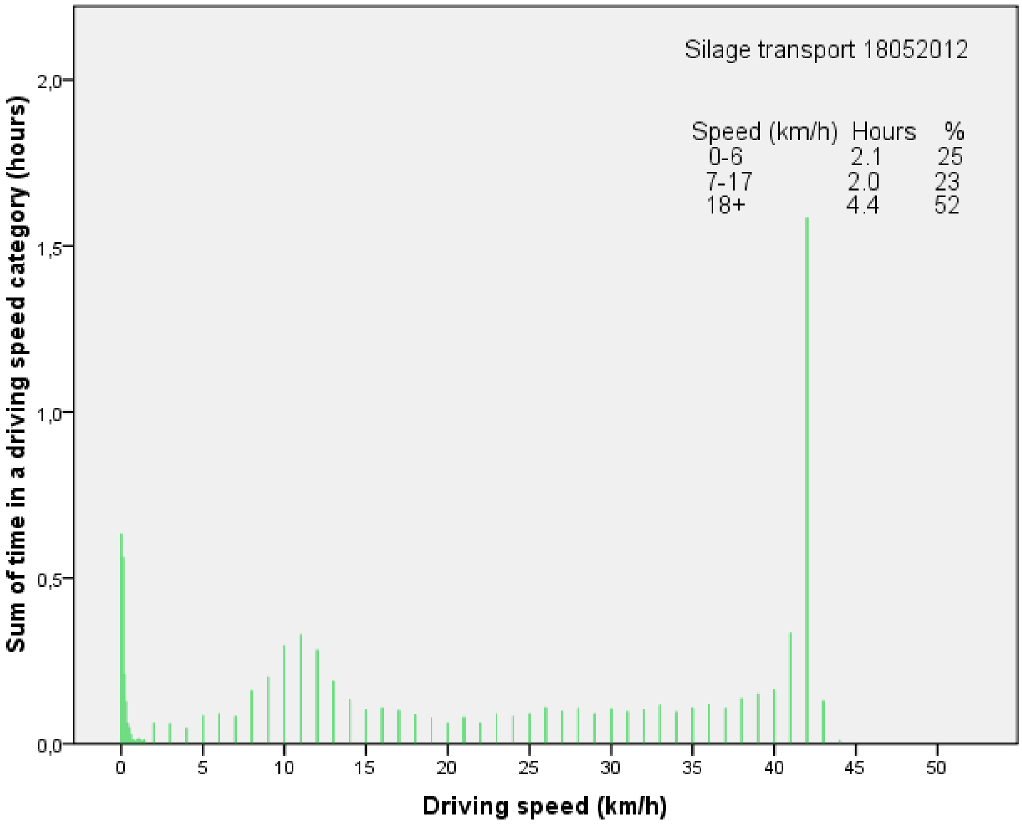

One straight segment driving 30 km/h without loaded trailer, tractor 05, driver 1
raw data (in m/s2)
time (s)

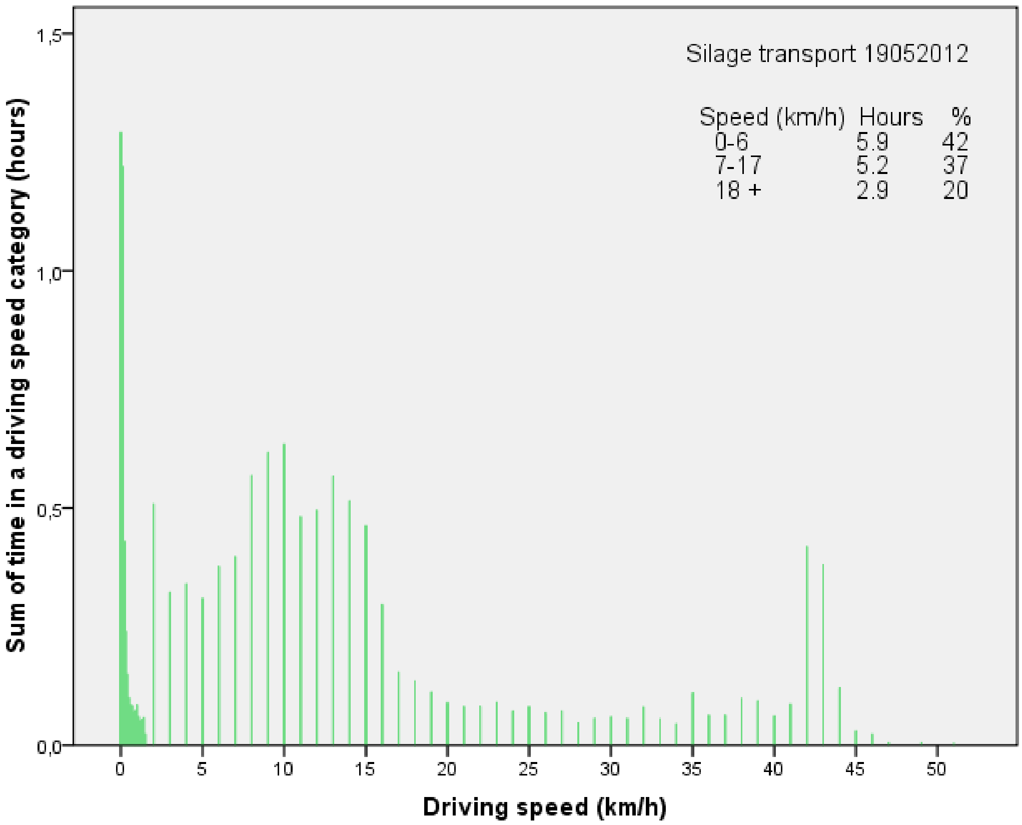

One straight segment driving 30 km/h with loaded trailer, tractor 05, driver 1
raw data (in m/s2)
time (s)

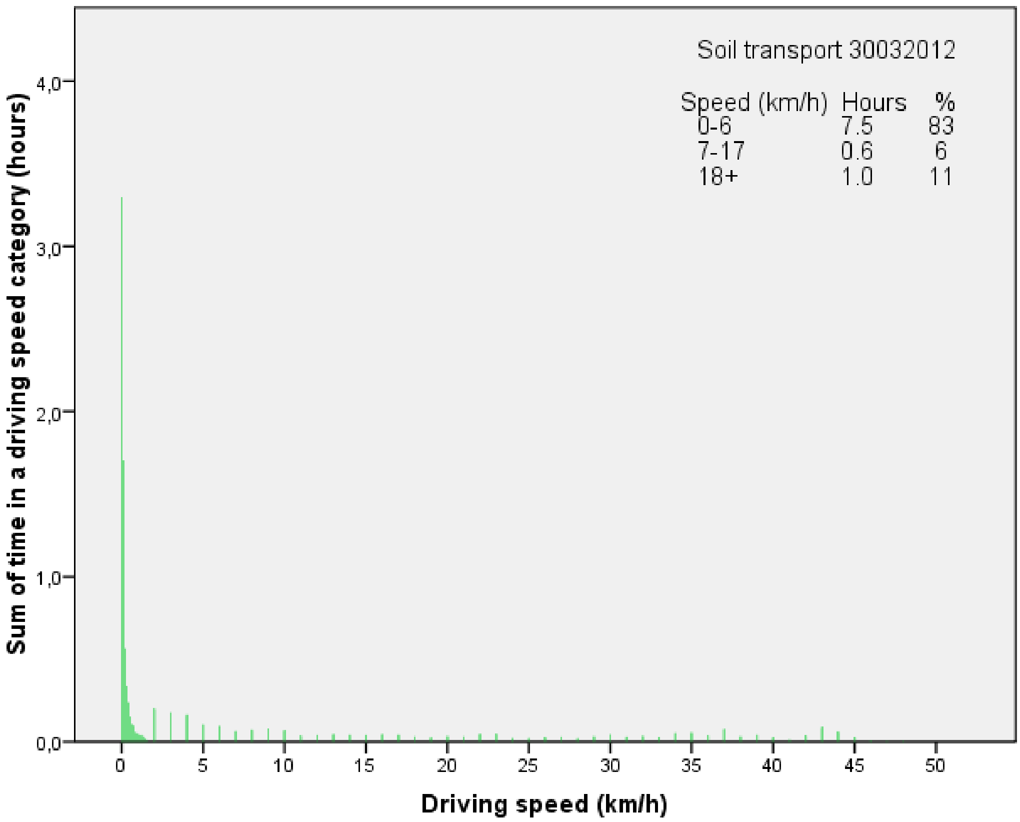
Annex E – Driving speed distributions in practice






Silage transport 18052012
Speed (km/h) Hours %
0-6 2.1 25
7-17 2.0 23
18+ 4.4 52
Sum of time in a driving speed category (hours)
Driving speed (km/h)
0,0
0,5
1,0
1,5
2,0
0
5
10
15
20
25
30
35
40
45
50


Silage transport 19052012
Speed (km/h) Hours %
0-6 5.9 42
7-17 5.2 37
18 + 2.9 20
Sum of time in a driving speed category (hours)
Driving speed (km/h)
0,0
0,5
1,0
1,5
0
5
10
15
20
25
30
35
40
45
50



Soil transport 30032012
Speed (km/h) Hours %
0-6 7.5 83
7-17 0.6 6
18+ 1.0 11
Sum of time in a driving speed category (hours)
4,0
3,0
2,0
1,0
0,0
0
5
10
15
20
25
30
35
40
45
50
Driving speed (km/h)