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Report

Exposure to whole-body vibration of drivers of state-of-the-art self-propelled wide area rotary mowers during mowing of public green areas in practice

Blootstelling aan lichaamstrillingen van chauffeurs van moderne zelfrijdende cirkelmaaimachines tijdens het maaien van plantsoenen in de praktijk

Huub H.E. Oude Vrielink

Report 2014-0212 (English version of 2013-3110)

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Colophon

About ErgoLab Research B.V. 'Knowledge works better'

ErgoLab Research was funded in 2006 and continued some Wageningen University & Research Centre (Wageningen UR) specialisms. ErgoLab Research aims to transfer specialist knowledge and academic skills in the area of work and health to working people, government, students in educational institutions, manufacturers and society in a comprehensible way, by research (measurements and testing), consultancy, training and coaching. Know-how and skills have been developed in more than 25 years of experience in fundamental and applied research, and knowledge transfer. The covered area is not restricted to labour and labour conditions (vibrations, physical load), but covers also engineering and technology, health behaviour, and academic skills in general.

In the area of human vibration evaluation and technology, ErgoLab Research has conducted a number of investigations and consultancy measurements. The reports, most of them also containing the detailed conditions and results of the measurements, can be downloaded from www.ergolabresearch.eu. Examples are:

- Analysis of the exposure to whole-body and hand-arm vibrations during work in the green area (2007)
- Measurement of daily exposure to whole-body vibration during transport of stapled do-it-yourself products using forklift trucks (2013)

Title	Exposure to whole-body vibration of drivers of state-of-the-art self-propelled wide area rotary mowers during mowing of public green areas in practice (*Blootstelling aan lichaamstrillingen van chauffeurs van moderne zelfrijdende cirkelmaaimachines tijdens het maaien van plantsoenen in de praktijk*)
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Preface

This report documents the measurements of whole-body vibration exposure of operators of self-propelled rotary lawnmowers during their normal tasks. These measurements were performed by ErgoLab Research B.V. The measurements were the initiative of the Dutch sector organization for the green area services VHG as well as the Dutch employees' organizations FNV Bondgenoten and CNV Vakmensen. The reason for the research was the outcome of measurements performed in 2006 and their interpretation in the Health & Safety Catalogue for the branch: a maximum of 4 hours of daily working time is advised for mowing of public gardens, given the current legislation. It was asked by the initiators whether technical improvements, if any, implemented in modern mowing machines and / or seats have resulted in lowering of the vibration exposure and, hence, can result in an elongation of the daily working time on the machine.

ErgoLab Research, an independent research and consultancy firm and specialist in vibration research, was asked to perform the measurements according to the latest standards, and to document and interpret them in a clear and thorough report and presentation. The present report is also meant as good documentation, as described in the Dutch Labour Conditions Act ('Arbeidsomstandighedenbesluit').

The following persons and companies are greatfully acknowledged for their willing cooperation and support:

- Landscaping company and gardening service Van Ginkel Veenendaal: Chris van den Dikkenberg (local manager) and the operators during the tests Arie Drost,Wilco van Hal, and Andries van de Vendel;
- The Dutch suppliers Van der Pols (Zuidland), Jean Heybroek (Houten), and Staadegaard & Zn (Lieshout) for providing the self-propelled lawnmowers;
- Michel Kuijpers (John Deere) and Willem van der Horst (Votex) for giving their advice on the correct settings of their mower during the measurements;
- The operators of self-propelled lawnmowers of the various gardening services for registering one or more of their working days in a diary;
- The counselling team for this project, composed of the following representatives:
    - Jan Batenburg (chair; VHG)
    - Ingrid Sangers (VHG)
    - Monique Daamen (FNV Bondgenoten)
    - Henry Stroek (CNV Vakmensen)
    - Sjoek van der Maarl (Stigas)
    - Theo Vulink (Fedecom)

Summary

This report, which is an update of an investigation performed seven years ago, presents the results of measurements of the exposure to whole-body vibrations (WBV) of drivers of self-propelled lawnmowers. The research was commissioned by the Dutch sector organization VHG as well as the Dutch employees' organizations FNV Bondgenoten and CNV Vakmensen. The current advice to restrict the daily working time on self-propelled lawnmowers, as formulated in the Health & Safety Catalogue for the branch on basis of the earlier measurements and the current legislation, hampers an efficient planning and execution of the work in practice for many employers. The aim of the research was to determine whether technical developments of the mowers at present are such that employees are exposed to lower levels of whole-body vibrations and, hence, that their maximal daily working time can be extended.

The research is performed in practice with help of three volunteering professional operators, all being employees of a landscaping company and gardening service in Veenendaal, The Netherlands. Three suppliers of self-propelled rotary lawnmowers most frequently used in The Netherlands (Toro, Ransomes, John Deere), voluntarily provided a most recent version of one of their machines. All mowers were in the same range with respect to motor power and dimensions, and had three decks of rotating blades. All operators tested each machine on a separate day at an interval of 2-3 weeks on the same set of five public green area plots. In addition, sitting on a stationary running machine and driving to and from the public green area plots over asphalt roads were measured. Each operator was asked to mow two of the plots at the speed they were normally used to drive. Further, two other plots were mown 'hasty', so simulating as if the operator was given insufficient time for the task. Finally, one plot was mown 'restrained', simulating the operator had been given too much time for the task. The measurements were performed in full accordance with the ISO-2631-1: 1997 guideline on the chair and at the chair base in the three directions X (fore-aft), Y (lateral), and Z (vertical), sampled at 4096 Hz, and stored on a portable computer. Data analysis was done off-line with help of continuously and simultaneously measured driving speed (using GPS) and video registration (an small action cam was mounted on the driver cabin). Chair damping was expressed as so-called SEAT value. To obtain an accurate estimation of the normal daily exposure time, several professional operators of self-propelled lawnmowers in The Netherlands were asked to keep a diary for one or more working days, in which they wrote their activities at minute level. A total of 13 drivers responded. The data from 7 drivers were accurate enough to be used, producing a total of 12 different working days.

For the three machines tested, whole-body vibrations measured on the chair during mowing varied between 0.63 and 0.76 m/s^2 (X; median: 0.69 m/s^2), 0.48 and 0.72 m/s^2 (Y; median: 0.59 m/s^2), and 0.44 and 0.54 m/s^2 (Z; median: 0.47 m/s^2) during normal mowing speed (range values given are medians over operators). The average driving speed was 6.1 km/h. In all cases, vibrations in the horizontal plane (X or Y) were highest and restricted the maximal daily working time. Exposure during driving over asphalt roads to and from the public gardens were 0.33 - 0.40 m/s^2 (X; median: 0.39 m/s^2), 0.28 - 0.42 m/s^2 (Y; median: 0.34 m/s^2), and 0.39 - 0.50 m/s^2 (Z; median: 0.40 m/s^2) for the three machines.

Restrained driving considerably reduced the exposure to whole-body vibration: median values over drivers and machines were 0.58 m/s^2 (X), 0.49 m/s^2 (Y) and 0.41 m/s^2 (Z). The average driving speed (5.9 km/h) was hardly reduced compared to mowing at normal speed. Hasty mowing increased both average driving speed (7.7 km/h) and exposure (0.74 m/s^2 for X as being the median value over drivers and machines, 0.75 m/s^2 for Y and 0.57 m/s^2 for Z).

Chair damping appeared independent of driving behaviour. SEAT values were 107%, 100% and 52%, medians for X, Y and Z, respectively. These values imply that vibrations of the cabin floor are effectively damped by the seat in the vertical direction only. Compared to the research performed 7 years ago, the seats seem to be more effective in their damping in all directions.

From the survey of working activities of drivers of mowing machines, it appeared that the total daily working time is almost 9 hours, excluding pauses. The relative contribution of mowing itself was 63%. For driving over paved roads to and from public garden areas and for transport of the mower with help of car or bus, this was 13% and 8%, respectively. During 15% of the working day, tasks were done that had no exposure to whole-body vibrations (such as refuelling or maintenance).

When combining the exposure values measured with the outcomes of the normal daily working pattern, it appears that for all machines tested exposure to whole-body vibrations for a full normal working day exceeds the action value, defined as health limit in the Dutch and European legislation. When mowing at normal speed, the action value will be reached after 5-6 hours of work, given the division of tasks of a normal working day. If mowing in a restrained way, the action value will be reached after 7-8 hours of work.

To be able to use the self-propelled mowers for a full working day, it is necessary that technical improvements are to be implemented to reduce vibration exposure. In particular, attention should be paid to reduction of vibrations in the horizontal plane. Whether solely the application of horizontal damping systems in the chair itself will be enough remains to be shown: in the present research, no effect was seen from the presence of a fore-aft vibration damping system in the seat.

Another point of attention may be the following: in the present research high amplitude horizontal accelerations of the seat were observed to parallel high vertical accelerations of the cabin floor. It is worth investigating whether effective damping of the wheels or tyres will diminish this phenomenon, which is possibly related to angular accelerations around the axles. Note that eventually unwanted resonance effects because of damping systems already present in the chair should be avoided.

Content

1 Introduction, problem and aim

1.1 History in short

Since many decades, whole-body vibrations (WBV) are thought to be related to adverse health effects. Initially, researchers related WBV merely to nerve excitation and premature fatigue (Reiher & Meister, 1931). In later times, an association with back disorders was described by Dupuis (1969). Although since then this relationship was subject of frequent research, up to present a clear and causal relationship between WBV and the development of back disorders has not been demonstrated. Despite this, many researchers tend to conclude, on basis of various investigations and meta-analyses, that long-term exposure to WBV can be detrimental for the back (Hulshof & Veldhuijzen van Zanten, 1987; Bovenzi & Hulshof, 1999; Lings & Leboeuf-Yde, 2000). This is believed to hold especially for exposure to shocks (Waters *et al.*, 2007).
To be able to combine the strengths of the investigations on the effects of WBV on health, so that the complex exposure measurements and effects can be better compared with each other, the ISO Technical Committee 108 made standards since 1974: ISO-2631. The latest version is from 1997 (ISO-2631-1, 1997). The standard describes in detail how measurements are to be performed and data are to be processed and described. In addition, an attempt is made to define 'health guidance caution zones', to indicate at what levels daily exposure to WBV is becoming likely to be a health risk. However, the lack of firm scientific evidence makes that these caution zones are surrounded by uncertainty.
The frequently reported trend that more back complaints and disorders occur if exposure to WBV is higher and/or for longer time, made the European Commission to define legislation on this topic. On the EU level, this legislation was approved in 2002 (EU, 2002). In the Netherlands, it took another three years before it was implemented in the Labour Conditions Act ('Arbeidsomstandighedenbesluit'; Staatsblad 372, 2005). The law defines, amongst others, action and limit values for the daily exposure to WBV: 0.5 and 1.15 m/s^2, respectively. If for an employee during any working day the exposure to WBV exceeds the action value, actions should be taken to restrict further exposure. This can be for example the application of another working method or aid, performing maintenance of the machine, or restricting the working time with that machine of aid. Daily exposure may never exceed the limit value. The only exception on the latter is when machines or working aids are used that were purchased before July 6th, 2007. For these machines and aids, exceeding the limit value will be tolerated up to July 6th, 2014 for agriculture and forestry. The action and limit values hold for any working day. The axis (X: fore-aft; Y: lateral; Z: vertical) that has the highest exposure value is decisive.

Since the consequences of the legal vibration exposure limits were unclear for the Dutch agricultural sector, including forestry and maintenance of public green spaces, in 2006 a research was performed to measure the exposures to vibrations of those tasks that were most common and considered to have the highest risk. For the maintenance of public green areas, these tasks were amongst others mowing of public parks and sports fields (Oude Vrielink, 2007[a]).

1.2 Exposure to whole-body vibrations when mowing public green areas

In 2006, the WBV exposure of two operators on two different makes of self-propelled rotary lawnmowers was measured during mowing of public green areas (Oude Vrielink, 2007[a]). The public area was located in Wageningen, The Netherlands, and consisted of different irregular-shaped plots, separated by paved roads, and each containing different obstacles like benches and trees. In addition, driving to and from the public gardens was measured. The results showed a too high value of exposure to WBV in the horizontal plane. Median values were 0.61 (fore-aft) and 0.63 m/s^2 (lateral) for the mowing task itself. The vertical vibration exposure appeared below the action value: 0.46 m/s^2. Driving to and from the parks remained below or around the action value for all vibration axes. Given an assumed daily working duration of 8 hours and an estimated 80% of the time spent on mowing and 10% on driving, it was calculated that the action value would be reached after 4.6 – 5.8 hours. For an individual operator, however, this could already be after 2.8 hours. On basis of these measurements, the Health & Safety Catalogue for the branch formulated the advice that mowing of public green spaces by one operator should not be performed for more that 4 hours per working day, or should be done for a maximum of three days per week (Stigas, 2008). In addition, the Catalogue gives the advice to accelerate and brake in a restrained way, in order to reduce vibration exposure in the fore-aft direction.
In the literature there is only limited knowledge about WBV exposure of operators of self-propelled lawnmowers. Paddan & Griffin (2002) reported exposure values comparable with those mentioned in the previous paragraph, although types of machines and conditions are not clearly decribed: exposure varied from 0.56 to 0.76 m/s^2 for the dominant axis. Also Tiemessen and colleagues (2008[a]) reported higher exposure values in the horizontal plane compared to the vertical axis. Their values measured for both horizontal axes (1.16 and 1.22 m/s^2 for fore-aft and lateral, respectively), including the ISO-prescribed correction values of 1.4 (see paragraph 2.6 for an explanation), are considerable higher than those reported by Oude Vrielink (2007[a]). In vertical direction, a value of 0.56 m/s^2 was reported. The data were sampled from one operator on one mower. In an additional research the measurements were extended to nine mowers and operators (Tiemessen *et al.*, 2008[b]). Unfortunately, no information is provided on the WBV exposure per vibrational axis, and only the vectorsum over the three axes as a mean over all measurements is reported. From the latter value, it can be deduced that WBV vibration exposure is comparable or slightly elevated compared to the values reported by Oude Vrielink (2007[a]).
Various possible factors may explain the different outcomes between different measurements (for an overview is referred to Tiemessen *et al.*, 2007). For the mowing of public green area, the unevenness of the fields (for example as results of mole activities, digged holes or presence of tree branches) and driving speed are relevant. Other factors are the mass of the machine, tyre size, tyre pressure, chair damping, and construction of the machine. In respect to the latter, one may think of the position and height of the chair relative to the axles. Finally, also the operator himself is important: body mass and driving behaviour are co-determining WBV exposure.

1.3 Problem and aim

The restriction in daily working time on self-propelled lawnmowers, as formulated in the Health & Safety Catalogue, is problematic for most employers and employees in view of efficiency, costs, and task performance. It is therefore that the social partners, consisting of the Dutch sector organization for the green area services VHG and the Dutch employees' organizations FNV Bondgenoten and CNV Vakmensen – together being the most important interest representatives of employers and employees for the public green area maintenance and gardening services – initiated this project. It was asked whether the technical developments in state-of-the-art self-propelled rotary lawnmowers used at present in the public green area domain are such that WBV exposure for the operator is reduced compared to earlier measurements. And, hence, whether the daily maximal duration for mowing of public green areas can be elevated.

The question formulated above is not limited to developments in the lawnmower itself. It is also applicable to the seat mounted. Earlier measurements (Oude Vrielink, 2007[a]) showed that seats only damped effectively in vertical direction, while vibrations in the horizontal plane even were amplified compared to the cabin floor. It was therefore also questioned whether the presence of a seat having a horizontal damping system would contribute to a reduction of the vibration exposure.

In the research of 2007 mentioned, the exact amount and pattern of daily work of an employee on a mower was not determined accurately. The counselling group of that research estimated that 80% of the working day was spent on mowing itself, 10% on driving on paved roads, and 10% on other tasks without exposure. Since this was a rough estimation, is was asked in the present research to make a more accurate estimation of the task division on a normal working day, as being the basis of a correct calculation of the daily exposure.

If employers and employees, when purchasing a new lawnmower, also want to take into account the vibration exposure of the machine, the only hold mostly is the legally compulsory indication of exposure to vibrations in the manual. The values reported are to be based on either measurements in practice or on standardized tests described in norms. It is questionable whether the reported values match exposures experienced in practice. It also can be asked whether a deviation between reported and measured exposure values, if any, can be explained by taking into account the differences in conditions between practice and those described in the norms.

Finally, it is unclear whether the advice given in the Health & Safety Catalogue to perform the braking and accelerating in a more restrained way is effective and indeed resulting into a lowering of the WBV exposure.

Aim of the research was to make an accurate estimate of the exposure to WBV of operators of state-of-the-art self-propelled lawnmowers during a normal working day when mowing different plots of public green areas. The aim was answered with help of the following research questions:

1. What value has the WBV exposure for the operator for the whole set of tasks during a normal working day? What is the (quantitative) contribution of each of the tasks distinguished to this value?
2. Does the daily exposure remain below the action value for the complete length of a normal working day? What will be the maximal daily working duration before reaching the action value?

3. Does the exposure to shocks remain below the health caution level?
4. Is there a clear difference in WBV exposure when using machines of different makes? What is the difference between measured values and values indicated in the manual? Can these differences, if any, be explained considering the differences in tesing conditions?
5. Is the seat, as normally mounted in the cabin of the machine, effective in damping vibrations transmitted from the cabin floor? Is the presence of a horizontal damping system in the chair effective in reducing horizontal WBV exposure?
6. What is the influence on WBV exposure of an instruction to realize a difference in driving behavior? What is the relation between driving behavior and driving speed? What is the consequence of the difference in driving behavior for the task performance?
7. Is there any relation between personal characteristics of the operators (body mass, driving behaviour) and WBV exposure? Can this relation be described?
8. What are the possibilities for employees, employers, and manufacturers to further reduce the exposure to WBV during mowing of public green areas?

2 Materials, methods and procedure

Vibration exposure is measured during driving on three different mowers, each on a separate day (18-06-2013, 27-06-2013 and 09-07-2013), by three experienced operators. They were asked to perform the mowing task itself in three different ways: (a) at their normal speed, (b) in a hasty way (with the instruction given to the operator that he had insufficient time for the task), and (c) in a restrained way (with the instruction the operator had by far enough time for the task). The order of performing these ways of driving was not fixed for all operators and at each testing day. To be able to compare the outcomes over operators and machines, a certain plot was always mown according to a fixed instruction (a, b, or c). This means that on one testing day, all plots were mown three times. The order of the operators for each testing day was different.

2.1 Operators

The measurements were performed with three experienced operators (all men). They were selected in view of a sufficiently broad range in body mass. Some personal characteristics at group level are given in table 1. One of the operators reported complaints (pain or discomfort) in the low back during the 12 months preceding the measurements. These complaints did not lead to a different driving behaviour, as appeared on inquiry. He indicated these complaints were likely to be caused by the job. No complaints of other body regions were reported. All operators were voluntarily participating in the tests and signed an Informed Consent after being informed about the measurements, equipment and organization of the test.

Table 1: Personal characteristics and working experience of the operators (n=3). Data indicated are means, minimum and maximum values.

	Age	Body mass	Length	Experience mowing public gren areas	Labour on mower[1]	Labour on mower[2]
	(years)	(kg)	(cm)	(years)	(weeks / year)	(hours/week)
Mean	41	97	193	5	24	42
Minimum	25	83	190	2	3	40
Maximum	55	115	196	6	35	45

[1] number of weeks per year, without holidays. [2] i.e. inclusive regular pauses.

2.2 Machines

A representative of Fedecom, the branch organisation for manufacturers in agricultural and horticultural technology, was asked to select and approach the suppliers of self-propelled lawnmowers that were commonly used in the Dutch public green area maintenance. All three suppliers (see Preface) agreed to participate after they were informed about aim and set-up of the tests, and made their mower available.

The research was performed with three self-propelled lawnmowers, all having three decks with rotating blades. Some of the technical properties of the machines are given in table 2. Pictures of them are given in Appendix B.

Table 2: Characteristics of the self-propelled rotary lawnmowers involved in the measurements.

Mow-er	Make, type	Building year	Mass (kg), wheelbasis (m)	Power (kW), Mowing height (m)	Tyre type, make, size[1] and pressure	Chair type and -damping[2]
1	Toro 4010 D Grounds-master	2013	2107 kg 1.40 m	35 kW 0.064 m	Tubeless f: Kenda Turf 505 26x12.00-12 NHS, 190 kPa r: Kenda Super Turf 20x10.00-10, 190 kPa	Grammer MSG95G/731 Z: p,h X, Y: -
2	Ransomes HR 6010	2010	1350 kg 1.40 m	45 kW 0.063 m	Tubeless f: BKT LG-408 24x13.00-12 NHS, 137 kPa r: BKT LG-306 20x10.00-8 NHS, 120 kPa	Grammer MSG95A/731 Z: p,h X: m, Y: -
3	John Deere 1505 S II BM	2012	1480 kg 1.31 m	31Kw 0.065 m	Tubeless f: Trelleborg Soft grip 539 26x12.00-12 8 PR, 150 kPa r: Trelleborg T-539 20x10.00-10 6 PR, 90 kPa	Grammer MSG95A/731 Z: p,h X: m, Y: -

[1]: f=front tyres; r=rear tyres; PR = ply rating (higher value = more stiff)

[2]: m=mechanical; p=pneumatic; h=manually to be adapted by the driver;
X,Y,Z: damping present along the axis indicated, according to the definition given in ISO 2631-1 (1997)

2.3 Location, organisation and conditions during measurements

The mowers were delivered by the suppliers in the week before a testing day at the site of landscaping company and gardening service Van Ginkel Veenendaal B.V. After delivery, an instruction was given to one of the testing operators about the control of the machine (in the presence of the author of this report). The operator present ensured the transfer of the instruction to both other operators. The adjustment of the machines (i.c. tyre pressure and mowing height) was kept standard (see the table in the previous paragraph). The mowing height was comparable for all three machines.
The locations of the test were five different plots of the public green area in the north of Veenedaal, immediately south of the ring road Grote Beer. For mowing at normal speed, two plots were used north of the road Vuurvlinderronde and the east part of the road Donsvlinderstraat, up to approximately Aardbeivlinderstraat (see figure 1, numbers 1 and 2). The remainder north of Donsvlinderstraat (number 3) and the plot east from Maartvlinderstraat (number 4) were used for testing mowing in a hasty way. Finally, the plot north of the buildings of the Nachtpauwooglaan (number 5 in figure 1) was used to test restrained mowing.

Figure 1: View on the measurement location. On the map (obtained via Google Maps) are indicated the starting location (red arrow), route for driving to and from the plots (yellow arrow) and the five testing plots of public green area. Plots 1+2: normal speed; plots 3+4: hasty speed; plot 5: restrained speed.

Start- and/or end location for every operator was the site of Van Ginkel Veenendaal B.V. located at Castor. The route (smooth tarmac) to and from the public green plots was always the same: Castor – Vijgendam – Kleine Beer – Prins Bernhardlaan – Stationsstraat – Grote Beer – Nachtpauwooglaan or Dagpauwooglaan, in this or opposite order. See figure 1 for a graphical display of testing locations and route.
The first operator of a testing day drove the tarmac route to the testing plots, and performed the mowing in the order of number 1 → 5. The second operator performed the mowing in opposite order and drove back the tarmac route. The third driver of the day drove the tarmac route both to and from the plots and mowed in the order as indicated for the first operator. The tarmac route contained a traffic plateau and a speed bump, and had a length of about 1.5 km. Between the plots, it was necessary to drive short distances over paved paths (paving brick or tarmac).

The mounting of the measurement equipment was done in the morning immediately prior to the tests. The equipment was calibrated each day before the tests (see paragraph 2.5). All measurements started with a one minute sampling of the operator sitting at rest on a stationary machine with running engine. The driving over the tarmac route took on average 6.3 minutes (variation: 5.2 - 8.3 minutes). The duration of the measurements of the mowing at normal speed varied between 22.1 and 35.7 minutes (mean: 24.8 minutes). For mowing at hasty and restrained speed, this was 10.6 – 13.0 (mean: 11.7) and 14.2 – 24.2 (mean: 18.9) minutes, respectively.

Machine 1 was tested on June 18, 2013. The conditions on that day were dry and warm: the temperature varied between 24 and 32 °C. The 7 days before the test the total rain fall was 4.4 mm (KNMI, 2013; as an approach the amount for the official measurement location Deelen is taken), of which 0.9 mm fell in the three days immediately prior to the test. The conditions during the test of machine 2 (June 27, 2013) were more cool and wet: the testing day itself brought 3.9 mm of rain and the temperature was 12-15 °C. The week before that a total of 18.1 mm was reported, of which 4 mm fell in the three days immediately prior to the test. Most dry was the test of machine 3 (July 9, 2013), with zero rain fall and a temperature between 19 and 26 °C). No rain was reported in the three days prior to the test. During the whole week before the test a total of 6.6 mm of rain fall was measured.

2.4 Normal working day patterns in practice

A diary was made to estimate the duration of sitting on a self-propelled lawnmower for an operator in practice. The distribution was done by the employees' organizations FNV Bondgenoten and CNV Vakmensen under several operators associated. Every time the operator changed an activity, he was asked to write down the time moment in the diary. The following activities were distinguished, separated in two main groups, (A) sitting on the mower, and (B) not sitting on the mower: A1 Driving to or from public green area spaces over paved roads, A2 Mowing itself, A3 Driving over paved roads between public green area plots, A4 Other, B1 Activities needed for preparation of the mowing task, B2 Small maintenance activities, B3 Transporting the mower using a car or van, B4 Loading or unloading the mower before / after transport, B5 Pause, B6 Other. The category A4 for example was sitting on a stationary running machine.
A total of 13 operators returned one or more diaries. Six operators completed their diary in a too inaccurate way; their data were excluded from further analysis. The remaining 7 operators reported in detail a total of 12 complete working days. Two operators reported two, one reported four working days. Mean values for the activities over these days per operator were computed before group means per activity were calculated.

2.5 Measuring instruments and procedure

Procedures for the measurement of vibration exposure are very much standardized and described in ISO-directives. For the measurements documented here, the directives ISO-2631-1 (ISO-2631-1, 1997), ISO 2631-5 (ISO-2631-5, 2004) and ISO-8041 (ISO-8041, 2005) have been followed. WBV exposure of the driver was measured at the contact surface between driver and seat. In addition, measurements of vibration of the cabin floor at the chair base have been performed, at the point of fixation of the seat. All vibration measurements were performed along the three basicentric axes (see figure 2): X (frontal axis), Y (lateral axis) and Z[1] (vertical axis). WBV upon the seat was measured using a Bruel & Kjær (B&K, DK) triaxial accelerometer 4322 PE, mounted in a rubber-covered steel housing. The pad was fixed on the seat using adhesive tape (see figure

Figure 2: Visual illustration of the vibration axes X, Y and Z.

[1] In addition ISO recommends the following: (1) measurements are to be of sufficiently long duration, so that they give a representative image of the total job and include all of the variation in exposure; (2)acceleration signals are to be weighted according to the filter characteristics given in the norms; (3) vibration exposure is to be expressed as root-mean-square (RMS) value; (4) preferentially, a sufficient number of testing persons should be involved, and having a sufficiently large spread in body mass: ISO recommends to perform exposure measurements using at least 3 persons, if possible having the following body masses: 50-55 kg, 75 kg, 95-100 kg; (5) it is recommended to perform to measure a minimum of 3 repetitions per person per situation.

Figure 3: Illustration of the of the mounting of the accelerometer pad on the seat.

Figure 4: Illustration of the of the mounting of the accelerometer at the chair base.

3), 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 4).

The signals from the accelerometers, a total of 6 channels, were lead into two amplifiers (B&K, Nexus 2692; settings for signal filtering: high-pass 0.1 Hz, low-pass 1000 Hz) via shielded wires. The signals were then stored on a laptop 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. Filtering and processing of the signals occurred off-line according to ISO-guidelines with help of LabView (v. 8.0, National Instruments, US) and Matlab (v. 6.5.1, The Mathworks Inc., US) software. The complete measuring chain (from accelerometer to laptop) for each channel was calibrated the day before each of the measurements using B&K calibrator 4291 (certificate C1209213 d.d. 03-12-2012 , Bruel & Kjaer, Naerum, DK). 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 GPS 60, Olathe, US), mounted at a side of the mower. Position data were stored in the receiver at a frequency of 1 Hz. These data were transmitted from receiver to the laptop computer several times per day.The clock of the personal computer and that of the GPS receiver were synchronised each day before starting the measurements and after having transmitted the data.

To have a visual check on what happened during the measurements, continuous video registrations have been made from the driver and his front view. To this end, a small video camera (JVC Action Cam, GC-XA1 BE) was mounted to the back window 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, start and stop of mowing, standing still, driving over paved area, passing of bumps, kerbs or other surface irregularities, and inexpected events like hitting a tree or fixed object. 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 experimentator to check proper functioning of the equipment) were excluded from further analysis.

2.6 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 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[2]. 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 t_0 the moment of observation):

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

in which $a_w(t)$ 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, as recommended in ISO-2631-1 (1997).

As a third step, vibration signals (i.c. raw, frequency-weighted and running RMS signal) for seat and chair base (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

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

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 signal selected. With help of the outcome of formula 2, the Crest Factor was calculated: the modulus of the ratio of the most extreme (highest or lowest) value of the weighted instantaneous vibration signal $a_{wk}(t)$ and the RMS value a_{wk}.

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

[2] This means that all vibration values reported in this document are inclusive the ISO-2631-1 (1997) prescribed factor k.

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

in which VDV_k is the VDV value of the measurement of duration T for vibration axis k. Action and limit values for VDV are 9.1 and 21 $m/s^{1.75}$, respectively.

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

$$SEAT_{rmsk} = \frac{a_{wk}}{a_{cbk}} \times 100\% \qquad (4)$$

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

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

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 5, D_k, to the normal daily exposure time, according to

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

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

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

in which the following values for m_k are recommended: m_x = 0.015 MPa / (m/s²), m_y = 0.035 MPa / (m/s²), m_z = 0.032 MPa / (m/s²).

If the daily dose is indicative for the yearly exposure (i.e. 240 days / year), the ISO directive 2631-5 (2004) 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 3 below. For the evaluation of the effect of shocks, it is assumed in the present report that exposure will occur during 120 days per year, due to the season-bound nature of the work.

Table 3: 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

Finally: when reporting vibration measurements ISO recommends to give information on the frequency spectra of the measurements. Some examples of raw unweighted dataseries measured at the chair base and on the seat and their concomitant frequency spectra are given in the appendices C-E. Note that during these registrations the mowing occurred at a variable speed.

Table 4 summarizes the major outcome variables of the present vibration measurements.

2.7 Interpretation of measured values to daily exposure

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 for the three situations normal driving, hasty driving and restrained driving. Those tasks with WBV exposure (i.c. sitting on a machine with stationary running engine; driving over paved road, including bumps; mowing, including short distances of driving over paved paths and passing kerbs; transport of the mower with car or van) were distinguished from those without (see paragraph 2.4). The exposure value for sitting on a machine with stationary running engine was determined during the measurements. However, the transport of the mower with car or van was not measured. The WBV exposure during this situation was estimated using data reported in the literature for driving over main roads with van or bus (Nitti & De Santis, 2010; Lewis & Johnson, 2012; Thamsuwan *et al.*, 2013). In the investigations mentioned, the exposure varied between 0.2 and 0.7 m/s², for the Z-axis being mostly somewhat higher compared to both other axes. In the calculation of daily exposure, values of 0.3 m/s² (X, Y) and 0.4 m/s² (Z) are taken.

Table 4: Explanantion 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/s², 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 law measures should follow a value of ≥0.5 m/s² over an 8-hour working day. The weighing of the acceleration is frequency-dependent and is defined by ISO.
Crest	The Crest-factor is the absolute value of the most extreme (highest or lowest) value of the vibration exposure divided by the RMS value over the measurement period. ISO-2631-1 (1997) indicats that for values >9 exposure to shocks is relevant and that an evaluation on basis of solely a_w is not sufficient.
SEAT	Seat Effective Amplitude Transmissibility, or the weighted RMS vibration value measured on the seat as percentage of that measured at the chair base. It is a measure for the effectivity 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/s². 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 eefects of exposure to shocks. If daily exposure occurs year-round (i.e. 240 days / year), 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 clearly present if S_{ed} exceeds 0.8 MPa. 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.

For both other tasks, i.e. driving over paved roads to and from the public green area and mowing itself, the analysis made it possible to distuinguish between several events (these were: crossing of a bump, crossing of a kerb, stopping, driving over paved road, mowing itself; see paragraph 2.5). The overall WBV exposure for a task was calculated from the exposures determined for the individual events 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 diaries (see paragraph 2.4), the mean duration for each task was determined: see table 5. These task durations were combined with their exposure values, as calculated according to formula 8 above or obtained from the literature, to produce an estimate of the daily exposure to WBV according to

$$a_{wk(eq,day)} = \sqrt{\frac{\sum_{i=1}^{n} a_{wki}^{2} T_{i}}{T_{d}}} \tag{9}$$

in which $a_{wk(eq,day)}$ is the daily exposure at a normal working day (i.e. almost 9 hours), a_{wki} is the exposure calculated for each task i, T_i is the duration of each task i on basis of the diaries (table 5), T_d is the total length of the working day and k is the vibration axis X, Y or Z.

2.8 Presentation of the data and statistics

The results in this report are displayed in tables and in figures as timeseries, 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 (3 machines and 3 persons), no statistical calculations have been done on eventual differences.

3 Results and discussion

3.1 Length of a working day and tasks in practice

Table 5: Inventarisation of the duration (and range) of the diffeent tasks when mowing public green area with a self-propelled mower in practice. The operator is exposed to WBV during the tasks A-D; it is assumed that during execution of task E no exposure occurs. The data, displayed as hours:minutes(:seconds), are the mean values of 7 operators, reporting a total of 12 complete working days.

	Task	Duration (hh:mm:ss)	Minimum – maximum (hh:mm)
A	Sitting on a stationary mower, engine running	0:03:43	0:00 – 0:26
B	Driving over paved roads (including bumps)	1:09:17	0:09 – 2:17
C	Mowing of public green areas (including driving short distances over paved paths, bumps and kerbs)	5:36:51	3:53 – 7:16
D	Transport of the mower with car or van	0:41:30	0:00 – 1:24
E	Other tasks (preparation, minor maintenance, sharpening of blades, refueling, loading and unloading of the mower)	1:19:17	0:38 – 2:10
	Total task mowing of public green area (without pauses):	8:50:39	8:36 – 10:04

Table 5 shows the results of the inventarisation of the time expenditure during a normal working day of an operator of a self-propelled mower. The total length of a working day is almost 9 hours, excluding breaks. The main activity was the mowing itself (63% of the working time), followed by 'Other tasks' (15%) and driving over paved road (13%). The relative duration sitting still on a stationary machine was very limited (<1%).

The inventarisation was clearly different from the assumptions made in previous research of Oude Vrielink (2007[a]): not only the proportion of mowing itself appeared considerably lower (at that time estimated to be 80%, while it appeared 63% now), also a working day of 8 hours was assumed, which appeared almost one hour longer. Both deviations have an opposite effect on the estimation of the daily exposure. However, the considerably lower contribution of the mowing itself makes that in the present reporting the number of hours mowing (now: 6.8 hours) is slightly lower than assumed in the 2007 study (7.2 hours). On the other hand, in the previous study transport of the mower with another vehicle was not accounted for, while also this task contributes to some degree to the exposure.

The longer than 8 hours working day is in agreement with the Collective Labour Agreement for the green area maintenance and gardening services in The Netherlands (CAO, 2013), which indicates a maximum daily working duration of 9 hours. This longer working duration during the warmer part of the year can regularly be seen in the branch, and will mostly be compensated by shorter working days during the winter period. It provides the employers in the green area maintenance the flexibility to perform the work on basis of the demand.

3.2 Exposure measurements

3.2.1 *Mowing*

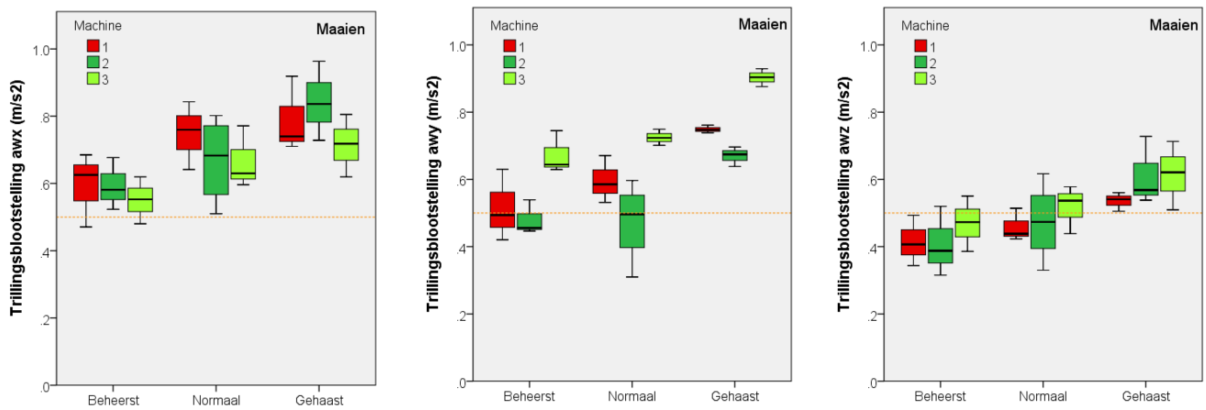
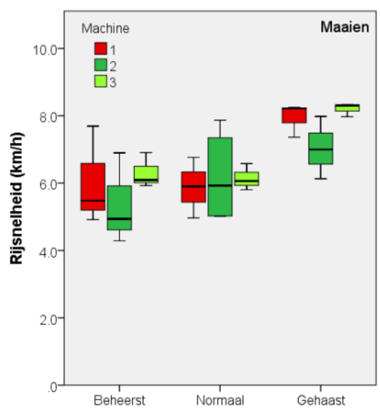


Figure 5: *Exposure to WBV ('Trillingsblootstelling' a_w in m/s^2) in fore-aft (x, left), lateral (y, middle) and vertical (z, right) direction for mowing ('Maaien') of public green area using self-propelled mowers, during restrained ('Beheerst'), normal ('Normaal') and hasty ('Gehaast') driving. The three machines tested are distinguished. The mowing task displayed includes short distances driving over paved paths. The figures summarize the data of three persons. The dashed line indicates the level of the action value for an 8-hour working day.*

Figure 5 displays the results of the exposure measurments for the mowing task itself. It can be seen that for every vibration axis X, Y, of Z the exposure increases if mowing occurs in a more hasty way, starting from restrained mowing. It can also be seen that the differences between the mowers used are smallest over the vertical axis, while largest laterally. Most obvious is the difference between machines 2 and 3 in lateral direction and, inversely and to a lesser extent, in the fore-aft direction. The figure illustrates that for all machines the highest exposure values are found in the horizontal plane (X and Y). Even during restrained driving, exposure along the fore-aft axis during mowing does not come below the action value as valid for an 8-hour working day. For a numerical display of the data is referred to appendix A.

The effect of a lower exposure when driving in a restrained way, as seen for all machines, cannot be explained well from an eventually reduced driving speed: see figure 6. The driving speed during restrained mowing (on average 5.9 km/h over all machines) was comparable with the speed during normal driving (6.1 km/h). Driving in a hasty way resulted in a clearly elevated average driving speed (7.7 km/h).

Figure 6: *Mean driving speed ('Rijsnelheid'; in km/hour) during mowing ('Maaien') of public green area using self-propelled mowers, during restrained ('Beheerst'), normal ('Normaal') and hasty ('Gehaast') driving. The three machines tested are distinguished. The mowing task displayed includes short distances driving over paved paths. The figures summarize the data of three persons.*



The results of the present measurements (median values over the machines and operators for the X, Y and Z-axis were 0.69 m/s^2, 0.59 m/s^2, and 0.47 m/s^2, respectively, for normal speed mowing) appeared to be quite comparable to those measured earlier (Oude Vrielink, 2007[a]): 0.61 m/s^2, 0.63 m/s^2 and 0.46 m/s^2 for X, Y and Z, respectively. Also during the latter test, the average driving speed was around 6 km/h. It is tempting, therefore, to conclude that in the past years no major improvements with regards to vibration exposure reduction have occurred. The basic construction is a frame with four wheels attached without dampers. The frame is directly attached to the cabin floor, on which the chair is mounted. A difference is that all of the machines were equipped with a modern and more recently developed chair with pneumatic damping along the vertical axis. In the fore-aft direction, the mowers 2 and 3 were provided with a mechanical damping system as well. The latter was meant to reduce vibrations and shocks along the X-axis.

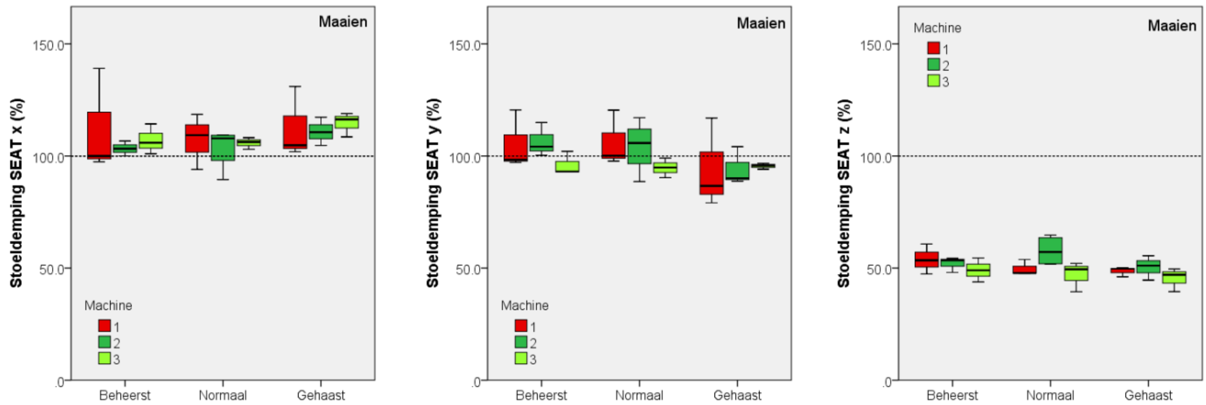


Figure 7: *Seat effective amplitude transmissibility (SEAT in %) in fore-aft (x, left), lateral (y, middle) and vertical (z, right) direction for mowing ('Maaien') of public green area using self-propelled mowers, during restrained ('Beheerst'), normal ('Normaal') and hasty ('Gehaast') driving. The three machines tested are distinguished. The mowing task displayed includes short distances driving over paved paths. The figures summarize the data of three persons. The dashed line indicates the 100% level, this is the RMS vibration value that is measured on and below the seat are identical.*

The figure 7 above shows the effectivity of damping of the chairs mounted on the mowers. It appears that the differences between the mowers (and chairs) are small. And also that the driving behaviour does hardly affect the SEAT values. In all panels, no difference can be seen between both chairs having a damping system in the fore-aft direction (machines 2 and 3) and the one without (machine 1). It must be said that the SEAT values are considerably lower than reported in 2007. At that time, these were 129%, 124% and 74% for the X, Y and Z axis, respectively. During mowing at normal speed, the values in the present test are 107%, 100% and 52%, respectively. An improved affective damping of the seat in combination with a comparable vibration exposure of the driver means that vibrations measured at the chair base (cabin floor) must have been larger in the present research compared to the 2007 test. Since the average driving speed was comparable, one explanation may be that the public green area plots have been more unequal in the present investigation. It might also have been that the soil immediately below the grass was more firm or stiff here. The latter can occur in periods of low rain fall (soil becomes more plastic if it contains more water; see for example Smedt, 2013). Two of the testing days in the present research (mowers 1 and 3) occurred in a relatively dry period (see paragraph

2.3). The 2007 report measurements occurred on September 19, 2006. The exact conditions before and during the measurements were not reported in the document. However, from the historical climatic data it appears that there was a considerable rain fall in the week before the measurements (KNMI, 2013): almost 11 mm, of which were 10 mm in the three days before the test. The, at that time, relative humid soil supports the way of reasoning made above. Another possible explanation, in combination with the previous, may be that two of the mowers during the present measurements drove on higher tyre pressures compared to the research of Oude Vrielink (2007[a]). Machine 3, however, had a comparable tyre pressure, and the exposure values measured on that mower were not lower compared to both other machines. In addition, in earlier research on agricultural tractors the influence of tyre pressure on WBV exposure was investigated extensively (Oude Vrielink, 2007[b]). No difference in exposure was found over a broad range of tyre pressures and driving speeds during driving over rough terrain. Note: since the construction and damping systems applied in the tractors are completely different from those in mowers, the interpretation of the latter outcomes to mowing of public green area must be done with caution.
Figure 8 shows the spread in WBV exposure between the different operators. The trend described earlier that WBV exposure increases with more hasty driving behaviour holds for each operator individually. Further, it is clear that operator 2 almost consequently experiences the lowest vibration exposure along all vibration axes. This operator was the one with the highest body mass. The operator 1 with the lowest body mass experienced the highest exposure in the fore-aft direction (figure 8, left panel). However, this was not the case for both other vibration axes. This becomes clear especially in the right panel (vertical vibration exposure). Complicating factor here is that this operator 1 appeared to have driven faster that both others: see figure 9. The median value of the average driving speed for this operator was even higher during restrained driving compared to normal.
It is known from the literature that both factors, body mass and driving speed, contribute in an opposite manner to the exposure to WBV (see e.g. Tiemessen, *et al.*, 2007). However, it does not fully explain the different exposures in the three vibration axes between the operators, as illustrated in figure 8.

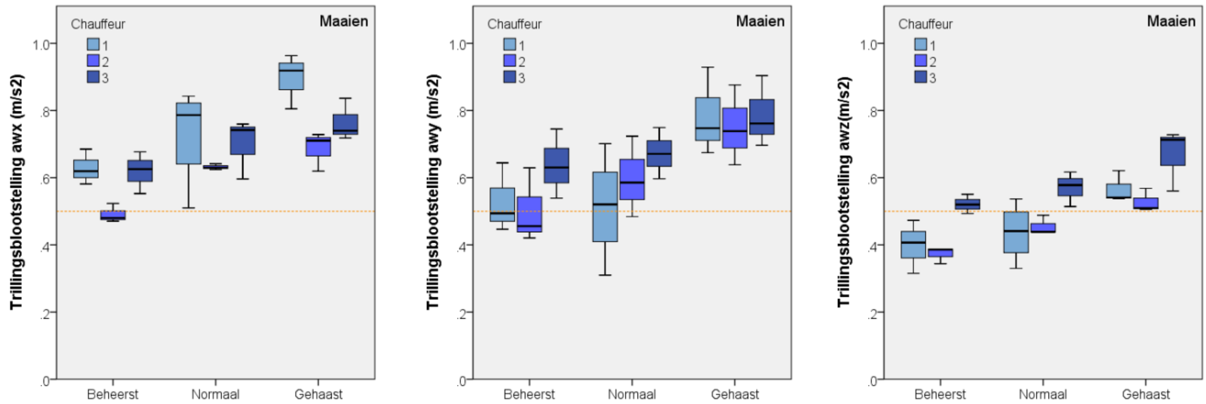
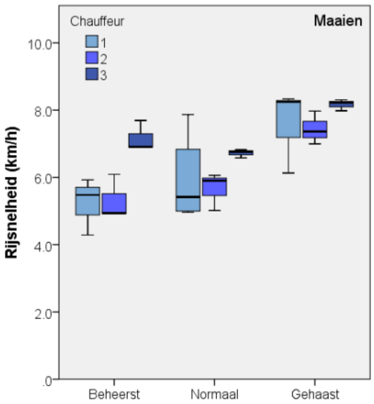


Figure 8: *Exposure to WBV ('Trillingsblootstelling' a_w in m/s^2) in fore-aft (x, left), lateral (y, middle) and vertical (z, right) direction for mowing ('Maaien') of public green area using self-propelled mowers, during restrained ('Beheerst'), normal ('Normaal') and hasty ('Gehaast') driving. The three operators ('Chauffeur') are distinguished. The mowing task displayed includes short distances driving over paved paths. The figures summarize the data of the three mowers. The dashed line indicates the level of the action value for an 8-hour working day.*

Figure 9: *Average driving speed ('Rijsnelheid'; in km/hour) during mowing ('Maaien') of public green area using self-propelled mowers, during restrained ('Beheerst'), normal ('Normaal') and hasty ('Gehaast') driving. The three operators ('Chauffeur') are distinguished. The mowing task displayed includes short distances driving over paved paths. The figures summarize the data of the three mowers.*



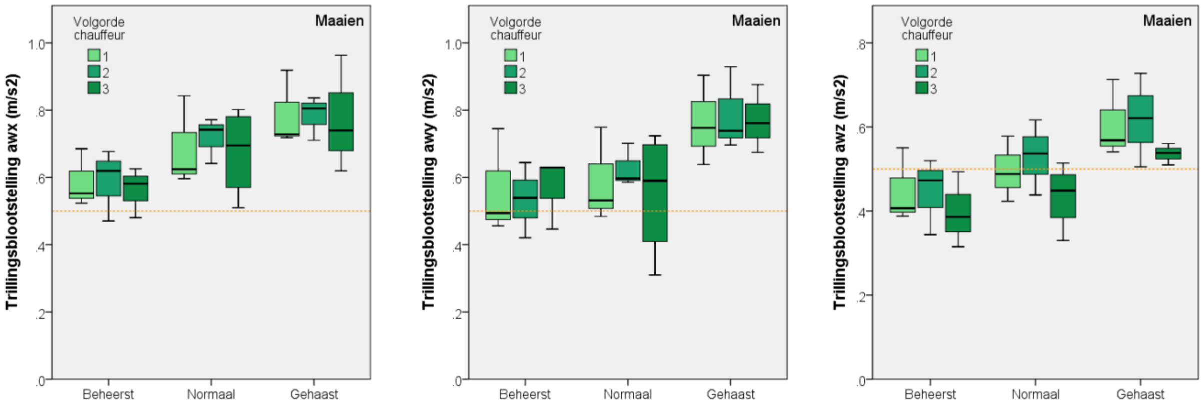
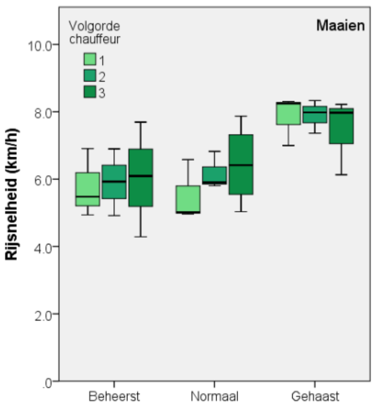


Figure 10: *Exposure to WBV ('Trillingsblootstelling' a_w in m/s^2) in fore-aft (x, left), lateral (y, middle) and vertical (z, right) direction for mowing ('Maaien') of public green area using self-propelled mowers, during restrained ('Beheerst'), normal ('Normaal') and hasty ('Gehaast') driving. The order of driving of the three operators ('Volgorde chauffeur') is distinguished. The mowing task displayed includes short distances driving over paved paths. The figures summarize the data of the three mowers, each of which driven by a different operator. The dashed line indicates the level of the action value for an 8-hour working day.*

Figure 11: *Average driving speed ('Rijsnelheid'; in km/hour) during mowing ('Maaien') of public green area using self-propelled mowers, during restrained ('Beheerst'), normal ('Normaal') and hasty ('Gehaast') driving. The order of driving of the three operators ('Volgorde chauffeur') is distinguished. The mowing task displayed includes short distances driving over paved paths. The figures summarize the data of the three mowers, each of which driven by a different operator.*



Finally, it was investigated whether the order of driving of the operators had a systematic influence on their exposure to WBV. Figure 10 illustrates that no effect can be seen for exposure in the horizontal plane. The exposure to vertical vibrations seems to be slightly lower for the third operator for every driving mode. Note that the spread in the data is quite large. The order of driving did not clearly influence the driving speed: see figure 11.

It was observed for all mowers that a relatively strong fore-aft RMS vibration peak on the seat coincided a peak in the vertical vibration registration of the chair base. This is illustrated in figure 12, which shows three sets of registrations, one set for each mower, of an arbitrary chosen time segment of 70-80s for normal driving. The figure shows running RMS registrations according to formula 1. The upper part of each pair is the registration at the chair base. Peaks in the vertical direction (green line) here (red arrows) are clearly damped from the viewpoint of the seat surface (green line of the lower panels of each pair), however coincide an increased peak along the fore-aft axis (blue line) there (indicated by a red arrow) compared to the registration at the chair base. For proper comparison, the scales of both registrations are kept similar. This phenomenon can be observed for all mowers during all testing conditions. In addition, it must be noted that this phenomenon is not observed consequently for all of the vertical vibration peaks, as illustrated with the black arrows.
It is speculated that the occurrence of angular accelerations around the axles of the mower can form the basis for an explanation for the phenomenon described above. This is made clear in figure 13. In a mower, the seat is positioned quite high above both axles. If during mowing of unequal grass patches the wheels of the front or rear axle axle receive vertical impulses from the grass (soil) surface, an angular acceleration will develop around the opposite axle. Because of this, a horizontal acceleration will occur at the seat surface, which will be larger if the vertical distance between axles and seat is larger. It is not difficult to imagine that the seat surface of the chair will be accelerated in horizontal direction considerably if the impulses on the tyres are strong. Strong impulses on the front tyres in this case also result in strong vertical accelerations of the seat base (figure 13, left panel), while impulses on the rear tyres have only limited effect on the vertical acceleration of the seat base (figure 13, right panel).
Whether the way of reasoning suggested above provides a full explanation for the phenomenon observed must be verified in additional research. If this is the case, it can provide the key to solutions to reduce the relatively high fore-aft accelerations. By reducing the bouncing of the wheels (for example by mounting different types of tyres) or by damping these bouncing wheels, angular accelerations around the axles can be diminished. It is also imaginable that a changed design of the seat damping system can more effectively cope with the phenomenon described. In all cases, a thorough tuning of the measures and testing is necessary to prevent the occurrence of resonance effects.

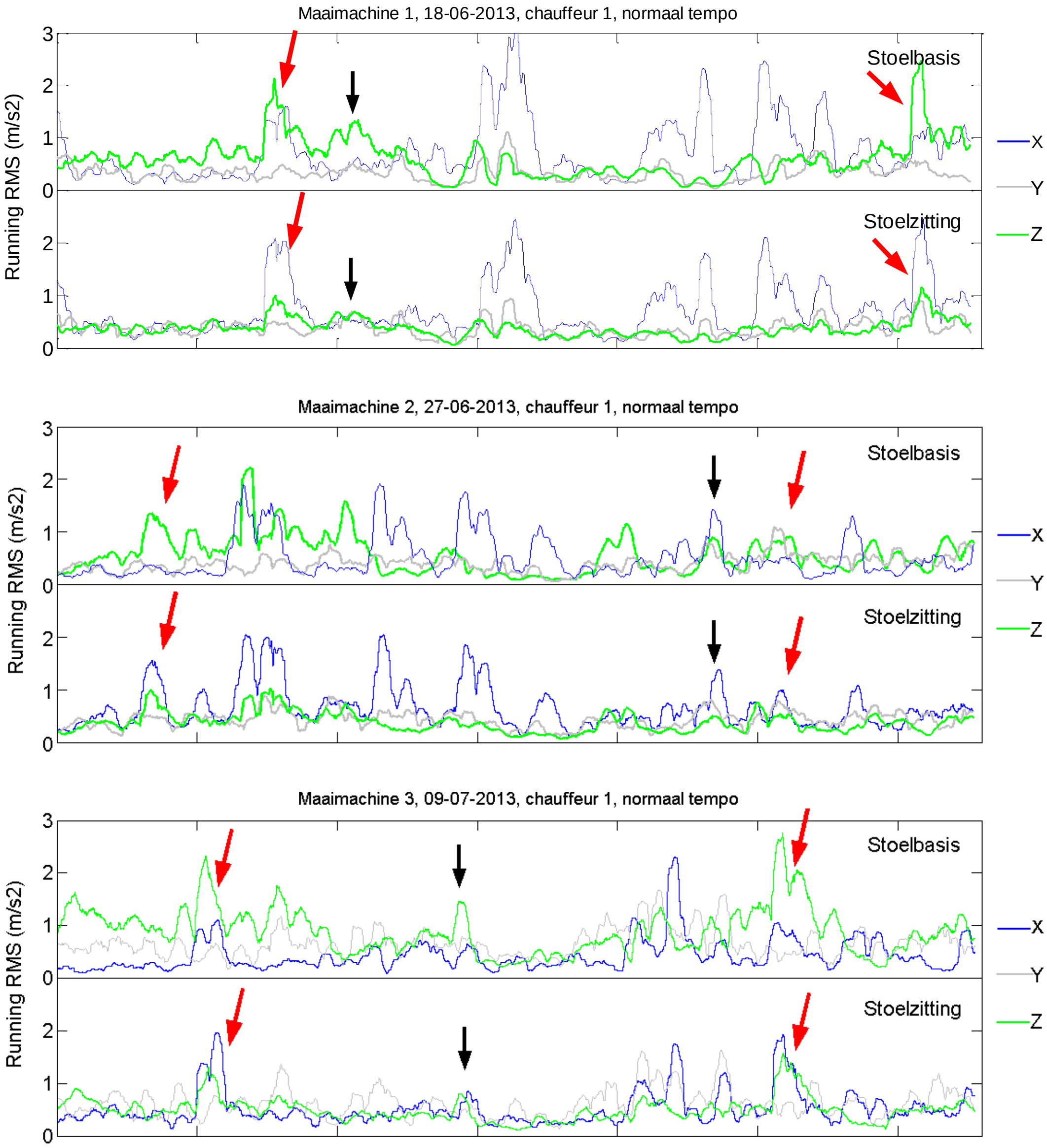


Figure 12: *Running RMS of the weighted acceleration data (in m/s²) along the three axes X, Y and Z, measured at the chair base ('Stoelbasis') and on the seat ('Stoelzitting') for one operator ('chauffeur') during normal mowing ('normaal tempo') on three different mowers ('Maaimachine'). The data shown comprise a period of 70-80s. The red arrows indicate the moments where a vertical acceleration peak of the chair base coincides an elevated fore-aft acceleration of the seat surface. During the moments indicated by the black arrows this phenomenon does not occur.*

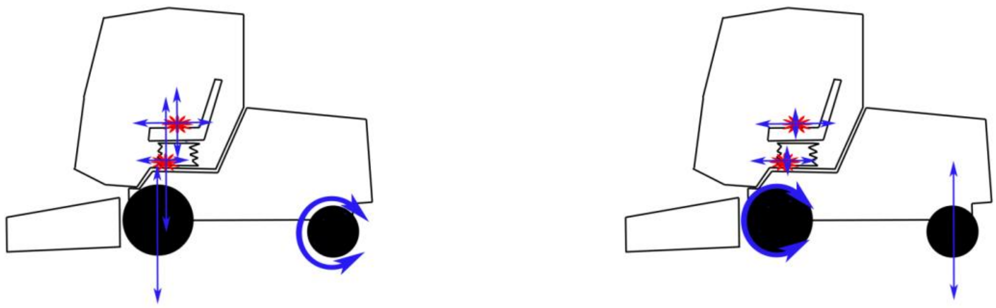


Figure 13: *Illustration of the possible explanations for the development of horizontal accelerations on the seat as a result of angular accelerations around the rear (left panel) and front axle (right panel), because of vertical impulses on the tyres and wheels. In addtition, the effect on the vertical accelerations of the chair base and seat surface are shown.*

3.2.2 Driving with mower on paved public roads

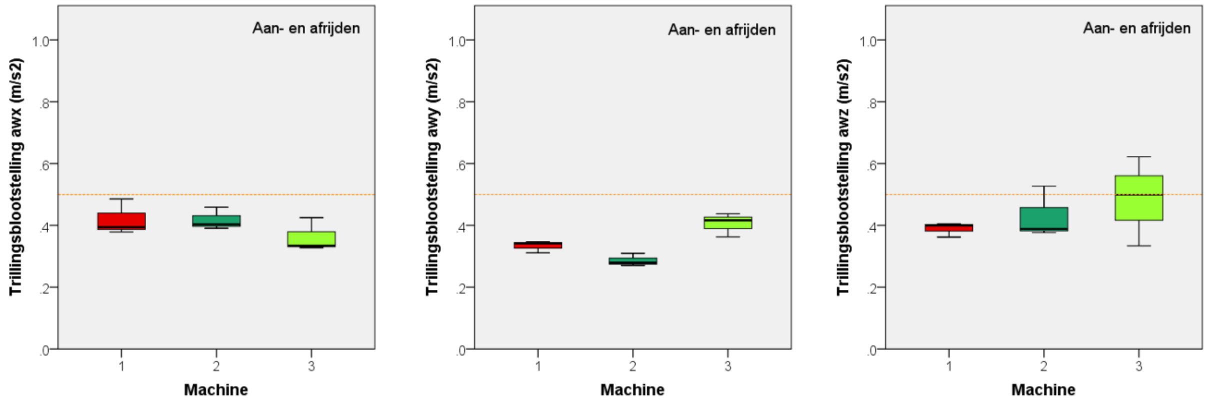
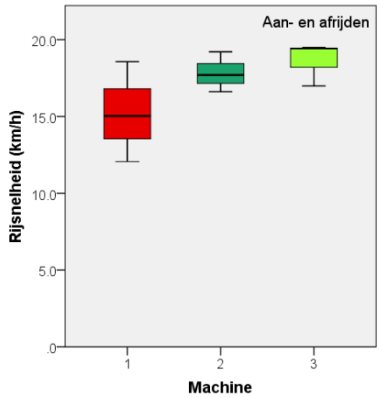


Figure 14: *Exposure to WBV ('Trillingsblootstelling' a_w in m/s^2) in fore-aft (x, left), lateral (y, middle) and vertical (z, right) direction for driving over paved roads to or from public green areas ('Aan- en afrijden') with a self-propelled mower ('Machine'). The route included a traffic plateau, a speed bump and two traffic lights. The figures summarize the data of three persons. The dashed line indicates the level of the action value for an 8-hour working day.*

The driving over public roads to and from the public green area plots is solely tested at normal (i.e. mostly maximal) driving speed. Figure 14 shows the results for the three machines for each of the vibration axes. Only incidentally, the WBV exposure reaches the action value for an 8-hour working day. The difference between the mowers has the same trend as observed for mowing: mower 3 seems to have a slightly lower exposure along the fore-aft axis, and somewhat elevated along both other axes. The lateral WBV exposure seems lowest for mower 2. The median average driving speed during driving showed quite some variation: 15.0 km/h, 17.7 km/h, and 19.4 km/h for mower 1, 2, and 3, respectively (see figure 15).

Figure 15: *Average driving speed ('Rijsnelheid'; in km/hour) during driving over paved roads to or from public green areas ('Aan- en afrijden') with a self-propelled mower ('Machine'). The route included a traffic plateau, a speed bump and two traffic lights. The figures summarize the data of the three operators.*



As was the case for mowing, the chair damping was effective in vertical direction (median 66% over all mowers) for driving over public roads, while accelerations along the fore-aft axis mainly were amplified (figure 16). The difference in chair damping between the mowers appeared considerable, especially when comparing mower 1 (164%) with mower 3 (107%), also in view of the mowing task itself discussed earlier (compare: figure 7). The origin of this is unclear. On the one hand, the different nature of the driving surface will result in a different vibration frequency spectrum at the cabin floor (chair base). It is possible that the seat mounted in mower 1 is less effective in damping these frequencies compared to mower 3. It is tempting to speculate that the difference between both machines is the result of the presence of a fore-aft damping system in the seat of mower 3. However, because also the difference between both machines can be observed in lateral direction, this explanation is still open to doubt. The seats mounted in both mowers do not have an additional damping system along the latter axis.

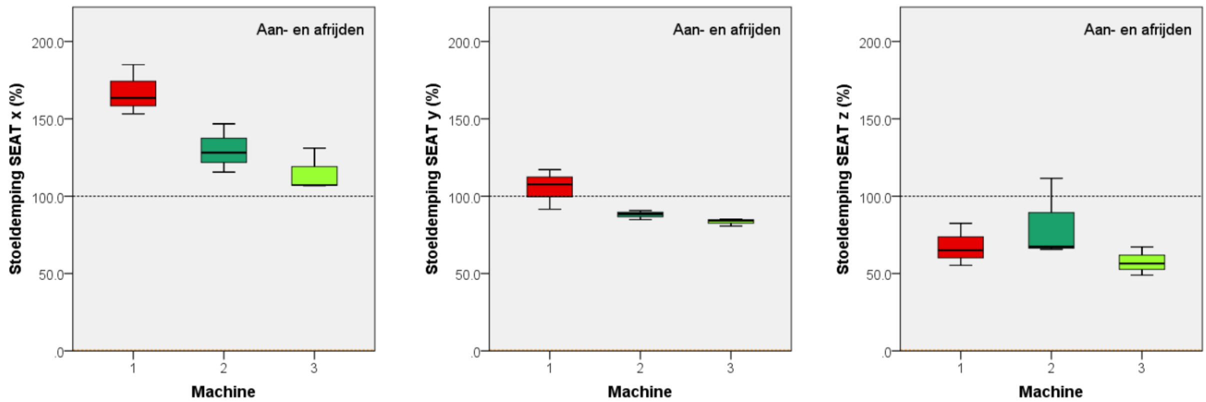


Figure 16: *Seat effective amplitude transmissibility (SEAT in %) in fore-aft (x, left), lateral (y, middle) and vertical (z, right) direction for driving over paved roads to or from public green areas ('Aan- en afrijden') with a self-propelled mower ('Machine'). The route included a traffic plateau, a speed bump and two traffic lights. The figures summarize the data of three persons. The dashed line indicates the 100% level, this is the RMS vibration value that is measured on and below the seat are identical.*

The figures 17 and 18 illustrate the differences in WBV exposure and driving speed between the operators. These differences appeared to be small. The same holds for the order of driving by the operators: see figures 19 and 20. The trends in eventual differences, as described for the mowing task (see earlier), can be observed here as well.

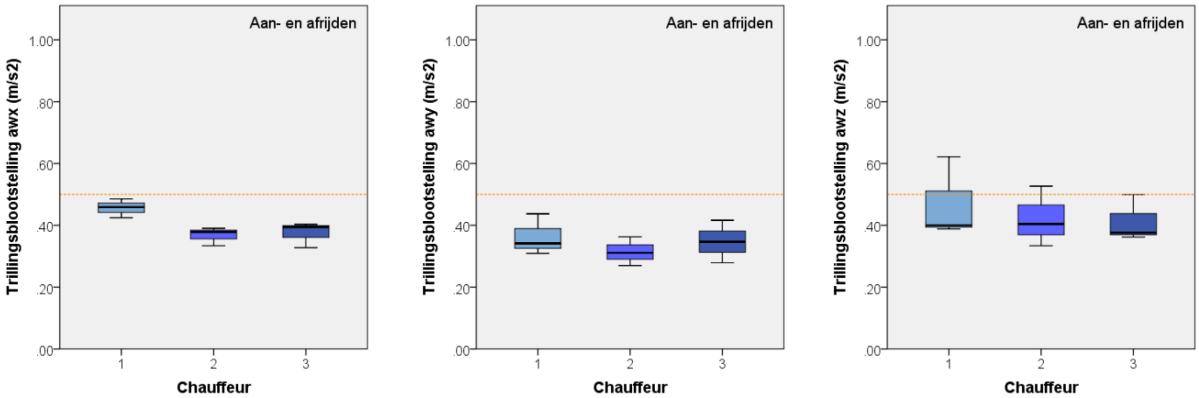
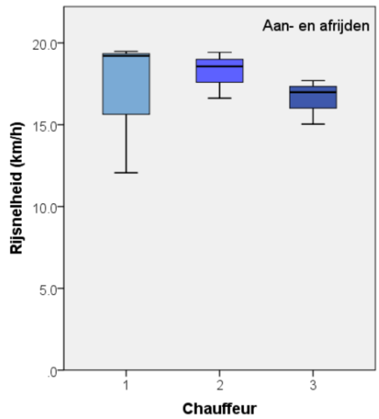


Figure 17: *Exposure to WBV ('Trillingsblootstelling' a_w in m/s^2) in fore-aft (x, left), lateral (y, middle) and vertical (z, right) direction for driving over paved roads to or from public green areas ('Aan- en afrijden') with self-propelled mowers per operator ('Chauffeur'). The route included a traffic plateau, a speed bump and two traffic lights. The figures summarize the data of the three mowers. The dashed line indicates the action value for an 8-hour working day.*

Figure 18: *Average driving speed ('Rijsnelheid'; in km/hour) during driving over paved roads to or from public green areas ('Aan- en afrijden') with self-propelled mowers per operator ('Chauffeur'). The route included a traffic plateau, a speed bump and two traffic lights. The figures summarize the data of the three mowers.*



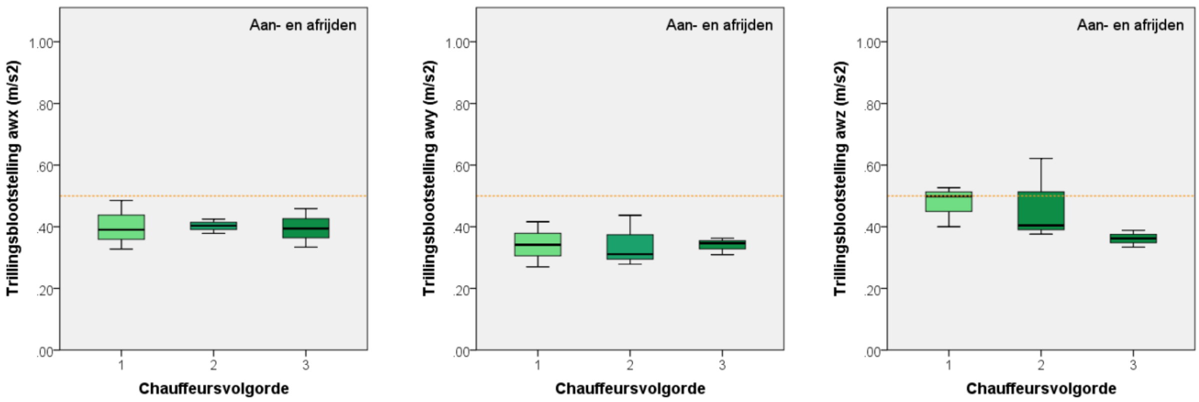
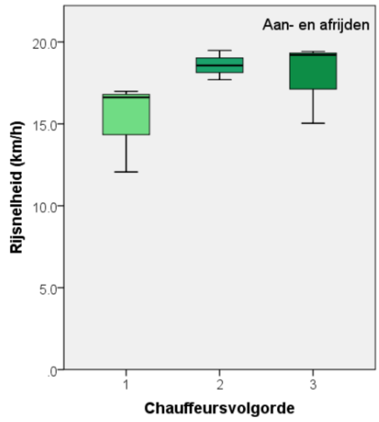


Figure 19: *Exposure to WBV ('Trillingsblootstelling' a_w in m/s^2) in fore-aft (x, left), lateral (y, middle) and vertical (z, right) direction for driving over paved roads to or from public green areas ('Aan- en afrijden') with self-propelled mowers as a function of operator order ('Chauffeursvolgorde'). The route included a traffic plateau, a speed bump and two traffic lights. The figures summarize the data of the three mowers, each of which driven by a different operator. The dashed line indicates the action value for an 8-hour working day.*

Figure 20: *Average driving speed ('Rijsnelheid'; in km/hour) during driving over paved roads to or from public green areas ('Aan- en afrijden') with self-propelled mowers as a function of operator order ('Chauffeursvolgorde'). The route included a traffic plateau, a speed bump and two traffic lights. The figures summarize the data of the three mowers, each of which driven by a different operator.*



3.2.3 Comparison with vibration exposure values reported by the manufacturer

Table 6: exposure to WBV a_w (in m/s^2), being the RMS value of the highest of the three vibration axes X, Y and Z, per mower as indicated by the manufacturer and as result of the measurements at present for mowing at normal speed (the dominant vibration axis is indicated between parentheses). The outcomes of the present measurements only include the mowing task itself. Reference is made to appendix A for a view on the results of all axes and tasks.

Mower	A_{eq} (m/s^2)	
	Indication manufacturer	Present measurements
1	0.29[1]	0.76 (X)
2	0.54[2]	0.66 (X)
3	<0.5[1]	0.72 (Y)

[1] determined accoring to EN 836 (1997); test was not described in the manual

[2] determined accoring to EN 1032 (2004), driving straight at 6 km/h with rotating mowing blades over a mown and level field

Table 6 gives for each of the mowers tested the exposure value reported by the manufacturer in conformity with the standardized tests EN 836 (1997) and EN 1032 (2003). Next to these, the exposure values for mowing at normal speed as measured in the present research are given. For none of the mowers, it was indicated by the manufacturer which of the vibration axes was dominant. The directives EN 836 and EN 1032 describe roughly how a test should be performed. EN 1032 describes the meausurement equipment and measurements themselves and is in conformity with ISO 2631-1 (1997). In addition, it is mentioned in the description that the test should be performed driving over a surface that is representative for the one in practice. EN 836 makes frequent reference to the EN 1032 norm. Apart from small differences between both norms, amongst others related to the body mass of the operator in the test, this norm (EN 836) describes how the test should be performed: driving straight at a velocity of 6 km/h over level and mown field, with the rotating blades turned on and in the lowest position. Each test should endure a minimum of 8s. In addition, it is indicated in the description that these testing conditions probably do not match those in practice. Hence, these will probably give an under-

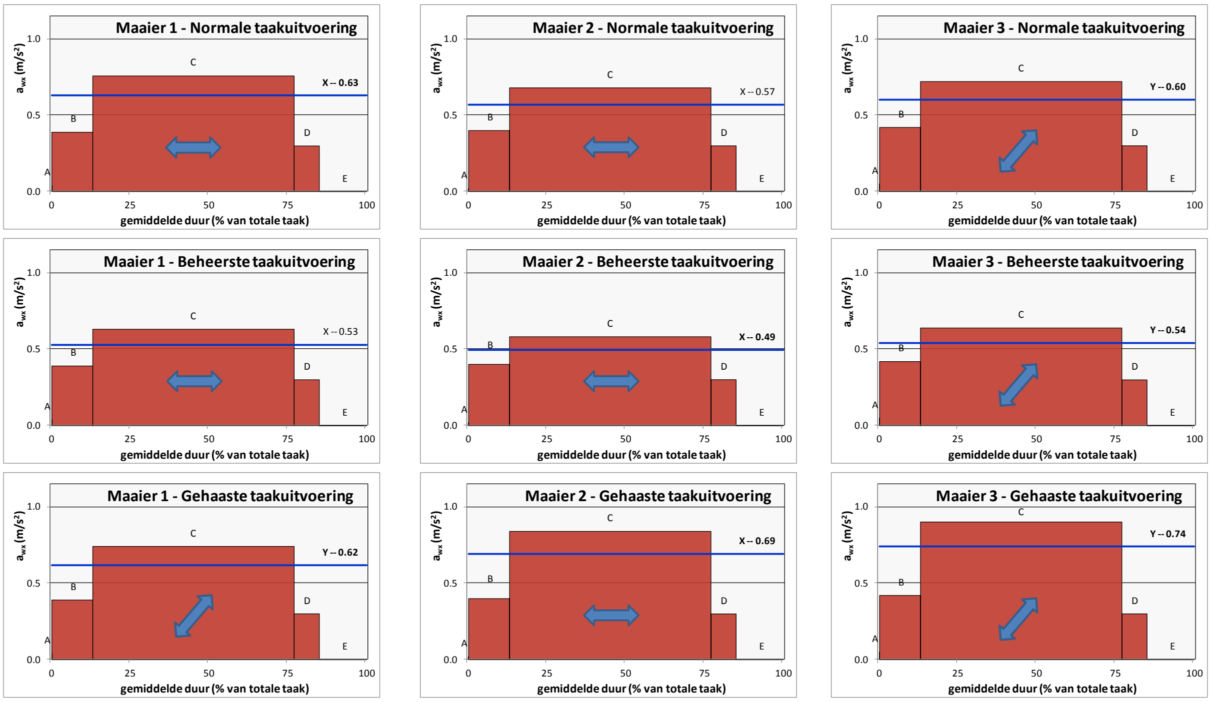


Figure 21: *Schematic representation of the contribution of every task (A-E: see table 5) to the WBV exposure a_w (vertical axis, in m/s^2) during normal (upper row; 'Normale taakuitvoering'), restrained (middle row; 'Beheerste taakuitvoering') and hasty (lower row; 'Gehaaste taakuitvoering') task performance using mower 1 (left; 'Maaier 1', 2 (middle; 'Maaier 2') and 3 (right; 'Maaier 3'). The horizontal axis of each plot is the duration of each task, summed and relative (in %) to the duration of a working day ('gemiddelde duur'). For the vibration exposure the dominant vibration axis is taken, which is indicated with the blue arrow (horizontally for X, inclined for Y) and the character immediately above the horizontal blue line. This blue line indicates the value of the daily exposure, given the tasks and their durations and exposure values, also indicated by the numerical indication above the line.*

estimation of the vibration that would occur in practice. The latter appears to be the case, as shown in table 6. It illustrates that the values reported in the manufacturer's manual cannot be used to get a reliable impression of the WBV exposure in practice.

3.3 Daily working time on basis of the measurements

The median exposure values measured per mower and per task were combined with the duration of each task as obtained from the dairies. The calculation resulted in a value of the daily exposure for each machine and way of performing the mowing task. The result is depicted in figure 21 for the vibration axis that was highest. The total daily working time (8.9 h; see table 5) is indicated horizontally as 100%; the durations of the individual tasks are shown according to their relative contribution.

It appears that mowing of public green area at normal speed cannot be performed with any of the mowers tested for a complete working day. The daily exposure value, as averaged over the operators, varied between 0.57 and 0.63 m/s^2, in which the horizontal vibration axis was dominant. These values measured mean that the action value will be attained after having performed the job for 5.1 to 6.2 hours (following the normal daily pattern). If the mowing task is peformed in a restrained way, daily exposure values range from 0.49 to 0.53 m/s^2. The action value will be reached after having performed the job for 6.9 to 8.3 hours. Mowing in a hasty way

will increase the WBV exposure considerably: 0.62-0.74 m/s^2. The action value will be reached after 3.7-5.3 hours.
The exposure to shocks (S_{ed}) as determined according to ISO-2631-5 (2004) will remain below 0.6 MPa when driving at normal speed (see appendix A) and, therefore, does not need further study. If mowing hasty the S_{ed} for mower 3 increases up to a value of 0.61 MPa. This means that in that situation and for this mower, there is a probability of developing health damage as a result of exposure to shocks.

4 Conclusions and recommendations

- The WBV exposure of operators of self-propelled rotary mowers while mowing public green areas, as measured in the present research, is of comparable level in comparison with measurements performed in 2006. It may be concluded that the basic technical design of the mowers has not changed essentially in view of WBV exposure reduction. However, the seats that have been mounted demonstrate an improved damping (i.e. a reduced transmissibility) along all vibration axes. Despite the latter, the exposure of the driver was not reduced. This might be explained taking into account the differences in terrain and conditions during the tests.

- Given the European and Dutch law, the present outcomes allow an employee to perform mowing of public green areas for a maximum of 5-6 hours per day. This time period includes driving on public roads to and from the public garden plots, transporting of the mower with another vehicle, and other operations without WBV exposure, like maintainance, fuel refilling, etc. The maximum daily working time is slightly higher compared to the 2006 research outcomes. This is maily due to an improved estimation of the daily time expenditure of the operators.

- A considerable reduction of the WBV exposure was obtained when the operators were asked to perform their task in a restrained way: the maximum daily working time in that situation can be expanded to 7-8 hours. Still, this is insufficient to allow mowing for the full working day, which was shown to be almost 9 hours (excluding normal breaks). The measurements demonstrated that restrained mowing was performed at almost the same average driving speed. It is likely, therefore, that acquiring a more restrained driving behaviour hardly affects the task performance (output), while having a clearly lowering effect on the WBV exposure. Conversely, a more hasty driving behaviour indeed results in an increased average driving speed, but also resulted in an elevated exposure to vibrations.

- Although the measurements demonstrated differences between the mowers tested, the present report is very reticent in drawing conclusions from this. All tasks that were measured on all machines were performed roughly the same. However, the weather and, hence, terrain conditions were not identical for all machines: one mower was tested in a period with relatively modest temperatures and high rain fall. The relatively low vibration exposure measurements for this machine can be explained from this difference in conditions during the tests.

- The research shows, consistent with earlier measurements, that vibration exposure in the horizontal plane was dominant and determining the maximum daily working time. In the past, this led to the suggestion to mount a seat with a horizontal damping system. The present results, however, do not support this suggestion: no difference was seen between both machines having a seat with a fore-aft damping system in addition to the vertical damping system and the mower with only a vertical damper.

- The exposure values as measured in the present research were compared to those reported by the manufacturers, as determined during a prescribed standardised test. This comparison confirms that the exposure values as documented in the manual of a machine cannot be used to get an impression of the exposure to WBV in practice. In addition, it is recommended even not to use these values to compare machines with each other, since it was demonstrated in the present research that exposure values in fore-aft and lateral directions can be quite different for different machines. These differences are not expressed in the present standardised test, which prescribes only driving straight over a rather smooth surface.

- For employers in the green area maintenance it is essential that self-propelled rotary mowers are redesigned so that vibrations exposure will be reduced. Special attention should be paid to reduction of vibration exposure in the horizontal plane. During the present measurements, it was observed that high levels of horizontal vibrations on the seat coincide strong vertical vibrations of the cabin floor (chair base). It is suggested that at least part of the horizontal vibrations is the result of vertical impulses transmitted by the tyres to the frame of the machine. It is worth investigating whether driving on softer tyres or application of damped axles have a reducing effect on the horizontal vibrations of the seat. Note that care should be taken not to introduce undesired resonance effects on the seat due to the interaction with the damping system already present.

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Samenvatting

Een update van een zeven jaar geleden uitgevoerd onderzoek naar de blootstelling aan lichaamstrillingen van chauffeurs van plantsoenmaaiers is uitgevoerd in opdracht van branchevereniging VHG, FNV Bondgenoten en CNV Vakmensen. Het advies tot beperking van de dagelijkse werktijd op de maaimachine, geformuleerd in de Arbocatalogus voor de bedrijfstak op grond van de meetresultaten destijds en de wettelijke normen ter bescherming van de gezondheid van werknemers, beperkt een efficiënte planning en uitvoering van het werk voor veel werkgevers. Het doel van het onderzoek was te bepalen of de technische ontwikkelingen van de maaimachines per 2013 zover gevorderd zijn dat werknemers aan minder lichaamstrillingen worden blootgesteld, zodat de maximale werktijd per dag kan worden verruimd.

Het onderzoek is uitgevoerd in de praktijk met vrijwillige medewerking van een hoveniersbedrijf in Veenendaal met zijn drie professionele chauffeurs. Drie leveranciers van de in Nederland meest toegepaste plantsoenmaaiers (Toro, Ransomes, John Deere) stelden vrijwillig een zelfrijdende maaimachine beschikbaar. Alle maaimachines waren van vergelijkbare grootte en vermogen en voorzien van drie dekken met roterende messen. Alle chauffeurs maaiden steeds dezelfde set van vijf plantsoenen in Veenendaal, per machine op een andere dag met een tussenruimte van 2-3 weken. Ook werd het aan- en afrijden naar en van de plantsoenen gemeten. Twee van de plantsoenen werden gemeten waarbij de chauffeur als opdracht had op zijn normale wijze te maaien. Bij twee andere kreeg de chauffeur de opdracht mee "gehaast" te maaien (alsof hij iets te weinig tijd had gekregen voor de opdracht). Het laatste plantsoen werd "beheerst" gemaaid (dus: de chauffeur kreeg meer dan genoeg tijd voor de opdracht). De metingen van trillingen werden op de stoelzitting en aan de stoelbasis in drie richtingen (X, dit is voor-achter; Y, opzij; Z, zijnde verticaal) uitgevoerd volgens ISO-2631-1: 1997 norm en online bewaard op een laptop. Verwerking van de gegevens gebeurde achteraf met behulp van de tevens continu geregistreerde rijsnelheidsgegevens (m.b.v. GPS) en camerabeelden vanaf de cabine. Effectiviteit van de stoeldemping werd bepaald als zogenaamde SEAT waarde. Als onderdeel van het juist schatten van de dagelijkse blootstelling is meerdere chauffeurs van plantsoenmaaiers gevraagd nauwkeurig een dagbesteding bij te houden in een voor dit doel ontworpen dagboekje. Dertien chauffeurs retourneerden één of meer dagboekje(s), waarvan de gegevens van 7 chauffeurs vanwege voldoende nauwkeurigheid bruikbaar waren. Het betrof in totaal 12 gehele werkdagen.

Lichaamstrillingen gemeten op de stoelzitting tijdens het maaien van plantsoenen varieerde tussen 0.63 en 0.76 m/s^2 (X; mediaan: 0.69 m/s^2), 0.48 en 0.72 m/s^2 (Y; mediaan: 0.59 m/s^2), en 0.44 en 0.54 m/s^2 (Z; mediaan: 0.47 m/s^2) bij gebruik van de drie maaimachines bij normaal rijgedrag (de spreidingen zijn medianen over de chauffeurs). De rijsnelheid bedroeg hierbij gemiddeld 6.1 km/h. In alle gevallen bleken de trillingen in het horizontale vlak (X of Y) het hoogst en beperkend voor de maximale dagelijkse werkduur. Voor aan- en afrijden bedroeg spreiding in de waarden respectievelijk 0.33 - 0.40 m/s^2 (X; mediaan: 0.39 m/s^2), 0.28 - 0.42 m/s^2 (Y; mediaan: 0.34 m/s^2), en 0.39 - 0.50 m/s^2 (Z; mediaan: 0.40 m/s^2).

Beheerst rijden leverde een aanzienlijke reductie in de blootstelling aan lichaamstrillingen op: mediane meetwaarden over alle chauffeurs en machines waren 0.58 m/s^2 (X), 0.49 m/s^2 (Y) en

0.41 m/s^2 (Z). De gemiddelde rijsnelheid bleek met 5.9 km/h nauwelijks lager dan tijdens normaal rijden. Gehaast rijden ging gepaard met zowel een hogere gemiddelde rijsnelheid (7.7 km/h) als hogere blootstellingen (0.74 m/s^2 voor X, 0.75 m/s^2 Y en 0.57 m/s^2 als mediane waarde voor Z).

De stoeldemping bleek nauwelijks afhankelijk van het rijgedrag tijdens het maaien. SEAT waarden bedroegen mediaan 107%, 100% en 52% voor respectievelijk X, Y en Z. Het betekent dat tijdens het maaien alleen in verticale richting de trilling vanuit de cabinebodem effectief wordt gedempt. Wel lijkt de demping in alle richtingen meer effectief in vergelijking met zeven jaar geleden.

Uit de inventarisatie van de dagindeling van chauffeurs van plantsoenmaaiers blijkt dat het maaien zelf zo'n 63% van de totale werkdag van bijna 9 uur exclusief pauzes vraagt. Het relatieve aandeel van aan- en afrijden en van het transport van de maaimachine met een bus of aanhanger bedraagt respectievelijk 13% en 8%. Overige taken als tanken en onderhoud waarbij geen blootstelling aan lichaamstrillingen is aangenomen bedragen samen 15% van de werkdag.

Met het combineren van de gemeten blootstellingswaarden en de gemiddelde dagindeling blijkt de blootstelling voor een volledige werkdag voor alle machines boven de actiewaarde als gezondheidsgrens voor een normale werkdag uit te komen. Het blijkt nog altijd niet mogelijk een volledige werkdag te besteden aan het plantsoen maaien, gegeven de verschillende taken volgens de dagindeling. De actiewaarde wordt, bij normaal rijgedrag, bereikt na 5-6 uur werk. Indien beheerst rijgedrag wordt aangeleerd wordt de actiewaarde pas na 7-8 uur bereikt.

Voor de praktijk in de groenvoorziening zou het wenselijk zijn dat de maaimachines trillingstechnisch worden verbeterd. Vooral zou hierbij aandacht moeten worden besteed aan het verminderen van de trillingen in het horizontale vlak. Of uitsluitend een verende stoel als demping in deze richting voldoende is blijkt onvoldoende uit de huidige metingen. Wel en nadrukkelijk wordt aanbevolen aandacht te besteden aan de geconstateerde overdracht van verticale cabinetrillingen op de voor-achterwaarts gerichte beweging van de stoel. Onderzocht moet worden of betere demping van wielen of banden resulteert in een verminderde overdracht. Hierbij moet goed worden nagegaan of niet eventuele ongewenste resonantie-effecten ontstaan door interactie van de maatregelen met de al aanwezige demping in de stoel.

Appendices

A: WBV exposure measured during the various tasks

Symbols used:

reference axis	: axis of the vibration measurement
t_m	: total measuring time 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 value 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, given t_d, in $m/s^{1.75}$
S_{ed}	: equivalent of daily static compression dose according to ISO-2631-5 (2004), in MPa

In the tables below, distinction is made to normal, hasty and restrained mowing.

1. Sitting on a standing machine, motor running stationary

reference	mowing	t_m	average	meas.	a_w	VDV	D	S_e	t_d	8h VDV	S_{ed}
axis	machine	(s)	speed (km/h)	(n)	(m/s^2)	($m/s^{1.75}$)	(m/s^2)	(MPa)	(s)	($m/s^{1.75}$)	(MPa)
x					0.040	0.12	0.39				
y	1	208	0	8	0.030	0.15	0.28	0.01			
z					0.030	0.14	0.18				
x					0.020	0.07	0.15				
y	2	157	0	4	0.030	0.13	0.19	0.01			
z					0.040	0.16	0.17				
x					0.060	0.14	0.19				
y	3	172	0	5	0.050	0.17	0.23	0.02			
z					0.060	0.18	0.21				

2. Distance driving over public asphalt roads

reference	mowing	t_m	average	meas.	a_w	VDV	D	S_e	t_d	8h VDV	S_{ed}
axis	machine	(s)	speed (km/h)	(n)	(m/s^2)	($m/s^{1.75}$)	(m/s^2)	(MPa)	(s)	($m/s^{1.75}$)	(MPa)
x					0.390	3.03	6.07				
y	1	1724	15.0	3	0.340	3.27	5.57	0.20			
z					0.400	2.53	2.58				
x					0.400	2.90	5.45				
y	2	1419	17.7	3	0.280	2.23	4.64	0.16			
z					0.390	2.82	2.93				
x					0.330	2.80	3.84				
y	3	1401	19.4	3	0.420	3.08	5.85	0.21			
z					0.500	3.39	4.27				

3. RESTRAINED PERFORMANCE: mowing of fields, including short distances of driving over pathed roads when moving from field to field.

reference	mowing	t_m	average	meas.	a_w	VDV	D	S_e	t_d	8h VDV	S_{ed}
axis	machine	(s)	speed (km/h)	(n)	(m/s^2)	($m/s^{1.75}$)	(m/s^2)	(MPa)	(s)	($m/s^{1.75}$)	(MPa)
x					0.630	5.10	7.82				
y	1	3464	5.5	3	0.490	4.55	6.52	0.23			
z					0.410	3.46	3.76				
x					0.580	5.36	7.51				
y	2	3372	4.9	3	0.460	4.26	6.37	0.22			
z					0.390	3.93	4.85				
x					0.550	4.85	6.57				
y	3	3341	6.1	3	0.640	5.51	8.72	0.31			
z					0.470	4.12	5.09				

3. RESTRAINED PERFORMANCE: total task, based on the time spent in practice (see table 5, A-C).

reference	mowing	t_m	average	meas.	a_w	VDV	D	S_e	t_d	8h VDV	S_{ed}
axis	machine	(s)	speed (km/h)	(n)	(m/s^2)	($m/s^{1.75}$)	(m/s^2)	(MPa)	(s)	($m/s^{1.75}$)	(MPa)
x					0.520					11.14	
y	1				0.408				32040	9.57	0.38
z					0.356					7.26	
x					0.490					11.56	
y	2				0.378				32040	8.44	0.37
z					0.364					8.25	
x					0.453					10.21	
y	3				0.533				32040	11.55	0.51
z					0.435					9.36	

NOTE: calculations are based on the present measurements only. Hence, transportation of the mowing machine with another vehicle and other tasks (table 5, D and E) are assumed not to have contributed to the exposure.

3. NORMAL PERFORMANCE: mowing of fields, including short distances of driving over pathed roads when moving from field to field.

reference	mowing	t_m	average	meas.	a_w	VDV	D	S_e	t_d	8h VDV	S_{ed}
axis	machine	(s)	speed (km/h)	(n)	(m/s^2)	($m/s^{1.75}$)	(m/s^2)	(MPa)	(s)	($m/s^{1.75}$)	(MPa)
x					0.760	7.29	10.25				
y	1	4826	5.9	3	0.590	5.85	7.90	0.28			
z					0.440	4.39	4.67				
x					0.660	6.66	9.47				
y	2	5235	6.5	4	0.480	4.87	6.69	0.27			
z					0.490	5.47	7.80				
x					0.630	6.33	8.06				
y	3	4819	6.1	3	0.720	6.83	10.13	0.36			
z					0.540	5.22	6.59				

3. NORMAL PERFORMANCE: total task, based on the time spent in practice (see table 5, A-C).

reference	mowing	t_m	average	meas.	a_w	VDV	D	S_e	t_d	8h VDV	S_{ed}
axis	machine	(s)	speed (km/h)	(n)	(m/s^2)	($m/s^{1.75}$)	(m/s^2)	(MPa)	(s)	($m/s^{1.75}$)	(MPa)
x					0.620					14.15	
y	1				0.482				32040	10.71	0.42
z					0.378					8.19	
x					0.550					11.78	
y	2				0.394				32040	8.64	0.40
z					0.434					9.94	
x					0.515					11.46	
y	3				0.587				32040	12.66	0.53
z					0.484					10.70	

NOTE: calculations are based on the present measurements only. Hence, transportation of the mowing machine with another vehicle and other tasks (table 5, D and E) are assumed not to have contributed to the exposure.

3. HASTY PERFORMANCE: mowing of fields, including short distances of driving over pathed roads when moving from field to field.

reference	mowing	t_m	average	meas.	a_w	VDV	D	S_e	t_d	8h VDV	S_{ed}
axis	machine	(s)	speed (km/h)	(n)	(m/s^2)	($m/s^{1.75}$)	(m/s^2)	(MPa)	(s)	($m/s^{1.75}$)	(MPa)
x					0.740	5.96	9.68				
y	1	2151	8.2	3	0.750	5.55	7.27	0.26			
z					0.540	3.89	4.56				
x					0.840	6.71	9.79				
y	2	2098	7.0	3	0.670	4.89	7.00	0.25			
z					0.570	4.76	5.65				
x					0.720	5.43	7.94				
y	3	2067	8.3	3	0.900	6.93	9.64	0.34			
z					0.620	4.64	5.76				

3. HASTY PERFORMANCE: total task, based on the time spent in practice (see table 5, A-C).

reference	mowing	t_m	average	meas.	a_w	VDV	D	S_e	t_d	8h VDV	S_{ed}
axis	machine	(s)	speed (km/h)	(n)	(m/s^2)	($m/s^{1.75}$)	(m/s^2)	(MPa)	(s)	($m/s^{1.75}$)	(MPa)
x					0.605					14.03	
y	1				0.608				32040	12.94	0.46
z					0.453					8.91	
x					0.683					15.33	
y	2				0.544				32040	11.62	0.44
z					0.491					11.29	
x					0.584					12.94	
y	3				0.731				32040	15.68	0.61
z					0.541					11.28	

NOTE: calculations are based on the present measurements only. Hence, transportation of the mowing machine with another vehicle and other tasks (table 5, D and E) are assumed not to have contributed to the exposure.

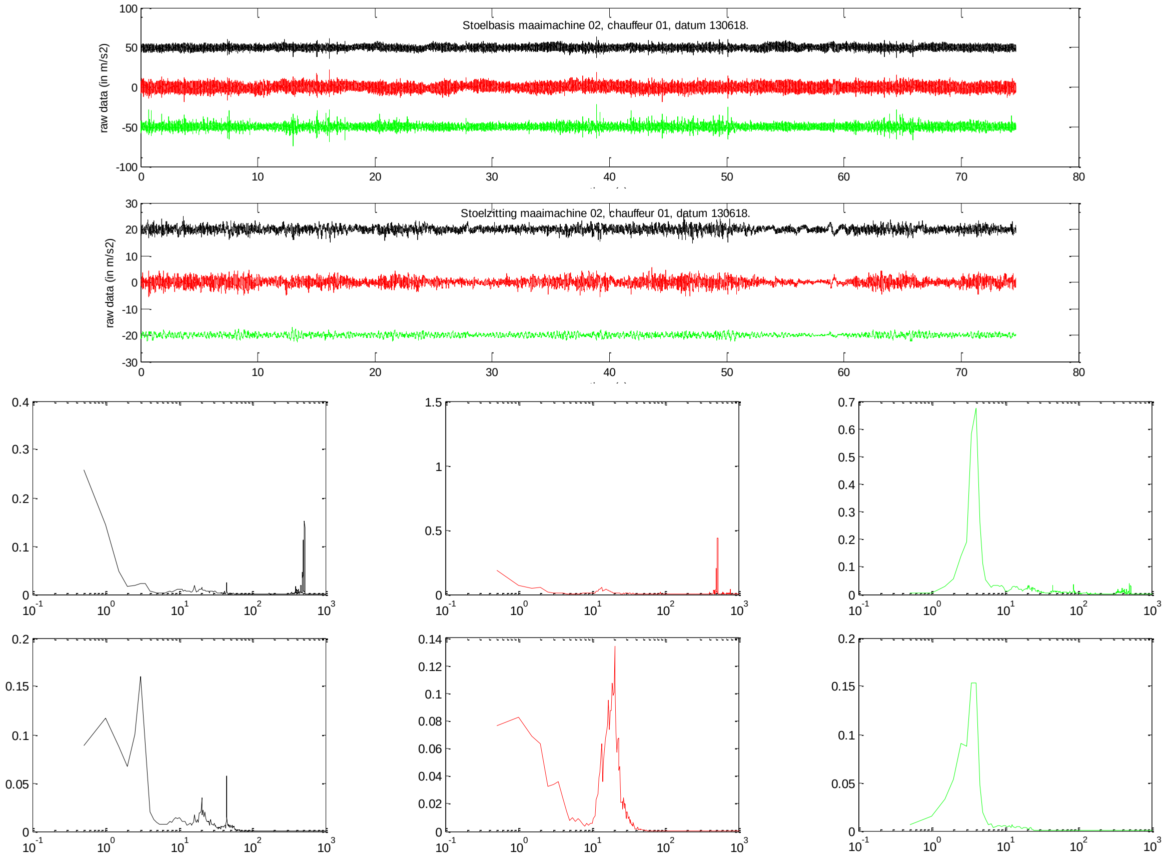
B: Photo gallery of the self-propelled lawnmowers involved

1. Toro 4010 D Groundsmaster

2. Ransomes HR 6010

3. John Deere 1505 S II BM

C: Example of a time series and frequency spectrum of mower 1

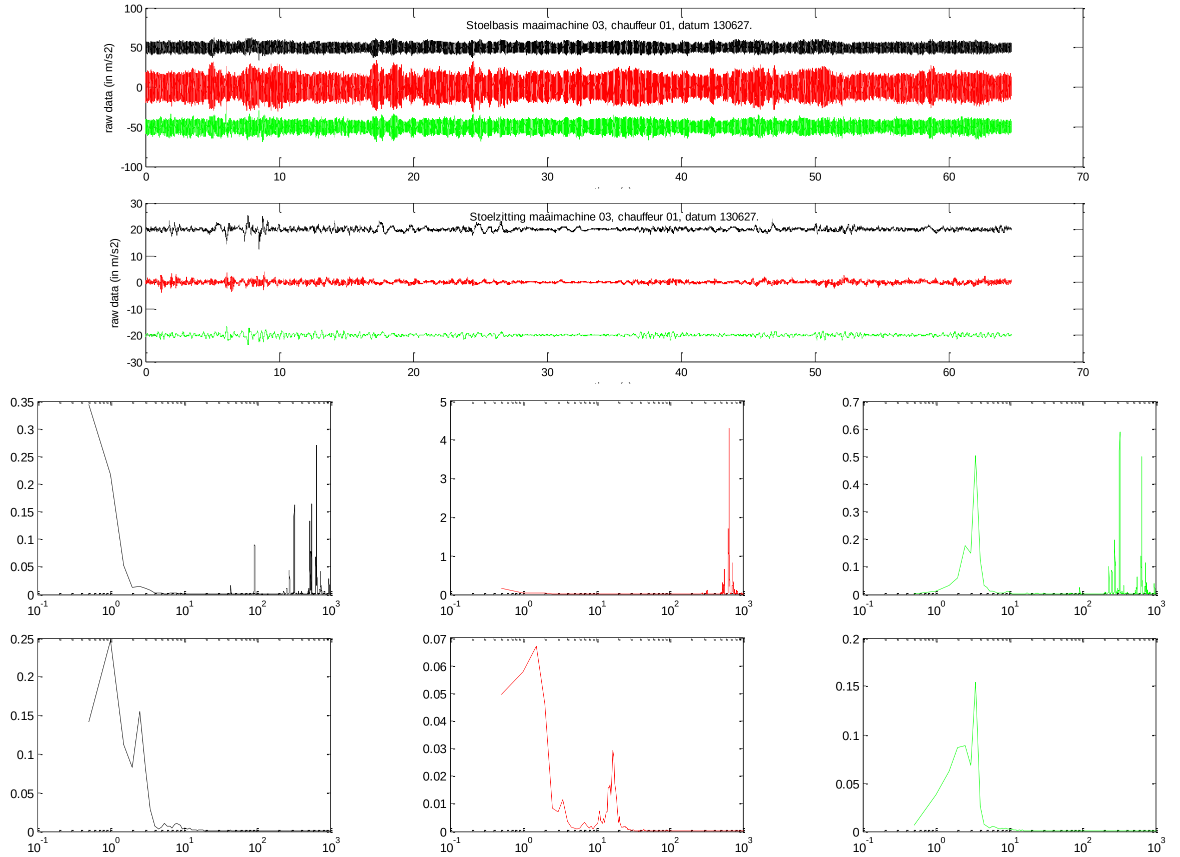


Raw unweighted and not-corrected data of the vibrations measured (in m/s^2) of mower 1 driven by operator 1 during a normal speed task as time series of approximately 75 s (the driving velocity during the mowing was varying), as measured at the chair base ('stoelbasis'; upper plot) and on the seat ('stoelzitting'; second plot) for vibration axes X (black), Y (red) and Z (green). For the sake of clarity of the plots, the data of X and Z are shifted +50 and -50 m/s^2, respectively, for the chair base. These values were +20 and -20 m/s^2 for the seat.

The lower six plots show the frequency spectra of the time series shown. The upper frequency plots are those of the chair base (X: black; Y: red; Z: green). The lower are those of the seat. The frequency plots are produced using Fast Fourier Transformation in Matlab. The horizontal axis scales from 0.1 to 1000 Hz in logarithmic scale. The vertical axis shows the relative power (in arbitrary units) of each frequency in the signal.

The frequency spectra on the seat show dominant peaks around 3-4 Hz and 20 Hz for the X- and Y-axes, and around 4 Hz for the Z-axis. The high frequencies (around 500 Hz) that can be found at the chair base in the horizontal plane cannot be detected on the seat.

D: Example of a time series and frequency spectrum of mower 2

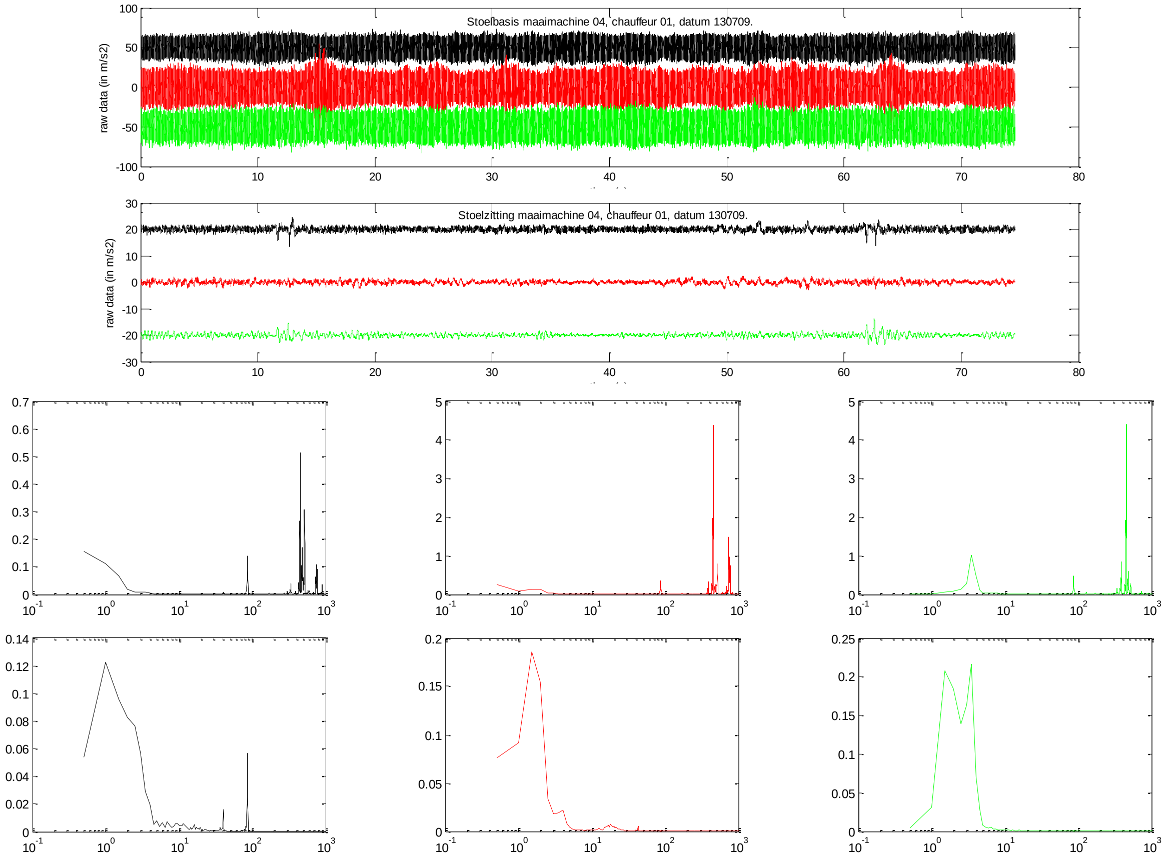


Raw unweighted and not-corrected data of the vibrations measured (in m/s^2) of mower 2 driven by operator 1 during a normal speed task as time series of approximately 64 s (the driving velocity during the mowing was varying), as measured at the chair base ('stoelbasis'; upper plot) and on the seat ('stoelzitting'; second plot) for vibration axes X (black), Y (red) and Z (green). For the sake of clarity of the plots, the data of X and Z are shifted +50 and -50 m/s^2, respectively, for the chair base. These values were +20 and -20 m/s^2 for the seat.

The lower six plots show the frequency spectra of the time series shown. The upper frequency plots are those of the chair base (X: black; Y: red; Z: green). The lower are those of the seat. The frequency plots are produced using Fast Fourier Transformation in Matlab. The horizontal axis scales from 0.1 to 1000 Hz in logarithmic scale. The vertical axis shows the relative power (in arbitrary units) of each frequency in the signal.

The frequency spectra on the seat show dominant peaks around 2-4 Hz and 10-20 Hz for the X- and Y-axes, and around 2-4 Hz for the Z-axis. The higher frequencies (above 100 Hz) that can be found at the chair base for all axes cannot be detected on the seat.

E: Example of a time series and frequency spectrum of mower 3



Raw unweighted and not-corrected data of the vibrations measured (in m/s^2) of mower 3 driven by operator 1 during a normal speed task as time series of approximately 74 s (the driving velocity during the mowing was varying), as measured at the chair base ('stoelbasis'; upper plot) and on the seat ('stoelzitting'; second plot) for vibration axes X (black), Y (red) and Z (green). For the sake of clarity of the plots, the data of X and Z are shifted +50 and -50 m/s^2, respectively, for the chair base. These values were +20 and -20 m/s^2 for the seat.

The lower six plots show the frequency spectra of the time series shown. The upper frequency plots are those of the chair base (X: black; Y: red; Z: green). The lower are those of the seat. The frequency plots are produced using Fast Fourier Transformation in Matlab. The horizontal axis scales from 0.1 to 1000 Hz in logarithmic scale. The vertical axis shows the relative power (in arbitrary units) of each frequency in the signal.

The frequency spectra on the seat show dominant peaks around 1-3 Hz for the X- and Y-axes, and around 1-5 Hz for the Z-axis. The high frequencies (above 100 Hz) that can be found at the chair base for all axes cannot be detected on the seat.