Validation and improvement of the ISO 2631-1 (1997) standard method for evaluating discomfort from whole-body vibration in a multi-axis environment

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By

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Declaration

No portion of this work referred to in this thesis nor the original work contained therein has been submitted to this or any other institution for a degree.

Signed ....

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Abstract

Doctor of Philosophy

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Ykä Marjanen

Vibration exposure can occur at work, commuting between home and work, and in leisure activities. Any form of transportation will expose humans to some degree of vibration. Exposure to vibration can cause health problems, but more likely comfort problems. Health problems are normally related to back pain. Comfort on the other hand is related to both physiological and psychological factors, which can have a wide range of effects from a general annoyance to a reduced work capability.

The standard ISO 2631-1 (1997) provides a guidance, which can be used to measure, evaluate and assess effects of whole-body vibration to discomfort. The standard allows several interpretations, which can lead to different results, as the standard does not provide an explicit guidance for selecting which axes and locations to measure and which averaging method to use for evaluating the axes. The suggested averaging method is the root mean square (r.m.s.) method, but additionally vibration dose value (VDV) can be used. This can lead to different results, as VDV emphasises shocks more than the r.m.s. method. The standard guides to measure and evaluate at least the seat translational axes, but the additional nine axes from the seat, backrest and floor are not mandatory. However, this can result in a different comfort value, as the values from the measured axes are combined. So taking into account all possible interpretations the assessment can vary significantly for the same environment.

The selection of the averaging method is not a technical issue, as both methods are supported by all commercial equipment. However, it is rare that more than three axes are possible to be measured with typical whole-body vibration measurement equipment, thus the majority of studies have published results based on only the seat translational axes. Especially the rotational axes have been missing in most studies. The full method (i.e. using all possible axes to calculate the comfort value) of ISO 2631-1 (1997) has been rarely used and there is very little information on how accurate the method is for assessing discomfort in a multi-axis environment. There are only a few studies that have used the full method, but there are no known studies which have actually validated the full ISO 2631-1 method.

The objective of the thesis was to validate and, if necessary, to improve the full method of the ISO 2631-1 standard for evaluating discomfort from whole-body vibration in a multi-axis environment. It was assumed that the ISO 2631-1 method can be used to predict discomfort in practice, but there are a relatively low number of studies to confirm this. Frequency weightings have been the focus of many published studies and it was assumed that these are broadly correct. Other aspects of the ISO 2631-1 method are the focus of this thesis. The goal was to keep a backward compatibility to previous studies and the current commercial equipment, thus several limitations were defined for the improvement of the standard.

Several laboratory experiments, field measurements, and field and laboratory trials were conducted to validate the standard method. At first it was concluded that practical equipment for measuring 12-axis data was needed as there was no commercial system available. The equipment and software was validated in two experiments, which showed that simple and affordable components could be used to develop equipment for the full method. Even though the standard does not include information about a six-axis sensor for measuring both translational and rotational axes, there was a method to validate the sensor.

The first field study included measuring several machines using all twelve axes. The analysis showed that the seat and backrest translational axes will contribute about 90 % of the overall vibration total value of the standard method, thus very little justification was found for including the seat rotational and floor translational axes. Similar results were found based on the data from the previous 12-axis studies. It was also found that the neglected axes could be compensated with a factor for estimating the overall vibration total value including all twelve axes. As the overall vibration total value is directly related to the number of used axes, the compensating factors can be used to compare results which used different axes.

The laboratory trial confirmed the results from the field study, and it was concluded that sufficient accuracy to predict discomfort can be achieved using just the seat translational axes, even though the correlation improved when more axes were included. It was found that the evaluation of discomfort was improved by the use of the frequency weighting curves and the r.m.s. averaging method. However, as the multiplying factors degraded correlation, it was concluded that a new set of factors should be calculated. The new factors showed that a higher emphasis on the seat horizontal axes should be given (x=2.7, y=1.8 and z=1.0). The new factors improved the correlation systematically for all subjects.

The field trial showed a similar trend, where optimised multiplying factors improved the correlation, but it was also noted that different multiplying factors are required for different environments, thus a procedure to optimise the standard method to different environments was developed. The trial showed systematic behaviour and the optimised multiplying factors were best for all subjects and groups.

Keywords: Discomfort, whole-body vibration, standard, ISO 2631-1, multi-axis, multiplying factors

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Abbreviations

OVTV	Overall Vibration Total Value
PVTV	Point Vibration Total Value
VDV	Vibration Dose Value
r.m.s.	Root mean square
r.m.q.	Root mean quad
r.s.s.	Root-sum-of-squares
WBV	Whole-body Vibration
LBP	Low Back Pain
BS	British Standards
ISO	International Standards Organization
m/s^2	Metres per second squared
PSD	Power Spectral Density
x-axis	Fore-and-aft axis
y-axis	Lateral axis
z-axis	Vertical axis
a_v	Overall vibration total value combined using root-sum-of-squares method

1 Chapter 1 – Introduction

1.1 Background

Vibration exposure can occur at work, commuting between home and work, and in leisure activities. Any form of transportation will expose humans to some degree of vibration. Exposure to vibration can cause health and comfort problems. Health problems are normally back and neck related, presenting as musculoskeletal pain. Back pain, to which vibration exposure might be a significant contributor (Griffin 1990), is one of the most common health problems in the world (Deprez, et al 2005, Hostens 2004). Comfort on other hand is related to both physiological and psychological factors, which can have wider range of effects.

Even though health is the most critical issue in general, only a fraction of people are exposed to vibration that is severe enough to be identified as the sole cause of long-term health problems (Rehn, et al 2005b). Most exposed people experience vibration that may cause discomfort, although it also constitutes a risk factor for low back pain. Discomfort can show as a general emotional or physical annoyance, such as lowered ability to concentrate, depending on the context and the emotional state of the human (Wilder, et al 1994). For example, reading in a train is more difficult because of vibration (Sundström 2006). As growing numbers of people spend time travelling there is a need to understand and improve the conditions. Although there is not necessarily a link between discomfort and health, it is generally assumed that improved comfort is associated with reduced health risk.

It is difficult to study whole-body vibration health effects directly due to ethical considerations. It also has been proven difficult to find any pathological proof of back pain using MRI or other scanning techniques (Videman, et al 2000), thus subjective opinion has been an important factor in cross-sectional studies of injury prevalence. Even though studies have shown increased prevalence of back pain when exposed to vibration, it has been difficult to isolate the effects from other confounding factors (Palmer, et al 2008). Most of the techniques used to evaluate whole-body vibration health effects are based on perception and comfort studies (Mansfield 2005), thus the method for evaluating the health effects is the same as for evaluating comfort.

Because of the harmful effects of vibration, research has been conducted to quantify methods for evaluating the effects. Currently there are several methods available for evaluating the effects of vibration and an internationally standardised procedure to measure and calculate values (ISO 2631-1 1997), which has been updated with an amendment in 2009. Also legislation has been produced to minimise the negative effects of vibration to work health by forcing all employers within the European Union to assess the risks arising from vibration exposure (Beazant 2005).

1.2 Problem description

Systematic research relating to the effects of vibration to whole-body vibration dates back to late 1960's. During the following decade the basis of the current knowledge was formed (Griffin, et al 1982). The main focus of the studies were the equivalent comfort contours, which showed that the human sensitivity to vibration was related to both amplitude and frequency (Griffin, et al 1982). Thus, it was necessary to weight (i.e. filter) the measured vibration data before evaluating the effects. Additionally some work was conducted relating to methods for averaging the vibration signal to a single value and combining the values of different axes (e.g. vertical, lateral and fore-and-aft) and locations (seat, backrest and floor) (Parsons and Griffin 1983). It was found that the vibration of different axes should be combined for a best result. The root mean square (r.m.s.) method was the first generally accepted method to average vibration data. Later, also root mean quad (r.m.q) and vibration dose value (VDV) were proposed as alternative methods if the vibration contained high shocks (Griffin 1986, Parsons and Griffin 1983). Root sum of squares (r.s.s.) was concluded the best method to combine the averaged values of each axis. A proposal of the method and guidance, which is in its current form in ISO 2631-1 (1997), was published in 1986 (Griffin 1986). The method included frequency weighting curves for all axes (translational and rotational) and locations (seat, backrest and floor), equations to average and evaluate the vibration data and multiplying factors to emphasise the axes when combining them. A year later it became a British Standard (BS 6841) for evaluating the effects of vibration to human health and comfort.

However, the full method described in ISO 2631-1 (1997) and BS 6841 (1987) has been rarely used and there is very little information on how accurate the method is for assessing discomfort in a multi-axis environment. There has been no study, which would have validated the method and described best practices, using either laboratory and field environments and field-like (i.e. non-stationary, random and multi-axis) stimuli. There are related studies (Donati, et al 1983, Fairley 1995, Parsons and Griffin 1983), but they have been conducted either based on earlier standards, earlier versions of the frequency weightings, without multiplying factors, using shock type stimuli on a fixed track, using short exposures (< 20 seconds) or using less than twelve axes.

Previous publications have indicated that parts of the standard method might not be valid. There have been doubts expressed regarding frequency weighting curves (Maeda, et al 2008, Morioka and Griffin 2006), multiplying factors (Maeda and Mansfield 2006b) and averaging methods (Maeda 2005). It has been suggested that the current method does not provide accurate results, which are comparable between environments (Mansfield and Maeda 2005b).

The equivalent comfort contours (i.e. frequency weightings) have been derived using single frequency sinusoidal or random narrow-band (i.e. 1/3 octave) vibration. The stimuli have been stationary (e.g. sinusoidal). In practice humans are exposed to non-stationary vibration, which is random, and skewed by the frequency content depending on the dynamic properties of the vehicle. No studies have been found to evaluate the applicability of the standard frequency weightings for non-stationary random vibration for predicting discomfort. Additionally most studies have used hard seats, thus the effect of seat cushion has not been included. This might have an effect on the relative contribution of different frequencies and axes. The lack of validation also concerns scaling factors and the averaging method.

The full method provides a single value (i.e. overall vibration total value, OVTV), which represents the combined effect of all axes to discomfort. The standard does not provide adequate information on how to compare the results or to understand how the value relates to discomfort. A table provided in the standard to assess discomfort has overlapping categories and no references have been provided for the validity or scope of the table.

The full method includes twelve axes measured from backrest, seat and floor, which are then calculated and combined as a single value (Figure 1). The translational axes from the seat have been considered the main axes, while rest of the axes are given as 'additional' axes. The OVTV value is significantly affected by the number of selected axes. There have been only a few studies that have investigated the effects of the 'additional' axes simultaneously with the other axes (i.e. multi-axis environment). The axes have been studied mostly in a single-axis environment. The studies indicate (Maeda 2004, Wyllie and Griffin 2007) that the 3-axis measurements from the seat might not be enough for evaluating discomfort from whole-body vibration.

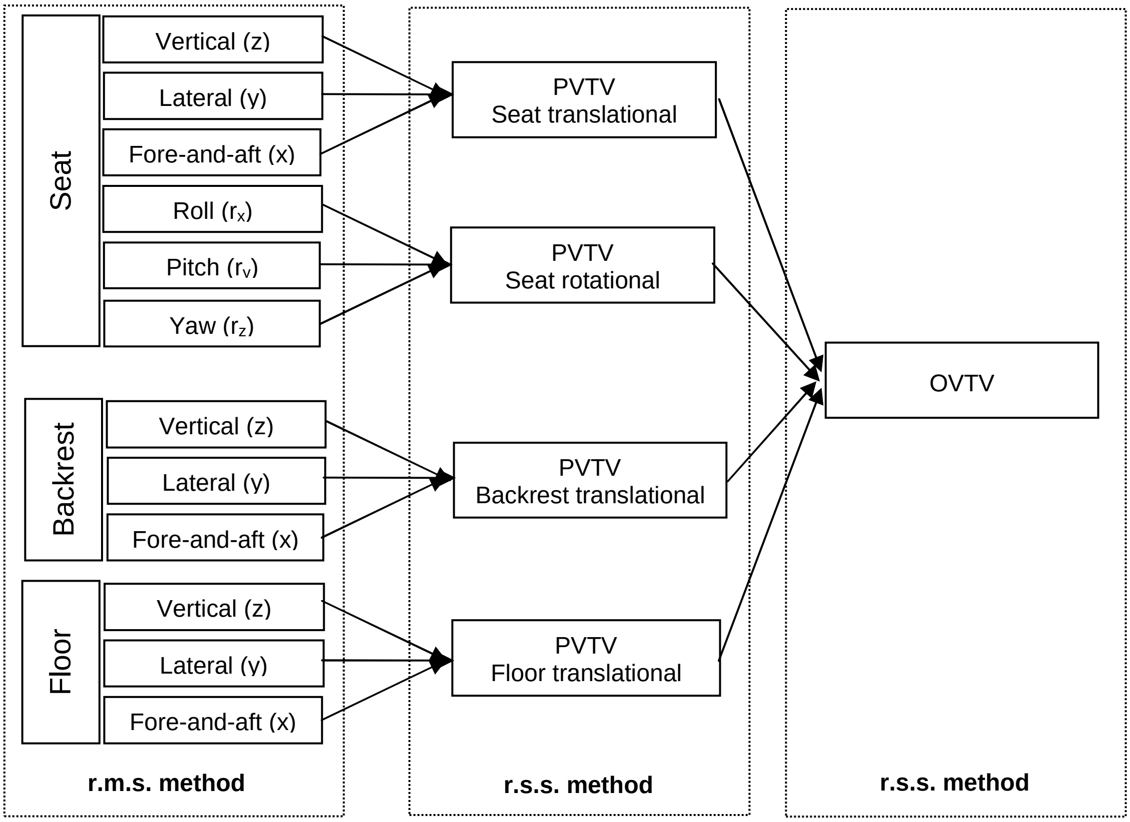

Figure 1. ISO 2631-1 (1997) standard method for combining the frequency weighted vibration data from each of the twelve axes to a single "overall vibration total value". The r.m.q and VDV methods can be used instead of the r.m.s. method for averaging the vibration data.

The full method requires equipment that has three separate sensor locations: two sensors for recording translational axes, and one sensor for recording both translational and rotational axes. Sensors measuring the translational axes are common, but rotational acceleration is more difficult to measure and few products are available, which are expensive and not available off-the-shelf. Because of the lack of published field measurements there is little information on the usability of measuring all twelve axes in the field, thus there is no guidance on how many axes are practically necessary for evaluating the discomfort from vibration. It would encourage more measurements if fewer axes were needed.

1.3 Objectives and hypotheses

The objective of the research was to validate and, if necessary, improve the full method of the ISO 2631-1 standard for evaluating discomfort from whole-body vibration. Even though it was assumed, that the method predicts discomfort at least adequately, there was a suspicion that parts of the method (e.g. frequency weightings) will not provide optimal results, thus the method can be further improved. The possible improvements were limited to such changes that would allow previous measurements and current equipment to be used. This restricts the optimisation to:

- Either frequency weightings are used or they are not (i.e. no new frequency weightings are produced);
- Either r.m.s. or VDV (or r.m.q) methods are used (no new averaging methods are suggested);
- No new measurement locations are introduced.

However, there are parts of the method, which can be changed more freely:

- New multiplying factors can be derived for all axes;
- Combinations of axes (i.e. locations and directions) to produce OVTV can be selected freely.

Further hypotheses, based on the previous studies (see Chapter 2), were:

- Applying frequency weighting will more likely have a small effect on discomfort predictions as the vibration frequency range found in the field is heavily skewed at low frequencies (below 5 Hz), which is also emphasised by the weighting curves (see Section 2.2.1);
- Higher multiplying factors should be used for the seat horizontal axes, especially if only seat translational axes are used to evaluate discomfort (Maeda and Mansfield 2006b);
- Emphasis of shocks by using a VDV or r.m.q. method might provide better correlation to discomfort than the r.m.s. method if the vibration has high shocks (Boileau, et al 1989);
- Including more axes to the evaluation will improve the correlation to subjective judgment (Parsons and Griffin 1983);
    - However, most likely the difference will be small compared to using just seat translational axes with correct emphasis (i.e. multiplying factors).

1.4 Thesis structure

A literature review was conducted for providing a comprehensive background on the evolution and history of the standard method, and to summarise the current knowledge and guidance on the effects from whole-body vibration exposure (Chapter 2). Based on the review general methods to conduct the thesis were chosen (Chapter 3).

Technical development of measurement equipment was considered necessary for measuring all twelve axes in the field. The equipment was validated in two experiments using a multi-axis test bench and compared to commercial equipment. The equipment was developed to fulfil the requirements for commercial equipment according to the relevant standard (Chapter 4).

Field measurements of the twelve axes were conducted to evaluate the relative contribution of the axes to OVTV by analysing the effects of frequency weighting and multiplying factors. Several typical work environments were measured and results from previous studies were used to determine the axes, which have a practical effect to discomfort (Chapter 5).

A laboratory trial was conducted for validating the standard method in a multi-axis environment by acquiring both vibration and discomfort judgments. Detailed analysis of combinations of axes, frequency weighting curves, multiplying factors and averaging methods were conducted to find a procedure for best possible correlation to discomfort. Additionally the data was used to optimise the standard method based on the allowed changes (Chapters 6 to 8).

A field trial was conducted for validating the findings from the laboratory trial and to suggest best practices for predicting discomfort from whole-body vibration. Similar methods to the laboratory trial were used; however several subjects were measured simultaneously (Chapter 9).

1.5 Scope

This thesis was limited to a seated posture of a passenger using a seat with a backrest support and a rigid body frame (i.e. typical car seat used in a passenger car). Each part of the thesis had specific limitations, but in general this thesis regarded only the effects of vibration to discomfort, thus other sources (e.g. noise) were neglected. The aim was not to develop a completely new method or model to predict discomfort, but to determine the limitations and to improve the current standard method as much as possible. For this reason the analysis and results were limited to the inherent problems relating to the theory and assumptions behind the standard method.

Based on the methods and environments the correlation results will not necessarily imply direct causality between subjective comfort and vibration exposure, but only that the variables have correlation.

1.6 Original contribution to knowledge

The following list summarises the main contributions of the thesis (contributions are presented in detail in Chapter 12):

1. Development of an affordable and practical 12-axis sensor system for field measurements;
2. Analysis of the practical importance of the twelve axes in the field based on the previous studies and new field measurements;
3. Laboratory validation of the axes and correlation between discomfort and vibration exposure of the standard method;
4. Analysis of the standard method by examining the role of frequency weighting, averaging method and multiplying factors;
5. Optimisation of new parameters to improve the correlation to discomfort;
6. Validating and testing the new proposed parameters and the current standard method in field;
7. Guidance on using the standard method with and without the optimised parameters in practice.

Additionally minor contributions of the thesis are:

1. Testing and validating cross-modal matching method of continuous judgment for acquiring discomfort judgments from subjects;
2. Detailed analysis of the current standard and its guidance;
3. Proposal of a method to optimise the new parameters for improving the standard method;
4. Development of equipment to allow judgment data to be gathered in field simultaneously with vibration;
5. Information on how to average discomfort judgments for best results;
6. Gender differences in discomfort judgments;
7. Guidance on how to conduct discomfort evaluation in practice.

1.7 Publications

A number of publications have been published based on the results of the thesis (Table 1). In total eight conference papers and two journal papers (in review) have been submitted. An additional journal paper regarding the field trial (Chapter 9) is planned to be submitted later.

Table 1. Publications based on the results of the thesis.

Topic of the paper	**Venue**	**Year**
Requirements for validating the standardized whole body vibration comfort evaluation method	Japan conference on human response to vibration	2006
Improving 12-axis measurement equipment for whole-body vibration comfort evaluation	Inter-noise	2006
Relative existence of 12-axis acceleration in different directions in mobile machinery work	42nd UK Conference on Human Response to Vibration	2007
Optimising the standardised method to evaluate discomfort from multi-axis whole body vibration	43rd UK Conference on Human Response to Vibration	2008
Measuring and evaluating discomfort from whole-body vibration in practice	2nd International Conference on Human Vibration Exposure, measurement and tests, Boden, Sweden	2009
Relative contribution of translational and rotational vibration to discomfort	Journal of Industrial Health and 4th International conference on whole body vibration injuries	2009
The relative contribution of twelve axes of vibration in field measurements for analysis according to ISO 2631-1	Journal of Industrial Health and 4th International conference on whole body vibration injuries	2009
Evaluation of discomfort in the field according to ISO 2631-1 standard	44th UK Conference on Human Response to Vibration	2009

2 Chapter 2 - Literature review

2.1 Introduction and aims of the review

Vibration exposure and its effects lie at the crossroads of many research disciplines: engineering, ergonomics, psychology, clinical medicine, and physiology. All disciplines have a similar goal of optimising the environment for the exposed persons, but different methods of achieving it. Engineering aims to minimise vibration exposure using technical solutions, while ergonomists try to optimise the environment using a human-centred approach. Psychology, clinical medicine and physiology concentrate on the human body and mind, and understanding how vibration causes stress. To find novel solutions, that will significantly minimise the negative effects from vibration, requires combination of knowledge across the different disciplines.

There are literally thousands of publications relating to whole-body vibration. The effects of whole-body vibration on a human body have been a subject of research at least since the early 20th century (Griffin 1990, Mansfield 2005, Oborne 1977). The effects are complex, non-linear and depend at least on the vibration amplitude, direction, frequency, duration and to which part of the body it is directed. A major part of the studies has been about measuring and analysing the vibration exposure levels concerning health for various work environments. However, not many have given consideration to the improvement of the methods currently used for evaluating and calculating the effects of vibration. There is a consensus that vibration exposure causes problems, but the mechanics of the causes are still not fully understood.

Based on the research conducted in 1970’s and 1980’s an international standard ISO 2631-1 (1997) was created to guide measurements and evaluation of whole-body vibration exposure relating to health, discomfort, perception and motion sickness. The standard is similar to the more concise British Standard BS 6841, which was introduced ten years earlier in 1987. Both of them use the same principal method for assessing discomfort, where 1) measured vibration data from selected locations and axes are frequency weighted (i.e. filtered), 2) averaged to a single value, 3) each averaged value is multiplied by a factor, 4) the multiplied averaged values for each axis and location are combined to form an overall vibration total value, which is 5) compared to a table or other values to assess discomfort from the measured environment. However there are still doubts and concerns expressed about the methods used for assessment (Griffin 2007). Based on the standard, legislation has been introduced in

Europe where there is a requirement to minimise the effects from vibration exposure (EC 2002).

Standards and legislation have focussed on managing and preventing health problems, most particularly to low back pain (LBP). Health effects have had the highest priority in research, however as most of our knowledge of health effects (and methods to evaluate it) come from perception and comfort studies, there is a clear link between health effects and discomfort judgment of a subject.

The purpose of the literature review is to summarise current knowledge on the effects of whole-body vibration to a seated person (Section 2.2), the methods for understanding and evaluating discomfort (Sections 2.3 and 2.4), technical requirements for measuring it (Section 2.5) and guidelines that can be used to assess it (Section 2.6). The review is concentrated on discomfort effects, but also other effects are reviewed because of close links between them. Even though there has been a large number of studies in this area, a relatively small number of publications can be considered important. The review will go through the literature regarding discomfort in the form of scientific publications, reports, standards, guidelines and legislation. Based on the review, the reader can understand more clearly the problems of vibration exposure and how health and discomfort are related to it.

2.2 Effects from vibration exposure

It is important to understand the effects of whole-body vibration, because millions of people expose themselves to it every day while working and commuting (Hostens 2004, Mansfield 2005, Palmer, et al 2003). It is almost impossible for any person to avoid vibration exposure living in a modern society. Just in the UK alone there are about 8.5 million people (estimated) who are exposed to whole-body vibration at work every day (Mansfield 2005). Vibration also affects passenger's ability to carry out tasks, such as eating, reading and writing (Oborne 1977). Under more extreme conditions vibration will have psychological and physiological effects, such as motion sickness, headaches, and even chronic health effects. About 1.3 million people in UK are exposed to vibration exceeding the action value of the Control of Vibration at Work Regulations (Brereton and Nelson 2005). Direct medical costs related to low back pain, which can be caused by vibration exposure, is in billions of dollars (Hostens 2004).

Whole-body vibration is defined as a motion transmitted to the human body as a whole through supporting surfaces, as opposed to vibration directed more locally, such as hand-arm vibration. Term “whole-body vibration” applies to standing, seated and recumbent persons (ISO 2631-1 1997). Because sitting is the most common posture in which a human body interacts with vibration, it is the most researched and understood (ISO 2631-1 1997). Driving and operating a machine and travelling are most frequently done in a seated posture. Other postures are rarer in work environments and have different physical effects to the human body (Mansfield 2005). Other postures are also more cumbersome to assess. For example a standing person tends to use legs to attenuate vibration. A recumbent person is on the other hand is normally associated with situations like patient transport or night-time travel, not generally with work. Both of these postures also have less association with low back pain than seated posture (Magnusson and Pope 1998).

Comfort and health effects relate in many ways. The methods used for health evaluation are mainly based on perception and comfort studies (Mansfield 2005). It is very difficult to even study health effects directly, because it is unethical to cause health problems purposely, and no personal long term vibration exposure history is available. It also has been proven difficult to find any visual proof of back pain using MRI or other scanning techniques (Videman, et al 2000), thus subjective opinion has been an important factor in published studies.

2.2.1 Discomfort

Discomfort is a highly subjective and personal opinion which varies between individuals (Griffin and Whitham 1977, Rybiak 2003), although some consistencies can be found amongst humans (Griffin, et al 1982, Parsons and Griffin 1980). In whole-body vibration research the interest has been to link the discomfort feeling to the vibration characteristics, such as frequency, amplitude, direction and duration, and to human characteristics, such as height, weight, age and gender. Human reaction to vibration is dependent on three factors: 1) characteristics of the vibration, 2) characteristics of the human and 3) characteristics of the environment. A seated person on a typical seat will usually perceive vibration from three locations (seat surface, backrest and floor). In a normal situation the vibration to a human is multi-directional, meaning that it is a combination of three translational axes (vertical, lateral and fore-and-aft) and three rotational axes (pitch, roll and yaw) (Figure 2). Back and floor vibrations can be analysed using translational axes, because in a rigid-seat environment the rotational axes can be assumed to be the same for floor and backrest as for the seat surface.

Figure 2. The twelve axes and locations used to determine vibration discomfort for seated subjects (Griffin, et al 1982).

In the context of work, discomfort can be related to fatigue, lowered concentration and work performance, and indirectly to work motivation and happiness (Wertheim 1998), which can increase workload and reduce performance (Newell and Mansfield 2006). Vibration can also cause drowsiness and irritation (Wertheim 1998). These factors are becoming more and more important in work environments. A worker-friendly workplace can also show benefits in productivity (Hoy, et al 2005). Although there is not necessarily a link between discomfort and health, it is generally assumed that improved comfort is associated with reduced health risk. Even though vibration is rarely the only contributor, it is possible to improve overall comfort by reducing it (Hostens 2004, Mansfield 2005).

Forming an opinion of vibration starts immediately when a human perceives it. There are different sensory systems in the human body that can sense the vibration. There is no single organ which the human uses to perceive the vibration or movement. The systems can be divided into visual, vestibular, somatic and auditory systems (Mansfield 2005). The feeling of discomfort is formed by the combination of these systems. Each of the functions perceive vibration in a different way. The eyes can clearly see high-displacement movement, which normally occurs in relatively low frequencies. The perception is based on relative changes in position with a reference object (i.e. movement of a building cannot be normally detected with other organs). The vestibular system of the inner ear senses linear and rotational acceleration. When a head is exposed to acceleration or changes orientation to gravity, the vestibular system detects the movement. The somatic system includes many elements, which sense the vibration through motion of joints and muscles and receptors in skin and abdomen. Different receptors underneath the skin can detect vibration up to 500 Hz. The auditory system on the other hand can indirectly detect vibration when motion produces change in air pressure (above 20 Hz). Depending on the vibration characteristics and environment where a human is exposed to it, the combination of the sensory systems provides information to the brain to form a cognitive model of the motion (Mansfield 2005). Additionally human comfort depends on both static and dynamic factors. Static comfort relates more to ergonomics, while dynamic comfort relates to the vibration characteristics.

Discomfort is a complicated term to define. Depending on the context and purpose it can be interpreted in many ways. Regarding work, the threshold for no (or acceptable) discomfort can be defined as *“a state where vibration does not hinder work performance”* or *“an environment where vibration does not cause any action to change it”* (Mansfield 2005). For passengers not conducting any obligatory tasks, the discomfort can relate to general annoyance, inability to fall asleep, and difficulties for reading and writing (Oborne 1977). The effects will change depending on how vibration characteristics relate to other sources, such as noise, and from other factors such as cost of the trip, expectations, tiredness, and so on. In the context of moving machines vibration can be regarded as always causing discomfort, and decrease of vibration will always decrease discomfort (it should be noted that in some special cases passengers expect vibration and will feel ‘uncomfortable’ without it e.g. helicopter transportation). In this study the term “discomfort” is used in the context of “ride comfort” of passengers. In this case the change in discomfort can relate to many things, such as improved work performance (i.e. reading or writing), decrease of annoyance, improved concentration or even improved happiness.

If one searches terms “whole-body vibration” and “comfort“ or “discomfort” using databases such as EngineeringVillage2, InformaWorld, SCOPUS and SpringerLink, which incorporate most of the engineering journals regarding whole-body vibration, a relatively low number of publications is found (Table 2). EngineeringVillage2 shows a total of 236 hits where some studies are duplicate from other keyword searches and some had no relevance to the topic of the thesis. InformaWorld shows 106 publications, which most of them duplicates to EngineeringVillage2. SCOPUS shows 90 and SpringerLink 26, which all of them duplicates from previous database searches. Less than thirty of the records were published in the 1960’s and 1970’s, 23 records in the 1980’s, 18 in the 1990’s and 25 between 2000 and 2009. Search term “rotational” or “rotation” provides only six relevant studies which were all made over 20 years ago. For an example term “whole-body vibration” alone produced over 1000 publications from the databases. Comfort research has not been popular in recent decades, possibly because the required knowledge to provide a contribution and lack of equipment (i.e. vibration test bench and 12-axis measurement device).

Table 2. Number of publications found from database referring to whole-body vibration and discomfort. EngineeringVillage2 database includes Compendex, Inspec, NTIS, GEOBASE, Referex and other engineering databases. Informaworld is site hosting journals and ebooks published by Taylor & Francis, Routledge, Psychology Press and Informa Healthcare. SCOPUS is the largest abstract and citation database of research literature and quality web sources. SpringerLink is an integrated full-text database for journals and books published by Springer. Search was made using keywords, abstracts and titles.

Database	**Search words used for all databases**	**The number of studies in the order of search words for each database**
EngineeringVillage2	1. “whole body vibration” AND “discomfort”	90+57+34+55
Informaworld	2. “whole body vibration AND “comfort”	41+42+7+16
SCOPUS	3. “whole body vibration” AND “ride comfort”	32+24+3+31
SpringerLink	4. “whole body vibration” AND (“rotational” OR “rotation”)	1+8+2+15

Perception, motion sickness and discomfort are linked together. Motion sickness though is more of a conflict between the sensory systems than purely the cause of the vibration (Mansfield 2005). Perception can be thought as the ultimate lower threshold for discomfort to occur, because it defines the lowest level of vibration that a human can feel.

2.2.1.1 Studies and results behind the ISO 2631-1 (1997) method

The method described in ISO 2631-1 (1997) has been derived from the same studies as BS 6841 standard, which was introduced in 1987 (British Standards Institution 1987). Thus all studies before 1987 can be considered to relate to the standard method.

The experiments conducted in 1960’s by Miwa (Miwa 1969, Miwa 1967, Miwa and Yonekawa 1974) and 1970’s and early 1980’s by Griffin, Parsons, Whitham and Corbridge (Corbridge and Griffin 1986, Griffin et al. 1982, Parsons and Griffin 1982, Parsons et al. 1982, Parsons and Griffin 1983) show the first systematic results on discomfort and perception thresholds to whole-body vibration for different axes. The studies focussed on axes that existed in a seated posture. It was the purpose of the studies to find out the effects of vibration on discomfort regarding frequency, amplitude, direction and location (Griffin, et al 1982). The main results of the studies were the equivalent comfort contours for each axis in relation to frequencies, directions and locations. Although there were other studies regarding perception and sensation as well (Oborne 1978a, Reiher and Meister 1932, Shoenberger and Harris 1971), the results from the aforementioned studies are the basis of current ISO 2631-1 (1997) and BS 6841 (1987) standards (Maeda 2005).

Different methods were used for finding out the comfort contours. Some used rating scales (Fothergill 1972, Jones and Saunders 1974, Oborne and Clarke 1974) while others used reference stimuli (Griffin, et al 1982, Parsons and Griffin 1982, Parsons, et al 1982). Almost all of the studies concentrated on one axis (e.g. vertical) at a time. All studies were made in a laboratory using sinusoidal or other artificial stimuli.

The axis in the first studies for evaluating the sensation contours was vertical. Miwa (1967) concluded that sensitivity to vibration was higher at lower frequencies and it decreased for higher frequencies for the same amplitude. This was also confirmed by Griffin et al. (1982) and other studies. Based on these studies it was shown that for vertical direction the human perception was most sensitive at around 5 Hz (Griffin, et al 1982). Although results were not exactly the same they showed similar tendencies. Figure 3 shows the comparisons of experiments and results for vertical direction made by Miwa (1967), Jones and Saunders (1972), Shoenberger and Harris (1971) and Griffin (1976). Figure 4 shows the median contours found by Griffin et al. (1982). The results are also consistent with the previous studies. No significant differences were found between men and women (Griffin, et al 1982).

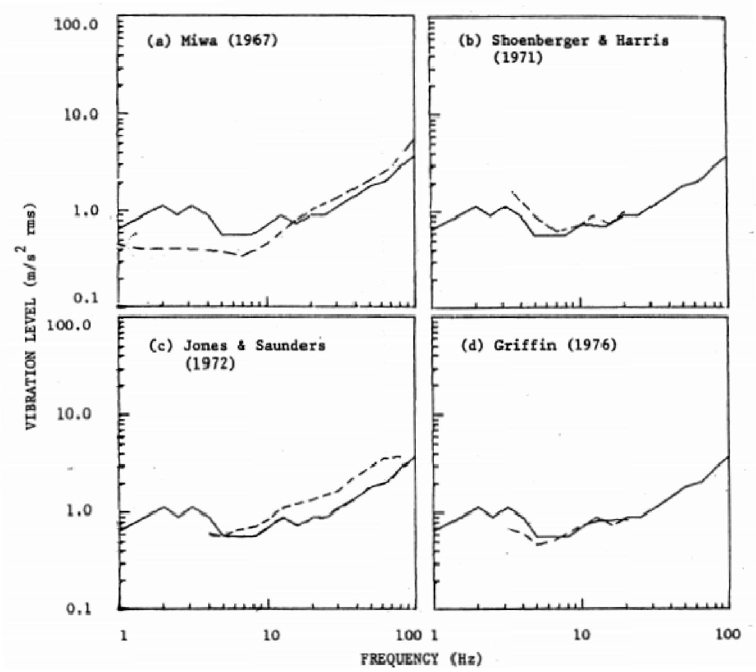

Figure 3. Median equivalent comfort contours of different studies for vertical axis at seat for a seated person compared between previous studies (- - -) and the reference study (---) (Griffin, et al 1982)*.*

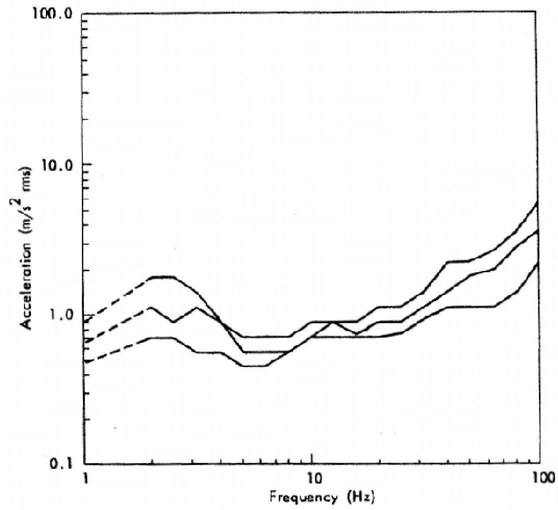

Figure 4. Median, 25th and 75th percentile comfort contours for vertical seat vibration (Griffin, Whitham and Parsons 1982).

The human body seemed to be most perceptive to horizontal vibration at very low frequencies (1 to 2 Hertz) and perception became more insensitive at higher frequencies (Griffin, et al 1982) (Figure 5). The studies did not find clear differences between lateral and fore-and-aft directions (without backrest). Results were compared also with the previous studies and similarities were found (Figure 6).

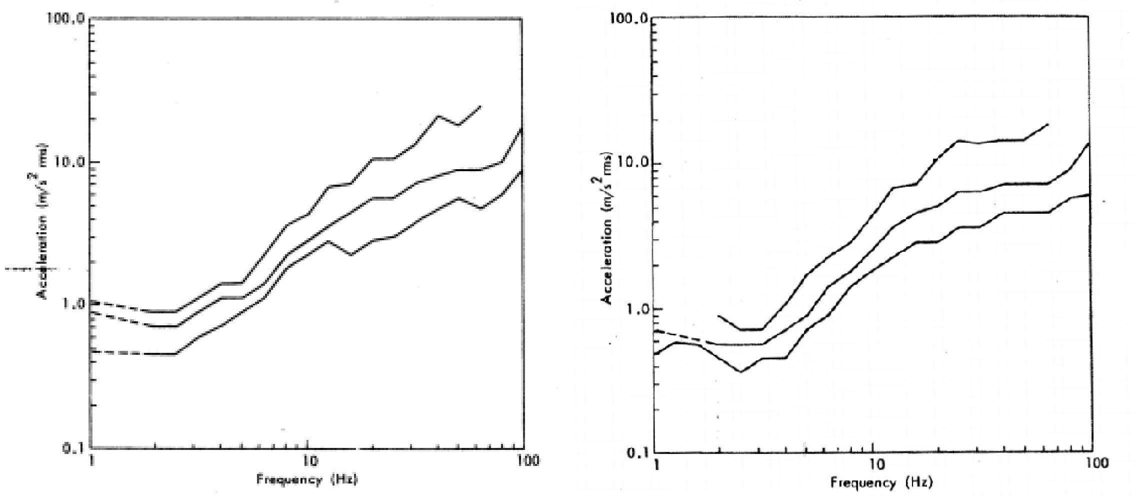

Figure 5. Median, 25th and 75th percentile comfort contours for fore-and-aft (left) and lateral (right) seat vibration (Griffin, et al 1982).

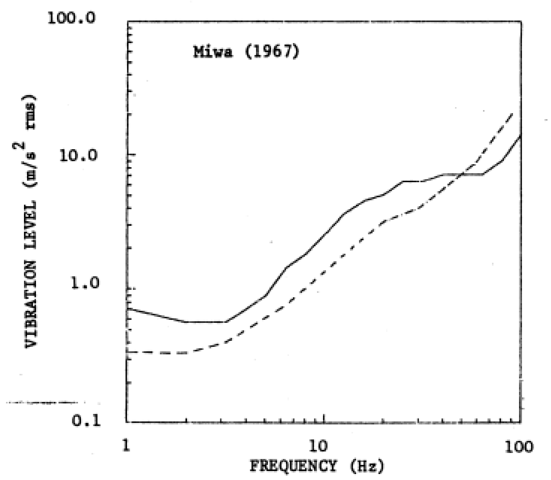

Figure 6. Median equivalent comfort contours for fore-and-aft vibration, compared between Griffin et al (1982) *and Miwa (- - -)* (Miwa 1967).

Miwa and Yonekawa (1974) published equal sensation curves for all translational axes using the vibration greatness method (Figure 7). There seemed to be a difference between sensations if sinusoidal or random vibrations were used. Random vibrations were felt more severe at higher frequencies. In contrast, sensation was more severe using sinusoidal stimuli at lower frequencies. Similar curves using sinusoidal stimuli (Figure 7: left) were obtained for both seated and standing postures.

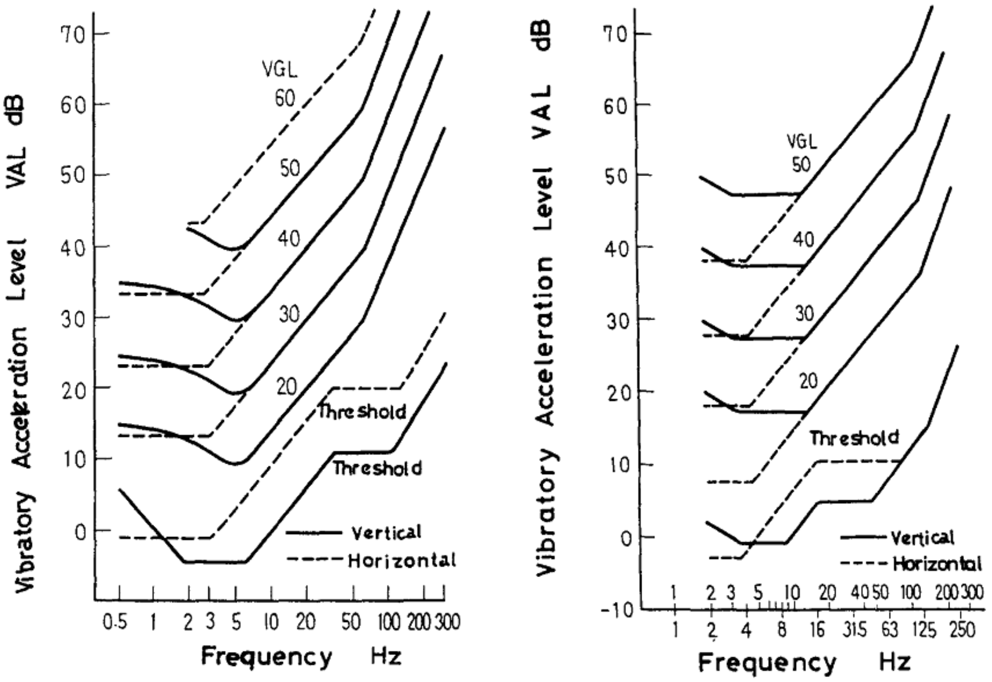

Figure 7. Miwa's studies on seat translational axes using vibration greatness method for sinusoidal stimuli (left) and random stimuli (right) (Miwa and Yonekawa 1974)*.*

In normal transport conditions the human sits on a seat using a backrest and feet resting on a floor. In this case the vibration will also be introduced through these locations as well and will most likely affect the comfort. Parsons et al. (1982) made a comprehensive study of the effects of seat and floor vibrations to subjective comfort. The conclusion was that the fore-and-aft direction had the most significant effect for back vibration (Figure 8: left). Vertical and lateral axes had similar effect, which was 5 to 10 times less than for fore-and-aft axis. All three translational axes from the floor had similar effect (Figure 8: right). At lower frequencies feet were less sensitive to vibration as felt from the seat surface, but were more sensitive to higher frequencies. The threshold on the backrest and floor also increased with higher frequencies as seen with the horizontal directions on the seat.

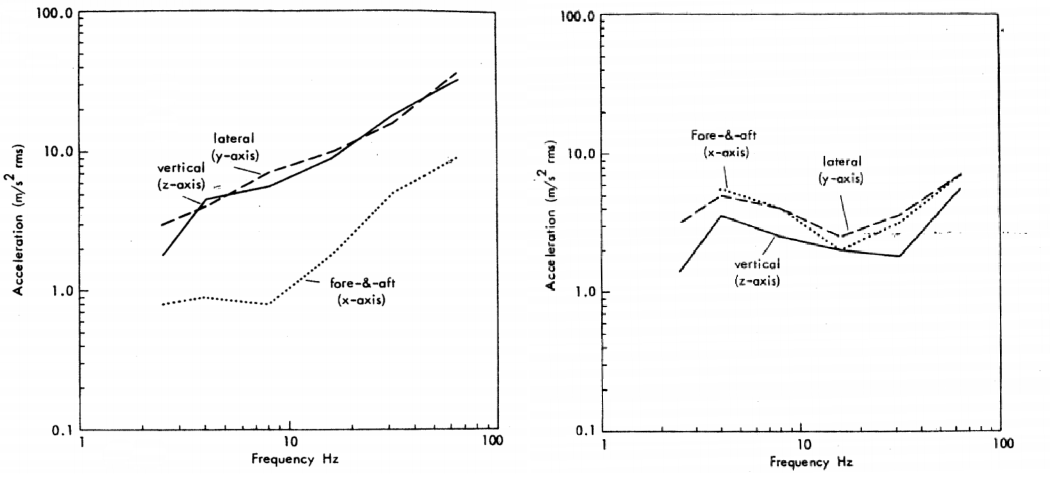

Figure 8. Comfort contours for three translational axes of back (left) and foot (right) vibration (Parsons, et al 1982).

In addition to translational motion, rotational motion also appears in many work environments (e.g. forestry harvester). If the centre of rotation is far from the human then it is perceived as translational motion (Parsons and Griffin 1982), but if the centre of rotation is close to the human it has its own effects and may contribute to discomfort. Rotational acceleration (rad/s^2) can be separated in to three independent axes, which are roll, pitch and yaw. Not many studies investigated the effects of pure rotational accelerations separately in laboratory environment. Based on the studies that did (Parsons and Griffin 1978a, Parsons, et al 1978, Parsons and Griffin 1982) the perception of the acceleration was decreased for higher frequencies (Figure 9).

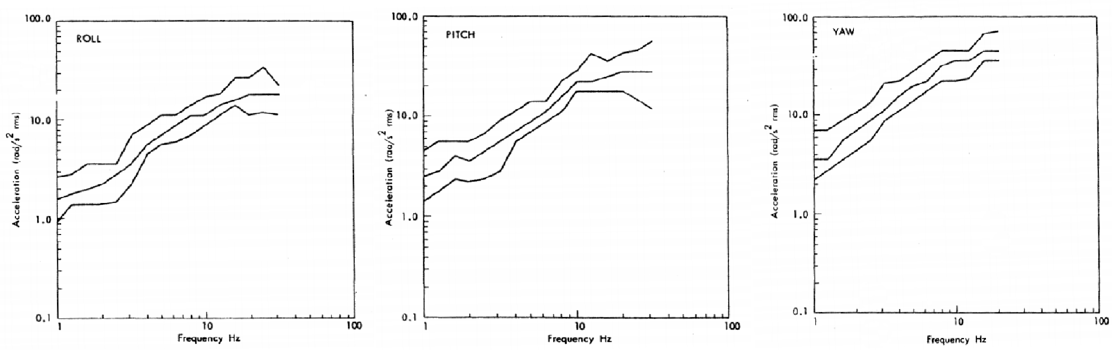

Figure 9. Median, 25th and 75th percentile comfort contours for roll (left), pitch (middle) and yaw (right) directions (Parsons and Griffin 1982)

The main conclusions from the early perception studies were: 1a) the horizontal axes (lateral and fore-and-aft) were considered equally uncomfortable and different to vertical axis and 1b) the rotational axes from the seat, backrest and floor translational axes had also an effect to discomfort, 2) there were differences between subjects depending on their physical characteristics 3) sensitivity to vibration seemed to relate to frequency, where higher frequencies (> 10 Hz) were more likely to be perceived less uncomfortable than lower frequencies (< 10 Hz). Vertical axis showed more sensitivity to higher frequencies than other axes. It was also concluded in the studies that vibration amplitude did not affect the comfort contours significantly and there were no differences between male and female.

It was found early on that human perception is non-linear depending on the frequency characteristics and amplitude of the vibration exposure. Oborne (1977) found that at lower intensity levels the higher frequency components (8-16 Hz) had more effect on comfort than lower components (0-4 Hz). However, when intensity increased to about 1.4 m/s^2 then lower frequency components became dominant factors for discomfort. This was a logical result as high intensity vibration at low frequencies induces motion sickness and hinders motor tasks such as reading.

The majority of the reviewed studies were concerned with human perception to different frequencies and amplitudes. Only few studies validating different averaging methods were found (Fothergill and Griffin 1977, Griffin and Whitham 1976, Parsons and Griffin 1983). The studies found that sinusoidal frequencies and random vibration can be effectively predicted using frequency weighting and r.m.s. (root mean square) averaging. Additionally the r.m.q. (root mean quad) method was suggested over the r.m.s. method if shocks or impulsive vibration was experienced (Griffin and Whitham 1980a, Griffin and Whitham 1980b). Griffin and Whitham (1977) showed that discomfort from multiple directions can be summed using r.s.s. (root-sum-of-squares) method, even though it was noted to be unreliable at least for some combinations of rotational and translational vibration (Parsons and Griffin 1978b). However the study case was limited. Parsons and Griffin (1983) applied the knowledge from the early laboratory studies to analyse correlation to discomfort by effects of different weightings and methods for combining axes. The conclusions showed that combining the axes will have better results than using the worst axis or worst frequency. The best correlation was found when using frequency weighted r.m.s. method and r.s.s. for combining the axes. However, little differences were found between the r.m.s. and r.m.q. methods.

The effect of duration of exposure on discomfort was also evaluated in the 1960’s and 1970’s by several authors (Griffin and Whitham 1976, Griffin and Whitham 1980b, Miwa and Yonekawa 1974). There was no clear evidence that relative discomfort changed when duration was increased (Griffin and Whitham 1976). However, the same authors later found that longer stimuli (up to 2 minutes) was more uncomfortable than shorter stimuli (Griffin and Whitham 1980b). Miwa and Yonekawa (1974) found a time dependency between vibration greatness level and exposure time. The effective range of exposure time was from 10 to 500 minutes. Griffin and Whitham (1980b) also found a fourth power relationship between duration and vibration magnitude to discomfort (doubling the amplitude required a 16-fold reduction in duration to maintain equivalence). The study used durations up to 32 seconds. However, no consistency and consensus regarding the time dependency was concluded in these studies (other than showing that a dependency most likely exists).

No publication regarding the validation of multiplying factors for combining several axes of vibration were found, which could be used to understand the factors presented in the standard (see Section 2.6 for explanation of the standards). However, the results from the aforementioned studies showed that the same vibration stimulus produced a different level of response depending on the axis and location. Thus, combining the responses of each axis requires a compensation factor to equalise the effect. The author assumes that this was the basis for the multiplying factors, even though this has not been stated in any known publication..

In addition to perception and comfort studies, biomechanical studies were undertaken to provide understanding of human behaviour under vibration (Mansfield 2005). Findings suggested that the human body has a main resonance (i.e. Eigen frequency) in the vertical axis around at 4-5 Hz. This was in the same area as perception and comfort studies concluded for being the most sensitive. The body's resonance behaviour in a seated posture in vertical axis was linked to the lumbar spine (Sandover 1988). The results for the horizontal axes (lateral and fore-and-aft) showed resonance frequencies in the area of 2-4 Hz.

Only one field study was found, which used all twelve axes and subjective judgments, for proposing and validating a new method based on the earlier studies (Parsons and Griffin 1983). The study used several cars in test track conditions to measure the twelve axes of vibration and a judgment from the subjects for twelve different road types. Most surfaces did not include high shocks, although a wide variety of different vibration characteristics was achieved. The subjects were driven individually for all tracks and cars. The subjects rated discomfort using a paper with a line labelled "little discomfort" and "much discomfort" on each end and marked a cross on the line to indicate discomfort, which was then converted to a number by measuring the distance of the cross from the start of the line. The study used weighting curves, which were created based on a laboratory study with the same subjects and tried several averaging methods (r.m.s., r.m.q. and maximum frequency level) and methods for combining the axes (r.s.s., r.s.q. (root-sum-of-quads) and worst axis).

The results showed that even though there was high variability between individual subjects, the trend was similar: 1) r.m.s. and r.m.q. methods were better for averaging vibration than using the maximum frequency level (no significant differences were found between the r.m.s. and r.m.q. methods), 2) r.s.s. and r.s.q. methods showed little differences, but were better than using the worst axis. The conclusion from the study was that in general the best overall method was to use the r.m.s. method to average individual axes and to combine them using the r.s.s. method. Additionally it was found that the seat vertical axis was the most dominant cause of discomfort. From the other axes fore-and-aft axes from the seat and backrest, and vertical axis from the floor had importance. Least important axes were the rotational axes and lateral axes from the floor. Despite high confidence of the results, the study was limited. The publication cannot be used direcly to assess the current standard method as it used frequency weightings, which were pre-standard versions and had no multiplying factors for the axes.

2.2.1.2 Laboratory studies and results validating the standard method

Equivalent comfort contours (i.e. weightings) in ISO 2631-1 (1997) (see Section 2.6.1) are based on an assumption that magnitude does not affect the relative weighting of frequencies. More recent studies have found that comfort contours are magnitude dependent (Ahn and Griffin 2008, Mansfield and Maeda 2005b, Morioka and Griffin 2006). Morioka and Griffin (2006) show consistency with the standard weightings, although at higher frequencies they show higher discomfort (Figure 10). More recent studies have found that the rate of increase in discomfort varies with the frequency and direction of vibration. For example, the rate of increase tends to be greater with low-frequency vibration than with high-frequency. It has been found that equivalent comfort contours depend on vibration magnitude, thus becoming less flat with increasing magnitude (Griffin 2007).

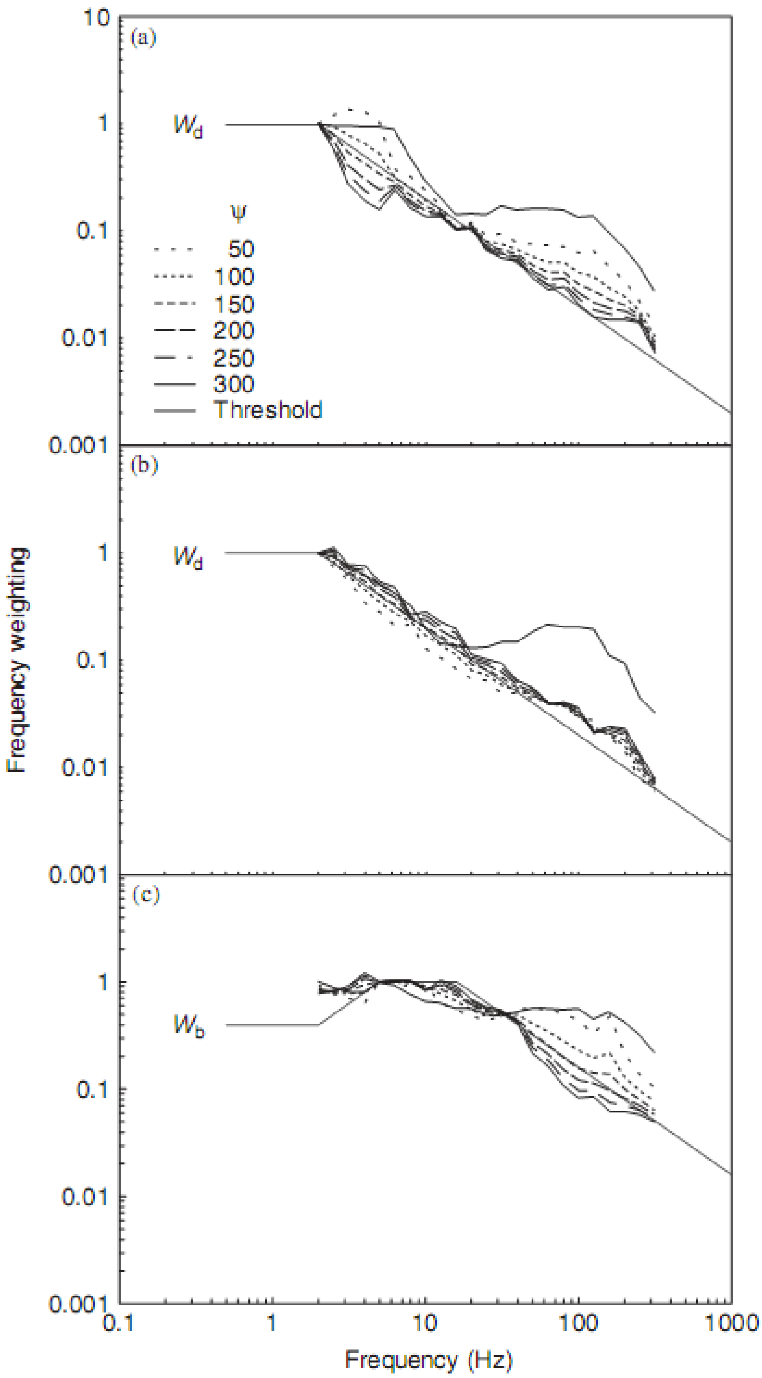

Figure 10. Comparison of BS 6841 standard weightings to newer findings. Effect of vibration magnitude on frequency weightings (inverted equivalent comfort contours normalised at 2Hz for fore-and-aft and lateral vibration and normalised at 5Hz for vertical vibration): (a) fore-and-aft, (b) lateral, (c) vertical. A sensation magnitude of 100 is equivalent to the discomfort produced by 1.0 m/s² rms (fore-and-aft and lateral vibration) or 0.5 m/s² rms (vertical vibration) at 20 Hz (Morioka and Griffin 2006).

It has been found that the horizontal frequency weighting (W_d) of the standard seems to underestimate the vibration effect compared to vertical direction (Maeda and Mansfield 2006b). The results from Maeda and Mansfield (2006b) showed that subjective responses had a same category value for all axes exposed to flat band stimuli from 1 to 20 Hz. When frequency weighting was applied the fore-and-aft and lateral axes showed smaller r.m.s. values, thus underestimating the response compared to the vertical axis. The authors concluded that a factor of 2.47 for the horizontal axes would equalise the difference. The results were in agreement with previous studies (Griefahn and Broede 1999, Mansfield and Maeda 2005a).

There have been also other studies for modelling human body, investigating standing and recumbent subjects, investigating combined effects of noise and vibration, and so on, but they can be regarded as out of the scope of the thesis.

2.2.1.3 Field studies and results validating the standard method

Most field studies, after the introduction of the standard, have only measured seat translational axes and not acquired judgments from the subjects, thus only partial validation can be made based on the results.

Alem et al. (2004) recommended not using the r.m.s. method at all for evaluating shocks or VDV for evaluating repeated shocks. Similar findings were concluded in other earlier studies as well (Griffin and Whitham 1980a, Kjellberg and Wikström 1985), which indicated that higher exponents than 2 would be better for evaluating shocks. Boileau et al. (1989) concluded that the r.m.s. method would underestimate the vibration when including shocks of high crest factors. These results were derived from measurements of forestry machines (skidders).

Wikström et al. (1991) showed that for most environments with shocks the r.m.s. method showed high correlation and no significant improvement was found using higher exponents (i.e. r.m.q.). The conclusion was that it was more important to consider to whole event instead of just evaluating the peak. The correlation for the r.m.s. method improved with longer duration of the window size (i.e. number of samples included in the calculation). Dose methods (i.e. VDV) were concluded for providing a good correlation as well, but if the compared events have similar durations, there is no advantage using the dose method. The study concluded also that worst axes showed higher correlation than the r.s.s. of the axes. However, the summation and weighting of axes was based on equal multiplying factors. Wikström et al. (1991) also noted that the proposed standard weighting curve gave worse correlation than using a flat weighting. They tested higher cut-off frequency (from 2 Hz to 4 Hz) and concluded improved correlations. Even though they used only seat axes, they found no justification for including all twelve axes.

Els (2005) used a military vehicle to expose subjects to high vibration magnitudes having also high emphasis on roll motions. He showed that the vertical axis had highest correlation using any method (e.g. weighted and unweighted r.m.s., VDV, VDI 2057 and Averaged Absorbed Power). Pitch and roll axes were experienced as translational axes, in this case vertical. The conclusion also was that there was no difference between the r.m.s. and VDV methods. The unweighted r.m.s. value showed similar results as the weighted r.m.s. value, which was assumed to be linked to the suspension system, which attenuates higher frequencies.

Mehta and Tewari (2000) reviewed several papers relating to seating discomfort for tractor operators. They concluded that no exclusive model or results were found to support any single method. Fairley (1995) concluded that the best procedure for predicting discomfort from vibration was that recommended by earlier ISO 2631 standard (1978). In this case the r.s.s. of the frequency weighted r.m.s. values showed best correlation. Monsees et al. (1988) found that the r.m.q. method had no advantage over r.m.s. method for predicting discomfort of tractor vibrations.

The results from the studies are summarised in Table 3. In overall the r.m.s. and r.m.q. methods were found to be the best for averaging the axes. Additionally VDV was suggested, but it is similar to the r.m.q. method. The r.s.s. method for combining the axes was found to be much better than just using the most severe axis, even though some conflicting results were found.

Table 3. Summary of field studies regarding suggested methods for manipulating vibration measurements to predict discomfort (including studies before and after the standard).

Author(s)	Study description	Metrics tested	Conclusions
Griffin and Whitham (1977)	To assess discomfort from dual-axis whole-body vibration	The most severe axis, the concept of masking and the r.m.s. of the equivalent levels of both axes	It is recommended to use the r.s.s. method to combine axes for practical purposes, but other methods should be further investigated
Parsons and Griffin (1978b)	To study the effect of position of the axis of rotation to discomfort for roll and pitch axes	The most severe component, the r.m.s. of the equivalent levels of the single-axis components and the arithmetic sum of the equivalent levels of the single-axis components	The most severe component method gives the closest results, but no significant differences were found compared to the r.m.s. method
Griffin and Whitham (1980a)	To study discomfort produced by impulsive whole-body vibration	The r.m.s. and r.m.q. methods	The r.m.q. method is suggested if vibration contains shocks or impulsive vibration
Griffin and Whitham (1980b)	To study time-depency of whole-body vibration discomfort	The r.m.s. and r.m.q. methods	The r.m.q. method is suggested if vibration contains shocks or impulsive vibration
Parsons and Griffin (1983)	Field study, which recorded 12 axes and subjects' judgments	r.m.s. and r.m.q. methods, and maximum frequency for averaging axes and r.s.s., r.s.q. and worst axis to combine axes	r.m.s. to average each axis and r.s.s. to combine axes were found the best combination
Monsees et al. (1988)	To study relationship between subjective assessment and objective measurements of tractor ride	The r.m.s. and r.m.q. methods	The r.m.q. method had no advantage over the r.m.s. method in tractor vibration
Boileau et al. (1989)	To study and to compare the results of the r.m.q. method to ISO 2631	The r.m.s, r.m.q and VDV methods	The r.m.s. method provides systematically lower values with vibration including shocks compared to the r.m.q. method
Wikström et al. (1991)	To compare different methods to evaluate mechanical shocks	Several variations of the r.m.s. and vibration dose methods (i.e. exponent values from 2 to 10)	The r.m.s. method was found to correlate best, but no large differences to r.m.q. or VDV (exponents 2 and 4) were found
Fairley (1995)	To study discomfort caused by tractor vibration	Several methods and variations (in total of 20) from different standard versions of ISO 2631, AFNOR, BSI, and INRS	The ISO 2631 standard from 1978 was concluded to have the best method: r.m.s. averaging for all seat translational axes and r.s.s. for combining the axes
Mehta and Tewari (2000)	A review of several studies relating to seating discomfort for tractor operators	Several methods used to the other studies	No exclusive or single model was found to be better than others
Alem et al. (2004)	To developed and compare new methodogy for assessing repeated shocks	The r.m.s, VDV and jolt (later called ISO 2631-5) methods	1) The r.m.s. or VDV methods are not recommended for assessing repeated shocks, 2) a new method (ISO 2631-5) was proposed and found better
Els (2005)	To compare different ride comfort methods in practice using military vehicle	All methods from ISO 2631-1, BS 6841, AAP and VDI 2057 (see later Sections for details)	1) The vertical seat axis gave only reliable prediction to discomfort, 2) no differences were found between the standard methods

2.2.1.4 Issues relating to the understanding of discomfort effects from whole-body vibration exposure

The perception and comfort studies, which are the basis for our current knowledge, were made using a single-axis or dual-axis vibrator and using single frequency (sinusoidal) signals at any time (Hacaambwa and Giacomin 2007, Maeda 2005). The assumption was that the effects of individual axes can be combined using linear methods. This assumption has not been conclusively proven, thus more research needs to be done to confirm the effects in a multi-axis environment (Holmlund and Lundström 2001). There are also other problems relating to the methods. Maeda (2005) has made a comprehensive list of necessary research still needed in comfort research. He points out the limitations and lack of verification of the current ISO 2631-1 standard and its subjective methods and values. Maeda (2005) shows that there is much more research needed to be done in the subjective scaling area of vibration exposure. There are other methods for determining subjective comfort, which have not been studied largely. Also the research has concentrated on the vertical axis in a seated posture and discrete frequencies. Despite the stated lack of knowledge, the studies done over twenty years ago are still the most informative and conclusive with respect to whole-body vibration comfort and perception.

No clear link between discomfort and duration of exposure has been found. Early studies did not find a consensus of a model for evaluating time dependency for vibration exposure. There are recent studies on time dependency, which have found it to be more complex and dependent on frequency and amplitude (Griffin 2007). It is logical to assume some form of time dependency where discomfort will increase as a function of time. However, no conclusive results have been produced or a model to estimate it (Griffin 2007).

The standard method suggests combining axes up to twelve axes, but there are no validated references for deciding which axes to use (see Section 2.2.1.4). Only two references for 12-axis measurements were found (Griffin 1990, Maeda 2004). The references showed weighted r.m.s. values for number of machines for all twelve axes. However, these two references are not enough to conclude the need for measuring the additional axes, thus more environments should be evaluated.

It is not yet clear how shocks contribute to the overall opinion, although it can be hypothesised to have a significant effect. Sudden large shock in the vibration is known to cause more discomfort, but this varies a lot depending on the control group's gender and age. There have been studies evaluating best methods for shock type vibration (Alem, et al 2004, Boileau, et al 1989, Els 2005, Griffin 1998, Lewis and Griffin 1998, Wikstroem, et al 1991), but no clear conclusions of the best overall method is given.

Other characteristics of vibration have been also been investigated, but they have proven to be more difficult than the amplitude (e.g. gender). Women tend to perceive the vibration as more unpleasant than men (Griffin 1990), although in earlier studies no statistical differences were found between the comfort contours (Griffin, et al 1982). However differences have been found in frequency responses between different body weights and between men and women (Kumar 1992). This could give a reason to hypothesise that body characteristics have an influence on vibration discomfort, thus women and men should have different opinions (Griffin, et al 1982). This has been concluded by later studies as well (Mansfield, et al 2001). When the vibration comfort is evaluated several variables can affect the results (example amplitude, duration, frequency components, sound, temperature, age, gender, personality, etc). This means that it is difficult to precisely evaluate the discomfort for an individual, but some statistical estimates can be given if enough information is available.

Rarely is vibration the only source of discomfort. In practice a human will be exposed to several factors simultaneously and discomfort is a combination of all the factors. There is little knowledge on multi-factorial effects on comfort (Kolich 2008). Most likely the dominant factor will be the basis for the opinion, but the relationship of a factor to discomfort in this type of environment is hard to evaluate. Most studies have been conducted in a laboratory, where other factors have been minimised. This might give a wrong indication of the effects of example vibration to discomfort if noise is also present. There are few studies that have addressed this issue (Fleming and Griffin 1975, Sato, et al 2007).

2.2.2 Health

When the human body is exposed to vibration the body reacts to it negatively (Pope, et al 2002). The effects can be partly controlled by using the body's muscles and postural adaptation, like in skiing or riding a snow mobile. However, the human body is not evolved for accepting vibration exposure and in the long run the vibration can cause health problems (Bovenzi, et al 2002). If posture is not optimal (e.g. back twisted) the harmful effects of vibration are amplified (Wilder and Pope 1996). Other factors that might advance the harmful effect are lifestyle habits (i.e. smoking, obesity), body's measurements (height, weight), duration of exposure (Mansfield 2005, Teschke, et al

1999), although there are inconsistent results of linking these factors to back pain (Hostens, et al 2004, Hoy, et al 2005). The current understanding is that a moderate vibration exposure alone is not unhealthy, but it becomes harmful if added with other negative factors or if there is already a problem with the back.

2.2.2.1 Low back pain

It has been long known that vibration exposure has a link to health problems, most particularly to low back pain (LBP) (Palmer, et al 2000). This has been concluded based on epidemiological studies (Bovenzi and Hulshof 1998, Seidel and Heide 1986), field studies (Mansfield 2003, Paddan and Griffin 2002b), medical reports (Pope, et al 2002) and ergonomic studies (Cole and Grimshaw 2003, Hoy, et al 2005). LBP is one of the most common work related health problems in the world and causes billions of Euros worth of costs to countries and companies (Deprez, et al 2005, Hostens 2004). There is a consensus between researchers that many back pain cases are related to vibration exposure either directly or indirectly (European Comission 2007).

LBP has been studied a lot in the recent years (Bovenzi and Betta 1994, Bovenzi, et al 2002, Bovenzi, et al 2006, Hostens, et al 2004, Lings and Leboeuf-Yde 1998). Many epidemiological studies have concluded a link between the vibration characteristics and exposure period and subject characteristics to the prelevance of back pain. Studies have been normally cross sectional or questionnaires either in a smaller community (e.g. harbour workers; agricultural workers) (Bovenzi, et al 2002) or country wide (Rehn, et al 2005a). Literature reviews have gathered results and conclusions of these studies to find any similarities (Lings and Leboeuf-Yde 1998, Seidel and Heide 1986, Shoenberger RW 1984, Stayner 2001, Teschke, et al 1999).

Based on the studies it has been suggested that some LBP cases are caused by vibration exposure (Bovenzi and Hulshof 1998, Seidel and Heide 1986). Numerous back disorders can be involved, such as sciatica, lumbago, general back pain, intervertebal disc herniation and degeneration (Pelmear and Leong 2002). Seidel and Heide (1986) concluded based on the large health data that whole-body vibration has an effect increasing the health risk. If heavy lifting is additionally involved in the work period, then there is even greater risk of back pain injury. Dose period seems to have an effect as well as certain frequencies and amplitudes. Although LBP and vibration has not been clinically linked together it is a statistical fact that LBP is associated with high level vibration exposure.

Bovenzi et al (2006) conducted a large study with almost 600 Italian workers to investigate prelevance of LBP in professions with whole-body vibration exposure. The study recorded detailed personal and work related data from the workers using questionnaires and measured several machines and work environments. The study found that occupations with whole-body vibration exposure were significantly associated with occurance of LBP. It also found that number of work years correlate with prelevance of LBP.

2.2.2.2 Other effects

Back pain is not the only vibration-related health problem. Research has been completed on other health effects of vibration (Griffin 1990, Ishitake, et al 2002, Rehn, et al 2004, Seidel and Heide 1986, Shoenberger RW 1979, Sommerich, et al 1993). The effects can be for example digestive disorders, hearing damage, neck pain (Magnusson and Pope 1998). The neck and shoulders have been considered in some studies (Rehn, et al 2002, Rehn, et al 2005a), although no definite relation has been proven or systematic conclusions produced. Vibration has also an effect on internal organs, for an example to gastric motility. A study (Ishitake, et al 2002) showed that vibration exposure, especially at low frequencies, has, even at short term, an effect to gastric motility. Even though the effect might not be strong for healthy persons, it shows that internal organs are sensitive to vibration, especially at their resonance frequency. Other problems might be sciatica, genitourinary problems and hearing damage (Griffin 1990). Vibration might cause changes also to heart-rate and respiration, however there are not enough studies for any firm conclusions. Based on the findings it can be speculated that a part of the comfort feeling can be produced from the body’s reaction. This hypothesis has not yet been proven.

2.2.2.3 Issues relating to the understanding of health effects from whole-body vibration exposure

Epidemiological studies are based on questionnaires and statistics. In vibration exposure the goal has been to evaluate the statistical factor of vibration causing LBP. The publications have made cross-sectional studies with other factors and tried to determine the percentage that vibration exposure might have caused (Rehn, et al 2002). Only few studies have focussed on the effect of dose period to the prelevance of back pain (Hostens, et al 2004). Because symptoms might not occur immediately, the vibration will cause problems in the long run, which in worst case scenario might be irreversible (Hulshof, et al 2002). It is not clear how exposure duration is linked to the health problems, but it is logical that longer durations increase the likeliness of the problems (Bovenzi, et al 2006). This is also the basis for the standardised methods, which have a time factor linked to the exposure value (ISO 2631-1 1997).

The epidemiological studies have had tens of thousands of people participating in the studies, but in critical reviews of the publications lots of problems have been found with the data and study procedure, thus not all publications have been found as good quality (Seidel and Heide 1986). The large number of studies has been unable to show that the vibration exposure and LBP is conclusively connected. Also there is not enough evidence of effect of the vibration exposure duration and LBP (Seidel and Heide 1986, Teschke, et al 1999). It is very hard to separate LBP caused by the vibration and other factors such as, lifting, ergonomics, lifestyle habits, weight, body structure (Griffin 1990, Teschke, et al 1999).

2.2.3 Motion sickness

Although motion sickness is related to discomfort and perception, the cause of it is outside the scope of this thesis. Motion sickness is believed to be produced by the conflict of body’s different sensory systems and has specific symptoms, like nausea (Mansfield 2005). The motion sickness is separated from health and comfort effects by its limited frequency range (0 to 0.5 Hz) (ISO 2631-1 1997). There are many variations of motion sickness, such as sea sickness, car sickness, etc, but the basis for all these variations are believed to be the same.

2.2.4 Summary

It has been shown that frequency, amplitude, location and duration of exposure have an effect on the comfort and perception of vibration. The equivalent comfort contours have been shown by many studies to have similar pattern, where lower frequencies should be emphasised. Discomfort is formed based on a combination of axes where vibration is present. It has been shown that axes should be combined for better correlation (Parsons and Griffin 1983). However, it was found that little research has been made since the introduction of the standard method to validate and improve the found results.

Similar to discomfort, several results for health effects have been concluded. It is strongly believed that vibration exposure can cause health problems in the long run (most commonly low back pain). Many studies have shown results implying this, but still there is no proven model to predict and assess health risks from the whole-body vibration. The position of the lumbar spine is very important for preventing back problems, thus ergonomics greatly influence the prevalence of the back pain (Hoy, et al 2005). This and other factors, such as lifting, make it extremely difficult to separate the effects from vibration exposure in health problems.

Even though a large number of studies have been conducted in this research area since the 1930's, there are still many issues that are not yet understood. Only a relatively small number of studies have contributed to the understanding of the effects. There have been few studies which have tested the ISO 2631-1 (1997) method in a multi-axis environment and even fewer which have used field-like stimuli. Additionally it has been rare that other than seat translational axes have been measured from work machines, even though it is not clear how the additional axes will contribute to a human's perception.

Whole-body vibration research has focussed generally on evaluation of health effects. Although health is usually the primary concern, the knowledge behind it is based mainly on comfort and perception studies. The hypothesis has been that human perception is linked to the body's "health" response. This has been also reinforced by human biomechanical studies, which have shown resonance frequencies in the same areas as human perception are the strongest and most clearly in the vertical direction (Mansfield and Maeda 2005b, Nawayseh and Griffin 2003). The knowledge behind the current health evaluation method (ISO 2631-1 1997) is based mainly on studies of human perception and comfort (Griffin, et al 1982, Parsons and Griffin 1978a, Parsons, et al 1978, Parsons and Griffin 1980, Parsons and Griffin 1982, Parsons, et al 1982). Earlier studies tested the perception thresholds of several persons to different frequencies and amplitudes. The results from those studies have formed the basis of the methods in use today for assessing health and comfort effects.

2.3 Methods for understanding the effects from vibration exposure

Before a method to evaluate health or discomfort can be developed, studies need to be conducted to find characteristics of vibration that cause the effects. This can be done by either asking subjects how they perceive vibration (i.e. subjective evaluation) or by measuring human body's dynamic response (i.e. biomechanical evaluation).

Methods for finding how humans react to vibration over a specific frequency range have been conducted since the 1930's (Oborne 1977). Most of the earlier studies used a sinusoidal stimulus (e.g. 3 Hz) and asked subjects to adjust the stimulus until they considered it to be "comfortable" or "perceptible". More recent studies have also used different methods, but are still based on laboratory environments and sinusoidal or flat spectrum stimuli (Maeda 2005).

Because of limited possibilities to directly measure physical effects from vibration on the human body, subjective methods have been mainly used for understanding both health and discomfort (Mansfield 2005). Perception and sensitivity to certain vibration characteristics indicate how humans sense different frequencies of vibration. Even though biomechanical studies can give a good indication of dynamic responses of body parts, which can be linked to most harmful vibrations, it does not improve the understanding of the psychological effects of vibration (e.g. threshold studies can find out the lowest levels of vibration at each frequency, which human can detect). It is also practically impossible (and unethical) to study how long exposure or high amplitude will cause permanent damage to the human body. The more ethical approach is to use the subjective methods.

There are various experimental methods used for comfort and perception research (Figure 11). The purpose of using the methods is to improve understanding on how the vibration characteristics link to the subjective feeling. This includes also developing a scale that can be used to evaluate comfort feeling based on the vibration measurements. One example of a comfort scale is presented in Annex C of the standard (ISO 2631-1 1997) (see Table 6).

The psychophysical methods used for vibration related issues can be divided into two categories: 1) constant measurement and 2) subjective scaling method (Maeda 2005). The constant measurement method has been used mainly for concluding the threshold of a human sense to characteristics of the vibration. The method uses a pre-determined scale for linking the subjective results. The subjective scaling method on the other hand has been used to find out the subjective scaling compared to the measured vibration value and it includes creation of a scale (Maeda 2005). Because the methods have a different approach they also will have different results. It is thus important to select the right method for the purpose.

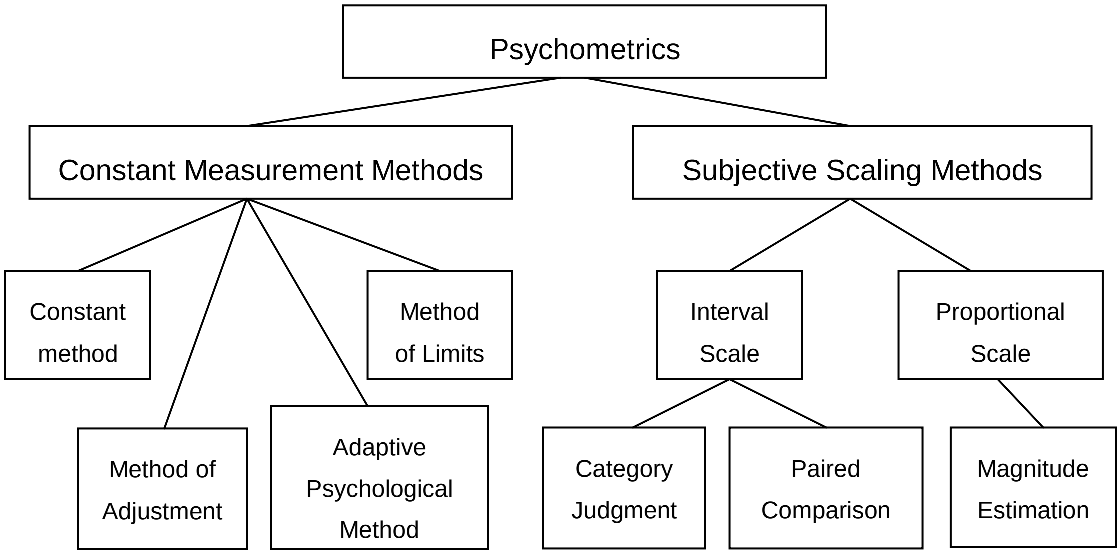

Figure 11. Examples of psychophysical methods for studying comfort and perception from vibration exposure (adapted from Maeda (2005)).

2.3.1 Constant measurement methods

It is advantageous to know the lowest levels of vibration that can be perceived at different frequencies, postures, locations and axes. Many studies have used this type of method in research (Fothergill 1972, Fothergill and Griffin 1977, Jones and Saunders 1974, Maeda 2005, Oborne and Clarke 1974).

2.3.1.1 Constant method

Where stimulus pairs presented by preliminary experiment are presented several times in random order (Havelock, et al 2008). Subjects are asked to judge each pair. The method takes a relatively long time as many pairs need to be judged.

2.3.1.2 Method of limits

A stimulus is presented by varying the stimulus parameters (i.e. frequency or amplitude) in a fixed step from low to high (Havelock, et al 2008). Subjects will compare stimulus pairs and judge which stimulus is lower and higher. The procedure is predetermined by the measurer.

2.3.1.3 Method of adjustment

Method of adjustment has been popular for finding out the vibration thresholds (Maeda 2005). The method can be described as: "*where subject adjusts the level of a standard* *frequency of vibration to have an equal subjective magnitude of another vibration*" – Kuwano, S. (Handbook of Signal Processing in Acoustics). This technique can be used to produce comfort contours in term of equivalent comfort.

2.3.1.4 Adaptive psychological method

Differing from aforementioned methods, in this method stimulus is changed depending on how subjects react to it (Havelock, et al 2008). It will require a computer to conduct the measurements and activity from the measurer. There are several methods of adaptive procedure (e.g. "up and down method").

2.3.2 Subjective scaling methods

Subjective scaling methods can be further divided to interval and proportional scale methods. The aim is to find subjective scaling to subjectively perceived quantity (Maeda 2005).

2.3.2.1 Magnitude estimation method

The Magnitude Estimation (ME) method is a scaling method for obtaining proportional scale of vibration. The method has been proposed by Stevens (1957). It can be suitable for determining if evaluation index corresponds to the subjectively perceived quantity. The goal is to link psychophysical magnitude of stimulus to a physical magnitude. Exponent n is found using test subjects and a seat cushion with specific stiffness. The method can be formulated as:

$$\psi = k\phi^{n} \tag{1}$$

Where ψ is psychophysical magnitude of a stimulus, ϕ is physical magnitude of a stimulus and *k* is constant and *n* is the growth of sensation exponent.

The method includes assessing a stimulus to a reference stimulus and judging the relative effect by giving a number relative to the reference stimulus. Normally a fixed reference stimulus is used (e.g. 5 Hz and 1 m/s^2 r.m.s.) and it is assigned as "100". Figure 12 shown previously by Morioka and Griffin (2006) shows results using the ME method.

Improvements to ME method has been proposed by Howarth and Griffin (1988). The model takes into account both static and dynamic properties:

$$\psi = a + b{\phi_s}^{n_s} + c{\phi_v}^{n_v} \tag{2}$$

Where ψ is psychophysical magnitude of a stimulus, *a, b* and *c* are constants, ϕ_s and ϕ_v are seat stiffness and vibration magnitude, and n_s and n_v are exponents determined by the rate of increase in discomfort associated with the stiffness and vibration magnitude.

Ebe and Griffin have used it for determining overall seat discomfort (Ebe and Griffin 2000b). At low vibration magnitudes the static properties of the seat dominate the comfort, but when magnitudes are increased the effect of dynamic properties have more influence (Figure 12).

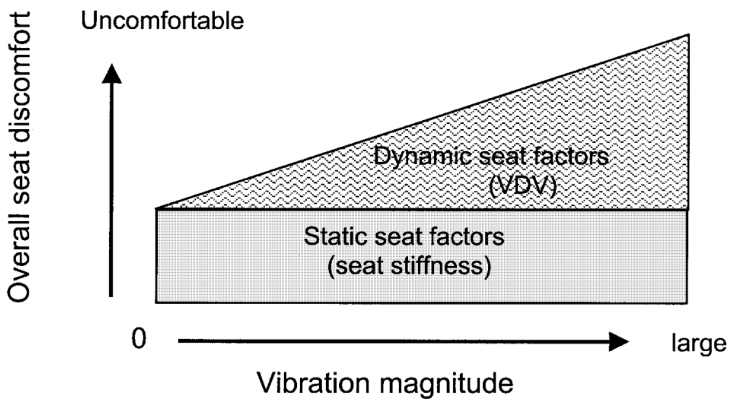

Figure 12. Ebe's model for predicting seat discomfort using static and dynamic properties (Ebe and Griffin 2000a).

Ebe's model did not include a time factor, which can be assumed to have an effect. Later Mansfield (2005) proposed an improved model, where also time was included (Figure 13). The equation is improved by including temporal factors:

$$\psi = s_s + f_t t + d_v a + i_{tv} ta \qquad (3)$$

Where ψ is the rating of discomfort, s_s is the static discomfort constant, f_t is a fatigue constant, d_v is the vibration discomfort constant, i_{tv} is an interaction variable, t is the time (mins) and a is the r.s.s. acceleration (Mansfield, et al 2007).

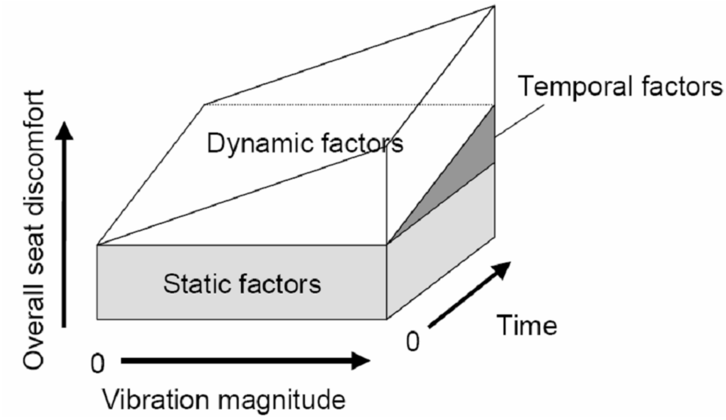

Figure 13. Improved model for predicting seat discomfort using static, dynamic and temporal factors (Mansfield 2005).

2.3.2.2 Difference threshold

The difference threshold is a method for obtaining the amplitude of two vibrations that can be just perceived as different. The importance in knowing the human perception for changes is that the improvement done for an example to car suspension is enough to be noticed as improved ride comfort. Usually, difference thresholds are determined using the UD (The Up-and-Down) method or the UDTR (The Up-and-Down Transformed Response) method.

2.3.2.3 Paired comparison method

In this method chosen stimuli are presented to the subjects as pairs and the subject will select a better one. Each combination of stimuli is paired and a matrix of proportion of time when one stimulus is preferred over another is created. The ranking of stimuli is calculated based on the matrix (Oborne 1978b).

2.3.2.4 Category judgment method

The category judgment method (Guilford 1954) seems to be good for linking a subjective phrase or word to the vibration characteristics (Maeda, et al 2008). The method implies that a reaction to a stimulus forms a normal distribution on a psychological continuity. The procedure for creating a scale starts with test subjects evaluating different stimuli using a pre-determined scale of phrases from “not uncomfortable” to “very uncomfortable”. The results are then summarised in a table by the categories representing the phrases and different stimuli. Each phrase represents a number scale from 1 to 5 so each stimulus will have a distribution of subjective responses. The table is converted to a relative frequency table, which is then converted to a normal distribution for each stimulus. The normal distribution results are then used to produce an average scale for each stimulus. Kaneko et al. (2005) have explained this procedure in their study.

2.3.2.5 Borg scale

The Borg scale has been used in some occasions as it combines ease-of-use of a category scale with the analytical flexibility inherent in numbers reported using a ratio scale. It has been widely used for fields of psychology, physiology and ergonomics to rate sensation of pain, fatigue and discomfort (Hacaambwa and Giacomin 2007).

2.3.2.6 Continuous judgment method

The continuous judgment method allows test subjects to evaluate feelings in real-time and the judgments can be correlated to the stimuli by averaging values in different time windows. The method has been developed for evaluating continuous impressions of sounds which vary over time (Kuwano and Namba 1985, Namba and Kuwano 1988, Namba and Kuwano 1979). The are several variations of the continuous judgment method: 1) by category, 2) by line length and 3) by selected descriptions.

Continuous judgment by category involves a predetermined category (e.g. “loud”, “very loud”). Subject will judge sounds by notifying the feeling continuously relating to any category. There is no need to notify feeling unless it changes. Normally a keyboard or buttons with the categories are used to allow easy way of judging.

Continuous judgment by line length allows subjects to express more subtle changes that could be too small to represent using predetermined categories. Thus cross-modal matching of sounds to line length can be analysed. There needs to be no fixed scaling or numeral for the line length and only the extremes are noted to the subjects (e.g. “no discomfort” and “high discomfort”).

Continuous judgment by selected description can be used to evaluate multi-dimensional impressions. This includes a list of adjectives which describes the stimuli. Example in sound studies the adjectives could be “beautiful”, “loud”, “soothing” and so on.

The continuous judgment method is developed for judging long term stimuli using instantaneous judgments in situations similar to everyday life. One of the merits of the method is that results can be easily stored in a computer for analysis in various viewpoints later. There is an inherent lag between reaction and stimulus. There has been studies investigating the reaction time for sounds (Kuwano and Namba 1985). It was concluded that an average 2.5 second delay was found. Even though the method has not been extensively used for evaluating discomfort from vibration, it can be assumed to work similarly as in the sound research. This is because the method was developed to understand subjective judgments of humans, not particularly noise characteristics, thus can be used basically with any factor.

2.3.3 Discussion of the methods

Each method can provide results and conclusions in its own limited scope. If only one type of method is used, then the results will be impossible to validate outside the scope of the research. For example the current subjective assessment table in the standard is based only on one method, thus it is difficult to evaluate the scope of the table for predicting discomfort in practice. Each method also has specific assumptions and procedures to be used correctly, thus not all methods can be used for example in field. Some methods have been criticised as biased (e.g. method of limits), while others have not been rarely used, thus does not have high confidence levels (i.e. vibration greatness) (Havelock, et al 2008).

The ME method has been most popular for finding comfort contours and correlation to discomfort. However, it has been also criticised (Hacaambwa and Giacomin 2007). The method requires a reference stimulus for comparison and the selection of the reference stimulus will affect the results. It is most practical to use reference stimulus before each studied stimulus, so that subjects will have short time duration between the stimuli thus still remembering the reference. Normally the stimuli have been short (i.e. few seconds) and sinusoidal or random flat band. The method also assumes that if a subject doubles the judgment number relative to the reference stimulus, then discomfort is also doubled. There are studies using the method in the field (Fairley 1995). In the field, the first object has normally been the reference stimulus and the rest of the objects are the studied stimuli. In this case the subject might have hard time of remembering anymore the reference stimulus. In an environment where there is no fixed reference stimulus available (i.e. in real life) the method is hard to use.

Only a few studies have used the category judgment method. Maeda et al. (1983) used it for producing a scale to evaluate localised vibration transmitted to hand and arm and Sumitomo et al. (1998) for identifying changes of subjectively perceived values of vibration of passengers of Shinkansen bullet trains before and after Kobe Earthquake of 1995. Kaneko et al. (2005) did a study of linking different vibration exposures of different frequency content to a subjective scale (Figure 14). The results showed that the scale was different for the same r.m.s. vibration level when the frequency content was different. The figure also shows the overlapping of ISO 2631-1 scale. The opinion of the authors was that using the category judgment method the subjective evaluation of vibration and physical value could be clarified. This can be true, but the method and the results show that different scales should be created for different vibration exposures.

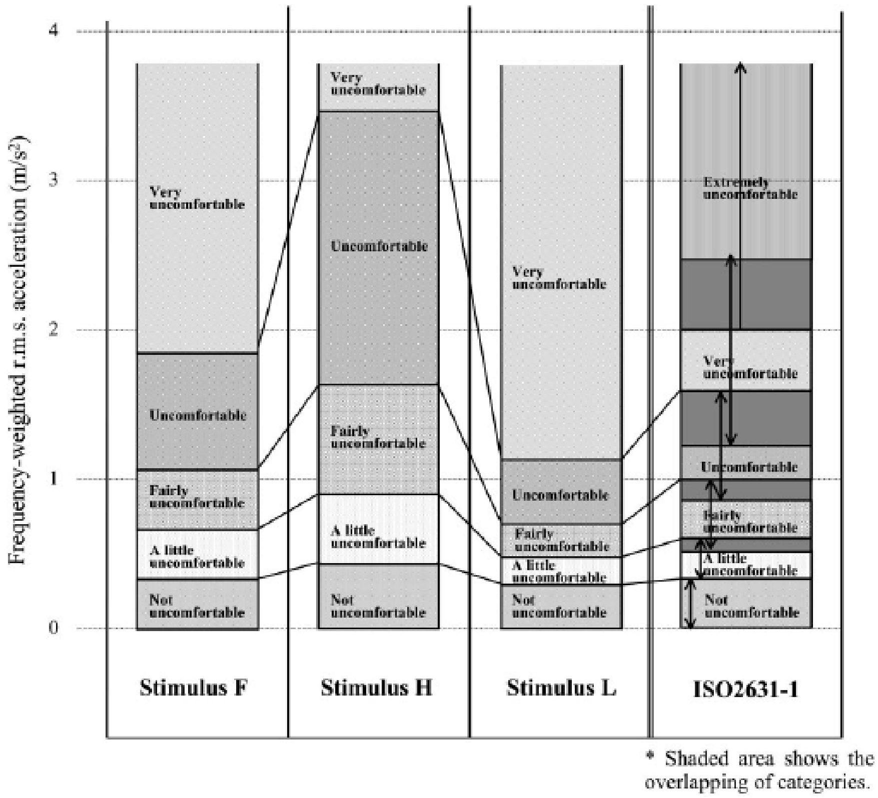

Figure 14. The difference of subjective scales compared to ISO 2631-1 scale and using category judgment method (Kaneko, et al 2005).

The continuous judgment method has been used in many studies regarding noise annoyance (Kuwano and Namba 1980, Kuwano and Namba 1985, Namba and Kuwano 1980, Namba and Kuwano 1982, Namba and Kuwano 1988, Namba and Kuwano 1979). However there are no references for using the method relating to vibration. Based on the information on the method, it seems suitable for field and evaluating discomfort of long exposure. It can be used to evaluate instantaneous discomfort for an undetermined stimulus. Because of lack of studies in vibration, it needs a validation study before it can be used.

Other methods have been also used, which were not discussed in this review. For example Oborne (1977) used a paper with a line drawn and subjects evaluated discomfort by marking a cross in the line. No specific category or scaling was given, thus the distance of the mark from the beginning of the line was used to form a number corresponding to discomfort. This type of approach has been popular in field studies.

In addition to selecting methods it is important to understand the role of the subjects. Already in 1976 a criticism of the study approaches for finding the effect of vibration on subjects was discussed (Oborne 1976). Many studies have been conducted only in laboratory and using students or staff, not “fare paying” customers. Test subjects will expect certain vibration levels and know that they are in a test. Their expectations are different from real customers.

The usability of the methods to evaluate vibration related discomfort is more accurate in an environment where vibration is the dominant factor or where other factors have been minimised. In these environments it is possible to assume that vibration is the primary cause of discomfort. In other environments the usability of the methods are decreased as they tend not to include any other factors (e.g. noise) in the analysis. This is in effect a limitation of field trials.

2.3.4 Summary

Several methods exist for evaluating comfort and perception from vibration. The methods have been derived from psychology studies, thus will require some knowledge in that area. It is important to select a correct method when studying effects from vibration, as each method has its own merits, limitations and scope. It is thus equally important to validate the findings using different methods to improve the validity of the results. Several methods were evaluated, which gave an understanding of possibilities for evaluating discomfort in field environments. It can be concluded that only few methods can be considered for the approach chosen in this thesis.

2.4 Methods for evaluating the effects of vibration exposure

The principal measurement and analysis procedure for evaluating health and comfort from vibration exposure is described in the standard ISO 2631-1 (1997). It is based on several studies conducted on subjects in a laboratory. Also other methods exist, which can be used to evaluate effects, mainly relating to health (i.e. physical effects). Some methods can be used for discomfort evaluation as well, but beyond frequency weighted r.m.s. method in ISO 2631-1 there are no validations of their applicability to discomfort (Els 2005).

Four main methods exist for objectively evaluating ride comfort (Els 2005): 1) ISO 2631-1 (1997), 2) BS 6841 (1987), 3) VDI 2057 and 4) Average Absorbed Power (AAP), but also additional methods exist, which have been used for specific purposes regarding comfort and health (e.g. Jerk or Spinal response method in ISO 2631-5). Even though the methods used in this thesis are limited to ISO 2631-1 and BS 6841 standards, it is necessary to understand other methods and reasons for their existence. This gives insight to different aspects of the vibration effects.

Most methods are based on manipulating acceleration signal measured near or between the human body and a vibration platform. The purpose of signal manipulation is to emphasise frequencies and axes that are most harmful to a human body. Typically a single value is calculated, which can be compared to other environments and criteria determining the severity. There are some methods which are based on force input or calculating transient shocks from vibration.

2.4.1 ISO 2631-1 and BS 6841 methods

Two main methods exist for evaluating the effects from vibration: 1) frequency weighted r.m.s. and 2) frequency weighted vibration dose value (VDV). These are the most widely used methods for producing results from vibration measurements. Both methods use same filters (i.e. weighting curves) to process the acceleration data and multiplying factors for emphasising each axis. The difference is that the r.m.s. method has second power averaging while VDV uses fourth power without averaging duration. Thus VDV emphasises more shocks than the r.m.s. method. Additionally BS 6841 introduced a r.m.q. method, which is similar to the r.m.s. method, but using fourth power averaging. It is also comparable to the VDV value, if exposure duration is known, thus linking both the main methods.

The methods described here are from ISO 2631-1 (1997) and BS 6841 (1987) standards, which are discussed in more detailed in Section 2.6.

2.4.1.1 Root mean square (r.m.s.)

R.m.s. method is a statistical measure of the magnitude of a varying quantity. It is especially useful for calculating mean of values which are both positive and negative (e.g. acceleration signal), as the method weights each value as positive. R.m.s. is calculated as:

$$a_w(T) = \left(\frac{1}{T} \int_o^T a_w^{\ 2}(t)dt \right)^{\frac{1}{2}} \tag{4}$$

Where $a_w(t)$ is frequency weighted acceleration (m/s^2) at time t and T is time (s).

2.4.1.2 Root mean quad (r.m.q.)

R.m.q. is similar to the r.m.s. method, except each value is calculated to the fourth power, thus higher values are emphasised more (e.g. shocks in vibration):

$$a_w(T) = \left(\frac{1}{T} \int_o^T a_w^{\ 4}(t)dt \right)^{\frac{1}{4}} \tag{5}$$

Where $a_w(t)$ is frequency weighted acceleration (m/s^2) at time t and T is time (s).

2.4.1.3 Vibration dose value (VDV)

VDV is similar to r.m.q., but it includes a time dependency. VDV value is calculated from the frequency weighted acceleration data using the following equation:

$$VDV = \left(\int_o^T [a_w(t)]^4 dt \right)^{\frac{1}{4}} \tag{6}$$

Where a_w is frequency weighted r.m.q. value at time t and T is time of measurement period (s).

2.4.1.4 SEAT value

The SEAT value can be used to determine how well does a seat attenuate vibration from the floor. The SEAT value (%) is calculated by comparing frequency weighted r.m.s. (or VDV) values from the seat surface and floor and is supported by the standard method (ISO 10326):

$$SEAT = \frac{a_{wseat}}{a_{wfloor}} \cdot 100 \tag{7}$$

Where a_{wseat} and a_{wfloor} are frequency weighted r.m.s. values from floor and seat for each axis.

Even though some studies have used the SEAT value as a predictor for dynamic seat comfort (Van der Westhuizen and Van Niekerk 2006), it is designed and mainly used for evaluating characteristics of a seat damping. Paddan and Griffin (2002a) conducted a large study (100 vehicles) to evaluate the effectiveness of seating to minimise whole-body vibration. The results showed that in most machines the seating attenuated vibration, but could be even more improved with another seat. It is likely that a smaller SEAT value (i.e. better attenuating) can suggest also improved comfort, but it most likely cannot be used as a single predictor.

2.4.2 Other methods

2.4.2.1 Vibration greatness

Vibration greatness (VG) is a method derived from acoustics (Miwa and Yonekawa 1974). The basis of the method is to use either octave (i.e. simple method) or one-third octave (i.e. complex method) bands to produce a single value that corresponds to the loudness or to the loudness level of a given sound. Vibration greatness uses the same principle for evaluating the effect of vibration to humans as for loudness. Vibration greatness level (VGL) corresponds to the loudness level and vibration greatness (VG) corresponds to the loudness. First a subjective threshold values for the vibration has to be determined. This can be done, for example, using a paired comparison method where a test stimulus is compared to a fixed stimulus (e.g. sinusoidal vibration). Based on this procedure vibration acceleration level (VAL) of each band can be obtained. The VAL values can be turned into VG values using a pre-determined table. Example of a table can be seen at Miwa's publication (Miwa 1969). Now the VG_T value can be calculated using equations 8 or 9 depending on which method is used:

$$VG_T = VG_{M,1} + 0.3((\sum_i VG_{i,1}) - VG_{M,1}) \tag{8}$$

$$VG_T = VG_{M,1/3} + 0.13((\sum_i VG_{i,1/3}) - VG_{M,1/3}) \tag{9}$$

Where $VG_{M,1}$ is largest VG value of all VG_i and VG_i is a VG value of a frequency band. Suffix 1 and $^1/_3$ denotes the method used (octave or one-third octave). The VGL value can be obtained from VG_T again using a table. The VGL value can be used to estimate subjective response of a specific vibration stimulus.

2.4.2.2 Jerk

Jerk (symbol *j*) is a term for third derivate of position, which also has an influence on comfort (Speckhart and Harrison 1968). Jerk has been studied and used for vibration control and ride comfort evaluation of trains, elevators, robots, and so on. Jerk is important when evaluating the destructive effect of motion on a mechanism or the discomfort caused to passengers in a vehicle. The movement of sensitive equipment needs to be kept within specified limits of jerk as well as acceleration to avoid damage. When designing a train the engineers will typically be required to limit the level of Jerk, because of passenger comfort.

2.4.2.3 Spinal response method of ISO 2631-5 for evaluating effects on multiple shocks

A random vibration exposure, which is experienced in real work environments, includes transient shocks as well as other kinds of vibrations. Even though aforementioned standardised methods include all vibration characteristics in the analysis, they tend to undervalue the effects of multiple shocks as they average the vibration data. For this reason additional methods have been developed, which separately evaluate the effects of shocks.

An addition to the ISO 2631 standard series was produced, which analyses the effects of shocks to health (ISO 2631-5 2004). Although the method is not directed at comfort evaluation (only health), it shows that vibration effects can be assessed also using methods other than frequency weighting and time dependency. The ISO 2631-5 method could be a basis for an additional method to assess shocks and their relation to comfort.

The purpose of ISO 2631-5 is to define a method for analysing the effect of multiple shocks in relation to human health. The standard is based on a lumbar spine response, because it is believed to be affected by shocks the most. The standard addresses the human exposure to multiple shocks only when the human is seated.

To evaluate health effects the standard introduces static compressive stress value (Sed). Sed is calculated from the sixth power sum of acceleration dose values multiplied with dose coefficients. If Sed value is below 0.5 Mpa there is a low probability of adverse health effects at lifetime exposure. Above 0.8 Mpa there is high probability. Results between 0.5 and 0.8 Mpa indicate moderate health effects at lifetime exposure. There are separate procedures for horizontal and vertical directions in the standard. Horizontal directions are assumed to have a linear response.

2.4.2.4 VDI 2057

VDI 2057 is a German standard, which is used for quantifying ride comfort. The first version was published in 1963 (Els 2005). Since then it has become more similar to that of ISO 2631-1 series (1985 version), but has a *K*-factor for comparison of subjective sensations of humans. The acceleration time signal is converted to frequency domain and r.m.s. values are calculated for each 1/3 octave center frequencies. *K*-values are used for weighting each frequency:

$1 \le f \le 4Hz\ K_z = 10 \cdot a_z \cdot \sqrt{f}$, $4 \le f \le 8Hz\ K_z = 20 \cdot a_z$, $8 \le f \le 80Hz\ K_z = 160 \cdot a_z \cdot f$

Where f is the frequency, a_z is amplitude in m/s^2 for vertical direction and K_z is a weighting factor for each frequency. The values can be calculated only for vertical direction and for a seated person. The resultant plot is compared with limit curves like in ISO 2631-1 (1985).

2.4.2.5 Averaged Absorbed Power (AAP)

The AAP method was developed in 1960's by the US military (Els 2005). The absorbed power can be calculated as:

$$AP = \sum_{i=0}^{N} K_i \cdot (A_{irms})^2 \qquad (10)$$

Where AP is absorbed power, K_i is a weighting factor for i 1/3 octave frequency, N is number of frequencies, A_{irms} is the averaged power for 1/3 octave frequency.

2.4.3 Discussion of the methods

Even though several methods exist for evaluating health and discomfort, in practice the r.m.s. and VDV methods have been mostly used, and there is only adequate information on assessing discomfort using the r.m.s. method. The VDV method might be better if comparison of exposures of different durations are to be compared or shocks are involved. The r.m.q. method has similar effect, thus can be regarded as better option if direct comparison to the r.m.s. values is required.

In a study it was concluded that a SEAT value could be used as a reliable metric to select the best seat for each vibration characteristic (Van der Westhuizen and Van Niekerk 2006).

Also the VG method has been rarely used in whole-body vibration research. Miwa (Miwa 1969, Miwa 1967) used it to determine perceptional thresholds and equal sensation characteristics for random vibrations for vertical and horizontal directions. More recently Maeda has used the VG method and also has evaluated the usability of the method compared to other methods (Maeda 2005). He concluded that VG method works well for single-axis stationary vibration, but not for multi-axis environment.

Jerk is an important factor when elevator speed control or train vibration control is designed, and it is reasonable to assume that it might relate to whole-body vibration comfort. There are no systematic studies concerning jerk and whole-body vibration comfort and it has not been standardised.

ISO 2631-5 was produced based on the research carried out for the U.S. military (Alem, et al 2004). The basis of the research was that in 1980's there were already reports indicating health effects of vibration exposure in military vehicles, even though these vehicles passed existing whole-body vibration standards. There is no indication of whether ISO 2631-5 methods correlate with discomfort judgment.

Els (2005) has made a test for comparing four comfort evaluation methods (BS 6841, ISO 2631-1, VDI 2057 and AAP) using military vehicles. He also used unweighted r.m.s. values as comparison. The measurements were not conducted directly by the procedure of the standard (no backrest or feet measurements), but rotational directions were calculated. The results showed that all four methods exhibited some consistency in evaluating the comfort to vertical vibration, but not to other directions. The study had limited scope and implied that the other methods (VDI 2057 and AAP) did not provide any new insight, thus there is no motivation to use them.

2.4.4 Summary

There are methods for evaluating discomfort from vibration, but most of them have not been tested or validated in practice. This is also a problem with the r.m.s. method proposed by ISO 2631-1 standard, because only few studies since 1997 have tested the method (Maeda 2005). The biggest problem is that the knowledge in the standard is based on single-axis studies and it is a good probability that human behaves differently in a multi-axis environment (Holmlund and Lundström 2001).

2.5 Measuring vibration

Evaluation of the effects from whole-body vibration requires measurement of the vibration in the form of acceleration. Based on the standards the vibration is measured between a human body and a vibrating platform. In whole-body vibration this generally means a seated person with sensors between seat backrest, cushion and floor. There are guidelines for measurement periods as well as installation of the sensors. Different number of sensors might be required depending if health or discomfort is evaluated.

2.5.1 Requirements

There are three standards that define the technical requirements, analysis methods and installation procedure for whole-body vibration. ISO 2631-1 (1997) is the main standard for whole-body vibration. It defines the method and basic guidance for conducting the measurements and analysis. ISO 8041 (2005) defines the guidance to develop and test the equipment for conducting the measurements and ISO 10326 (1992) defines the installation of the seat sensor more specifically (ISO 10326 1992). However none of the standards define technical or installation specifications for realising 6-axis seat sensor, which is required for the full evaluation procedure.

The technical requirements for measuring the 12-axis vibration are: 1) a 6-axis seat sensor, 2) one 3-axis sensor each for backrest and floor, 3) a data acquisition system to record the sensor signals and 4) software to calculate and analyse the results. The 6-axis seat sensor is needed to record three translational (fore-and-aft, lateral and vertical) and three rotational (roll, pitch and yaw) directions. Three translational directions are recorded from the floor and backrest (Figure 2; 12-axis coordinate system). All of the twelve axes need to be analysed as acceleration (m/s^2 for translational and rad/s^2 for rotational directions). This means that either acceleration sensors are used or the recorded data needs to be converted to acceleration data (e.g. if inclinometers or force sensors are used).

There are no specific requirements for the data acquisition process, except that the accuracy and tolerance of the whole equipment must be within the requirements of the ISO 8041 standard. The sampling process and filtering for the frequency weighting can be realised in various ways. In practice 256 Hz sampling rate and sensor sensitivity of 0.01 m/s^2 are the minimum requirements.

Because the standards do not specify either mechanical or electrical characteristics or the detection method for the 6-axis sensor, it can be designed in various ways. However the selection of the sensor type and detection method is crucial for developing the whole equipment, because it also defines the other components and their requirements. Literature search revealed at least three different approaches to record all six directions:

- 3-axis acceleration sensor for translational directions (m/s^2) and 3 inclinometers for each rotational directions (inclination [degrees]);
- 3-axis acceleration sensor for translational directions (m/s^2) and 3 gyros for rotational directions (angular velocity rad/s);

- 3-axis acceleration sensor for translational directions (m/s^2) and 3 acceleration sensors for detecting rotational directions (rad/s^2).

One of the practical limitations for realising the 6-axis sensor is the physical size. The sensor needs to be thin enough to be sat on and small enough to fit under a person's buttocks. This limits the height and width to about 150 x 200 mm, and thickness to 20-25 mm. Another limitation is the frequency range. To measure whole-body vibration the sensors should allow analysis of frequencies between 0.5 to 80 Hz of acceleration. So if other than acceleration sensors are used the data needs to be converted to acceleration for example using derivation, which amplifies noise. For example inclinometers normally detect frequencies between 0 to 20 Hz, so they are a poor choice for whole-body vibration measurements. Gyros on the other hand detect higher frequencies, but are more expensive and complex components than accelerometers. No single 6-axis accelerometer component was yet commercially available in 2005. Recently (2009) integrated 6-axis sensors have been introduced, which are based on measuring translational axes using accelerometer and rotational axes using gyros. Their suitability for whole-body vibration is not any better than using a number of accelerometers.

2.5.2 Commercial equipment

Because there is no proper guidance in the standards, only a few have designed and tested a 12-axis measurement system and developed a 6-axis sensor pad (Whitham and Griffin 1977, Yamashita and Maeda 2003). An early seat pad design, called SIT-BAR, made twenty years before the current standard was tested by Whitham and Griffin (1977). The goal of the study was to assess a method measuring whole-body vibration on soft seats. In more recent publications, Yamashita and Maeda (2003) have developed equipment for 12-axis comfort measurements and analysis. Based on this development commercial equipment has been produced by IMV Co (Figure 15). Only ISVR at the University of Southampton and IMV Corporation has developed the equipment for 12-axis comfort measurements and analysis. Neither ISVR nor IMV Co. actively markets the equipment and in any case the cost would be tens of thousands of Euros. A more recent paper about six axis measurements of skidders reported a development of 6-DOF seat pad sensor (Cation, et al 2008), which was a prototype for research purpose.

Figure 15. Commercial 12-axis measurement equipment for discomfort evaluation by IMV Co (cropped from a product flyer).

It seems that the equipment sold under "whole-body vibration" have been designed for health analysis as they only include possibility to measure using one tri-axial sensor (i.e. seat pad). None of these equipment feature a possibility to measure 12-axis accelerations for comfort assessment.

2.5.3 Measurement procedure

Sensors are installed to seat surface, backrest and floor (Figure 16). The distance of the backrest sensor from the seat surface should be about half of the height of the backrest. A floor sensor should be as close as possible to feet and aligned with the seat and backrest sensors.

Figure 16. 12-axis measurement system installed on a bus seat according to standard guidance (Yamashita and Maeda 2003)*.*

There are no restrictive guidelines on how long to measure. It is suggested by ISO 2631-1 that measurement should be at least 108 seconds and multiple repeats should be made for improving statistical accuracy. All relevant information about the environment and installation should be documented, as well as the vehicle and seat information.

2.5.4 Variation relating to the measurement results

Normally vibration is measured in short duration (60 seconds to few minutes). One problem with short term measurements is that the variability might be high. This means that the measurements might not give statistically good values. Based on the short term measurements it is also hard to even quantify how much variability there is in certain work environments. Not much effort has been taken to quantify the variability of vibration exposure of work machines in work environments (Newell, et al 2006). It has been shown that some work machines tend to have different vibration levels even at the same work environment, because of changing circumstances (e.g. operator, speed, loads). Based on the current way of measuring it is difficult to evaluate the individual effects of vibration to a person in a period of time. One factor that has not been much discussed in the measurement publications is that the measurement setup has also psychological effects on the operators. This means that it is very hard not to disturb the operator in any way when conducting the measurements in a “real” work environment, because at the minimum the operator knows it is being measured. Newell et al.

(Newell, et al 2006) reported a suspicion that an operator in their study drove aggressively just because of the measurements. The author has also had a similar personal experience.

2.5.5 Summary

Although ISO 2631-1 describes the directions, locations, frequency weightings, multiplying factors and guidance to interpret the values of 12-axis measurements, it does not give adequate technical details or references on how to build the necessary sensor system. There is a reference only to the requirements of a 3-axis sensor pad for health evaluation and to the general technical specifications of the measurement equipment.

The availability of affordable and practical equipment is an essential part of research as especially comfort research will require many measurements to have any statistical meaning. If equipment is not available then other research areas are chosen, as is evident based on the literature research on comfort.

2.6 Standards and guidelines

Whole-body vibration measurement procedures and analysis methods have been standardised since the 1970's (Table 4). The most important and widely used standards have been ISO 2631-1 series (1974, 1985 and 1997) and the British standard BS 6841 (1987). The work of BS 6841 has been closely linked to ISO 2631-1 work, because some of the groups working with the standards have been the same (Griffin 1998). There are other methods and standards available as well, but they have been more specific and local, such as German and Austrian standard VDI 2057 and Average Absorbed Power (AAP) method used by USA military (Els 2005) (see methods in Section 2.4.2). However, most of the national standards around the world are based on the ISO 2631-1 methods.

The purpose of the standards has been to systemise the process of analysing and evaluating the effects of vibration exposure. In short, the standards include the analytical equations for calculating representative values and procedures for performing the measurements. They also include technical detail and requirements for the measurement equipment and installation of the sensors. They refer to sub set of standards that define more precisely the techniques for measuring and signal processing the vibration.

Table 4. Publication dates and code names of the main vibration standards.

Year	Standard
1974	ISO 2631
1979	ANSI S3.18
1985	ISO 2631/1
1987	BS 6841
1997	ISO 2631-1

The standards help to systemize the research and evaluation. This has been very successful in whole-body vibration research, because practically all publications have used the methods proposed by the standards or at least compared the results to them. Most of the publications have used the frequency weighted r.m.s. method described by the ISO 2631-1 standard.

The review will only consider the newest standard versions of ISO 2631-1 and BS 6841, because they differ from the older standards significantly.

2.6.1 ISO 2631-1 (1997)

2.6.1.1 Background

ISO 2631-1, which is the only international standard for evaluating whole-body vibration, has been updated over a 12-13 year period to the current 1997 version. Currently an amendment is being finished, which will introduce small additions to the standard, but will not affect the basic principles and methods (ISO/TC 8/SC 4 2008). The standard defines the evaluation procedures for health, comfort, perception and motion sickness (ISO 2631 1997). The standard describes a 12-axis measurement procedure for comfort evaluation of a seated person. This includes acceleration measurements from the backrest, seat and feet. The seat measurements should include also rotational axes. The health part is focussed on a seated posture and effects to the lumbar spine, as the standard acknowledges that this situation is the only one where enough research has done. The standard is used widely around the world. It is in frequent use mostly in western countries and especially in Europe, but also in many other areas (e.g. South Africa).

2.6.1.2 Content of the standard

The standard regards comfort as a subjective opinion caused by a multi-axis vibration (Figure 17).

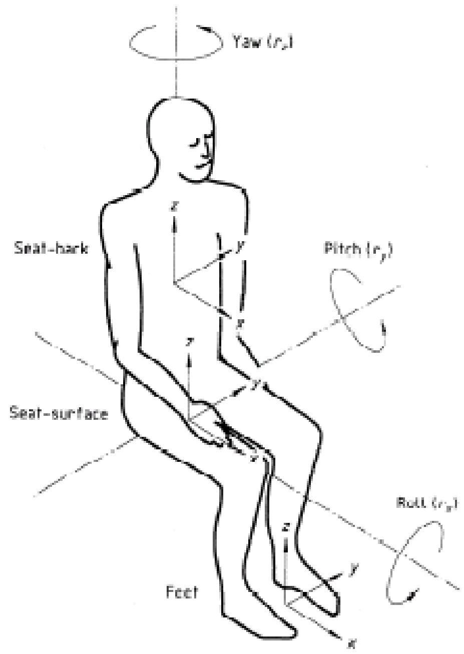

Figure 17. Axes and locations where vibration should be measured for analysing discomfort of a seated person (ISO 1997).

The main method for analysing all effects from vibration exposure is the frequency weighted root mean square (r.m.s.) (Equation 4). Before the r.m.s. values can be calculated, the acceleration data needs to be frequency weighted (i.e. filtered). The purpose of weighting the acceleration data is to model the frequency response of the human. The standard gives analytical equations for designing the frequency weighting filters, thus there is an option to use different filtering schemes (i.e. digital or analogue). There are weighting curves defined for all axes, measurement locations and applications. The standard determines also multiplying factors for each of the axes to compensate for the different vibration effects at different locations / directions (Table 5).

Table 5. Frequency weightings and multiplying factors defined in ISO 2631-1 for analysing 12-axis measurements for a seat person for evaluating discomfort.

Location	**Direction**	**Weighting**	**Multiplying factor**
Backrest	Fore-and-aft	W_c	0.80
Backrest	Lateral	W_d	0.50
Backrest	Vertical	W_d	0.40
Seat	Fore-and-aft	W_d	1.00
Seat	Lateral	W_d	1.00
Seat	Vertical	W_k	1.00
Seat	Roll	W_e	0.63
Seat	Pitch	W_e	0.40
Seat	Yaw	W_e	0.20
Floor	Fore-and-aft	W_k	0.25
Floor	Lateral	W_k	0.25
Floor	Vertical	W_k	0.40

There are three principal weigthing curves, that are used for evaluation motion sickness, health, discomfort and perception of whole-body vibration (Figure 18). Additionally there are three weighting curves (Figure 19) that are used in special cases, such as in 12-axis comfort analysis. For the full 12-axis discomfort evaluation four different weighting curves are needed.

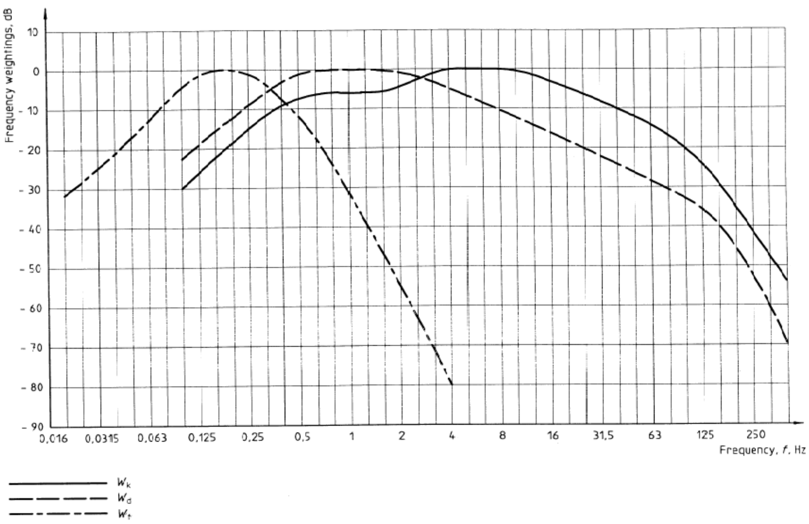

Figure 18. Principal weighting curves of ISO 2631-1 for vertical and horizontal axes for evaluating comfort. W_k is used for vertical axis from seat and all floor translational axes. W_d is used for seat and backrest horizontal axes (ISO 2631-1 1997)*.*

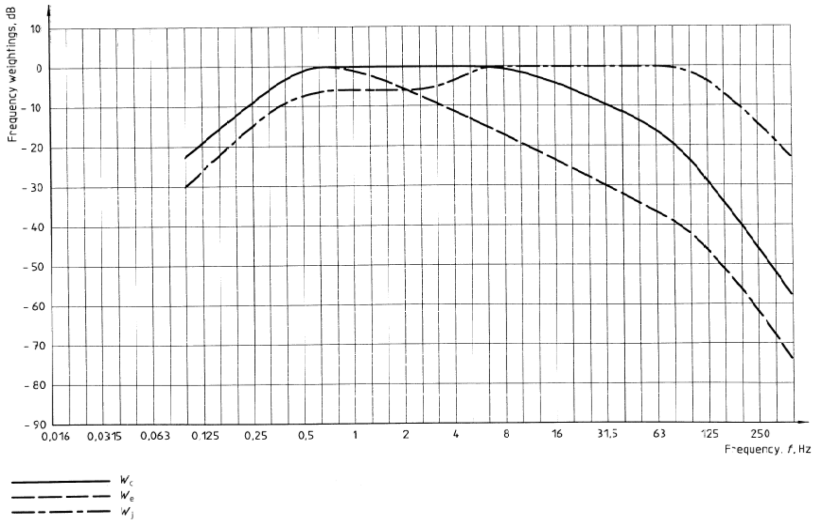

Figure 19. Weighting curves of ISO 2631-1 for rotational (W_e) and backrest fore-and-aft axis (W_c) (ISO 2631-1 1997).

A crest factor for each axis should be calculated. The crest factor is defined as the ratio between the highest frequency weighted acceleration peak divided by the frequency weighted r.m.s. value. If the ratio is over 9, then the standard requires the use of additional methods, because the r.m.s. value will most likely underestimate the evaluation. The additional methods are "running r.m.s.", which is calculated the same way as r.m.s. except using a small integration window (e.g. one second), and the vibration dose value (VDV), which is a fourth power dose method (Equation 6). The reason that the running r.m.s. value is calculated is to determine a maximum transient vibration value (MTVV), which simply is the highest single running r.m.s. value of the measurement period for each direction. If the crest factor limit is exceeded, then either MTVV or VDV values should be compared to the r.m.s. values using the following criteria:

$$\frac{MTVV}{a_w} = 1.5 \tag{11}$$

$$\frac{VDV}{a_w \cdot T^{1/4}} = 1.75 \tag{12}$$

where a_w is a frequency weighted r.m.s. value and T is time of measurement period (s).

If either of the values in Equations 11 or 12 is exceeded (depending on which one is used) then both the r.m.s. and additional evaluation values should be reported. No additional information on how to use the running r.m.s., VDV or MTVV values or which one of the methods to choose is given in the standard.

Next step is to combine the frequency weighted r.m.s. values using a vector sum equation for all measurement locations. This produces a single value called “point vibration total value” (PVTV) for each location that is measured (for the seat the translational and rotational values are calculated separately). Each r.m.s. value should be multiplied with a multiplying factor depending on the posture, vibration direction and location, when values are vector summed. If any direction in any location is less than 25 % of the highest value in the same location, then that value can be excluded from the vector sum (i.e. neglected from the evaluation).

When the PVTV for each location has been produced an “overall vibration total value” (OVTV) can be calculated by r.s.s. for all locations. If any PVTV in any location is less than 25 % of the highest PVTV in another location then that value can be excluded as well. OVTV can then be compared to other such values from different measurements and/or additionally to subjective comfort levels described in the standard’s Annex C (Table 6).

PVTV (a_{pvtv}) of translational or rotational axes from a location is calculated:

$$a_{pvtv} = \sqrt{k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2} \tag{13}$$

where k_x, k_y and k_z are the multiplying factors for the axes x, y and z (or roll, pitch and yaw) and a_{wx}, a_{wy} and a_{wz} are the frequency weighted r.m.s. values of x, y and z (or roll, pitch and yaw) axes. OVTV (a_v) is calculated by combining necessary PVTVs:

$$a_v = \sqrt{\sum_j a_j^2} \tag{14}$$

where a_j is a point vibration total value of location j and j is either seat, backrest or floor.

The report of the analysis should include the frequency weighted r.m.s. values (with multiplying factors) for each axis, point vibration total values (PVTV) for all locations and the overall vibration total value (OVTV). If the crest factor limit of 9 is exceeded, then also the crest factor and any additional methods and their results should be reported as well. Also measurement duration, frequency spectra and any conditions that might be important should be reported in any case. OVTV can be compared to the subjective response scale given in the standard’s annex C (Table 6), although it is given only as an approximate indication.

Table 6. Approximate indications of likely reactions to various magnitudes of overall vibration total values in public transport (ISO 2631-1 1997).

Magnitude of overall vibration total value	Discomfort response
Less than 0.315 m/s^2	Not uncomfortable
0.315 m/s^2 to 0.63 m/s^2	A little uncomfortable
0.5 m/s^2 to 1.0 m/s^2	Fairly uncomfortable
0.8 m/s^2 to 1.6 m/s^2	Uncomfortable
1.25 m/s^2 to 2.5 m/s^2	Very uncomfortable
Greater than 2.0 m/s^2	Extremely uncomfortable

Figure 20 shows the standardised measurement and analysis procedure for seated persons of the standard, which was described above.

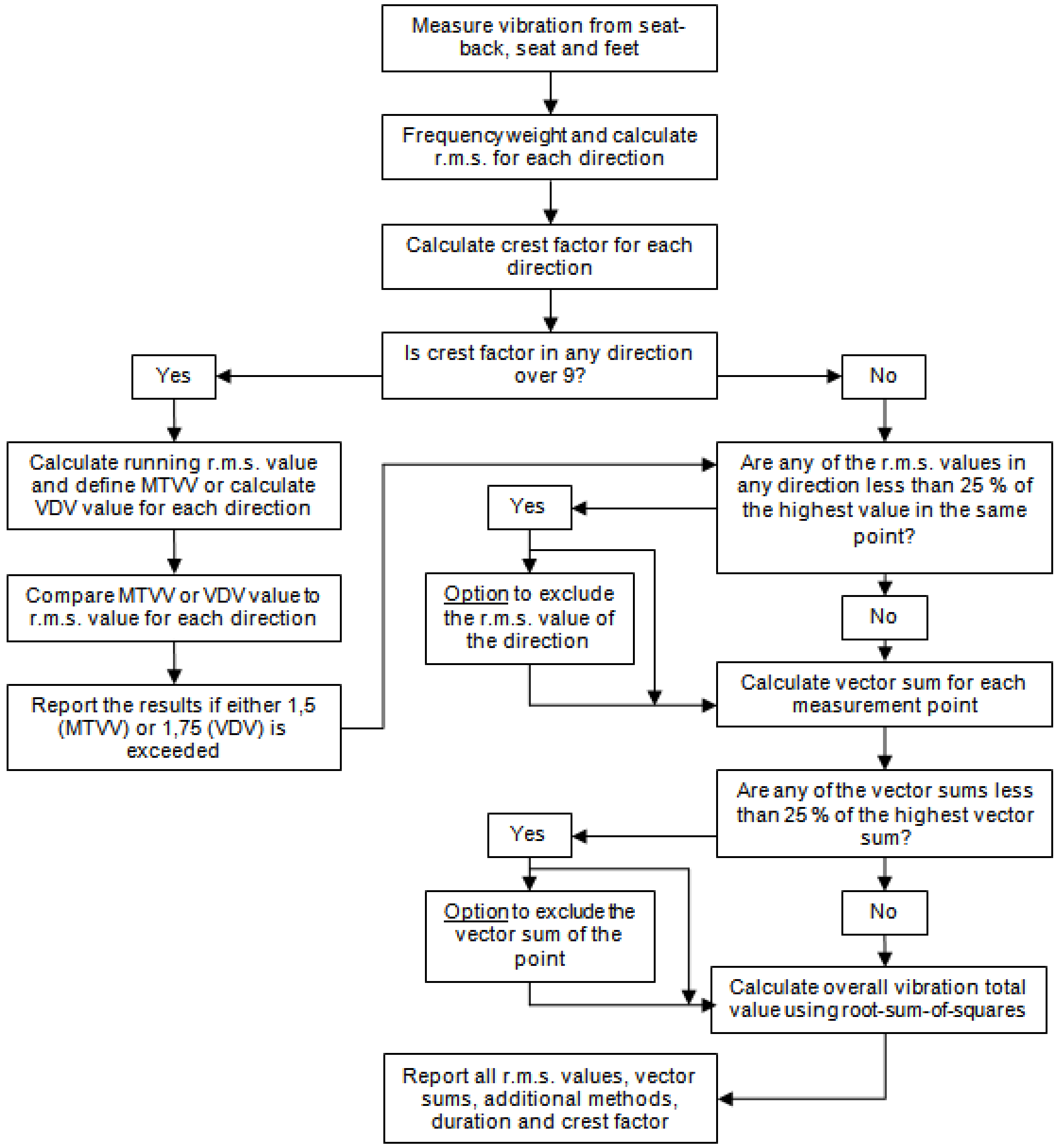

Figure 20. Measurement and analysis procedure of ISO 2631-1 standard for evaluating comfort from whole-body vibration.

2.6.1.3 Interpretation of ISO 2631-1

The standard implies that vibration causes discomfort and that the mechanism of it is complex. This can also be said of the procedure that the standard describes for evaluating it. Although it is logical that the r.m.s. method cannot be used in every situation, the guidance on when it is appropriate to use it is confusing. Griffin has explained this for the health evaluation procedure (Griffin 1998), which has the same basic problem.

As this study is focussed on comfort, the information relating to it is evaluated. First of all, compared to 1985 version (ISO 1985), the newest version (ISO 2631-1 1997) is more careful of what to conclude from the analysis of comfort:

"For simplicity, the dependency on exposure duration of the various effects on people had been assumed in ISO 2631-1:1985 to be the same for the different effects (health, working proficiency and comfort). This concept was not supported by research results in the laboratory and consequently has been removed. New approaches are outlined in the annexes. Exposure boundaries or limits are not included and the concept of "fatigue-decreased proficiency" due to vibration exposure has been deleted."

Thus it shows that new research has concluded the evaluation of comfort to be even more complicated than previously understood. The standard then continues to explain the causes of vibration exposure:

"Whole-body vibration may cause sensations (e.g. discomfort or annoyance), influence human performance capability or present a health and safety risk (e.g. pathological damage or physiological change)."

This shows that discomfort and problems relating to it are important and acknowledged, even though the methods for analysing them are still inadequate.

So far the standard has been consistent with its statements. However when reading further the problems of the standard and the complexity of the subject is more evident. Just after introducing the basic measurement guidance and the r.m.s. method the standard narrows the usage of it by stating that crest factor exceeding 9 will most likely mean that r.m.s. is underestimating the effects of vibration. In a note the standard even further undermines the r.m.s. method:

"For certain types of vibrations, especially those containing occasional shocks, the basic evaluation method may underestimate the severity with respect to discomfort even when the crest factor is not greater than 9."

When the crest factor limit is exceeded the standard implies that the basic evaluation method (i.e. r.m.s.) most likely underestimates the effects and refers to the additional methods (i.e. VDV, running r.m.s. and MTVV). However, the r.m.s. method is still considered the main method and should be reported in any case. There is no guidance on how to use the additional methods for comfort evaluation or comparison with the other values. They are only used for evaluating the usability of the r.m.s. method.

The clauses for comfort evaluation are also inconsistent, because they confuse the usage of the method. First of all the application paragraph states that:

"For the comfort of seated persons this clause applies to periodic, random and transient vibration in the frequency range 0.5 Hz to 80 Hz which occurs in all six axes on the seat pan (three translational: x-axis, y-axis and z-axis and three rotational: r_x-axis, r_y-axis and r_z-axis). It also applies to the three translational axes (x, y and z) at the backrest and feet of seated persons...".

It further goes on explaining comfort in next clause by stating:

"The weighted r.m.s. acceleration (see clause 6) shall be determined for each axis of translational vibration (x-, y- and z-axes) at the surface which supports the person."

This statement only describes translational axes, not rotational. It might give the wrong impression, especially if the previous clause has not been read well, that only translational axes are necessary to be measured. In the main text the standard only gives multiplying factors for the three translational axes from the seat. However note 3 in the clause informs that:

"In some environments, the comfort of a seated person may be affected by rotational vibration on the seat, by vibration of the backrest or by vibration at the feet. Vibration at these positions may be assessed using the following frequency weightings…"

And then the multiplying factors and frequency weighting curves are given. After reading the three paragraphs stated above it seems that it leaves the evaluation of how to measure comfort to the user, because there is no clear guidance on if the full 12-axis measurements are needed. The standard does not state that you have to measure all axes. It gives that possibility, but emphasises only the translational axes on the seat and refers to other axes if they affect the comfort evaluation. Because there is no guidance on when to measure them, it is hard for the user to conclude what axes should be included. Without measuring the twelve axes it might be difficult to conclude what axes actually cause discomfort, especially when the standard does not give any guidance on what environments this should be considered. Additionally the size of the calculated OVTV value is related to number of included axes, thus less axes will mean less discomfort.

The standard gives a possibility to use the translational axes measured from the seat to estimate the effects of backrest using 1.4 multiplying factors for horizontal axes. There is no reference to any study that can confirm the validity of the multiplying factors and the guidance is given in a small note, which can be easily missed.

For combining the values of the axes the standard states that:

"Where the comfort is affected by vibrations in more than one point an overall vibration total value can be determined from the root-sum-of-squares of the point vibration total values (e.g. translation on the seat and at the back and feet)."

Again the standard leaves an option to either combine the values or leave them separate. It also allows excluding one or more axes if certain requirements are met:

"If the weighted value determined in any axis (or rotational direction) is less than 25 % of the maximum value determined at the same point but in another axis (or rotational direction) it can be excluded. Similarly, if the point vibration total value in one point is less than 25 % of the point vibration total value which is maximum, it can be excluded."

Thus, in theory only one axis could be enough for comfort evaluation and assessment (e.g. when a large shock for any axis occurs). In practice this in not the case, at least not with mobile work machines, as the dominant axes change depending on the work phase. In worst case this does not lead to any significant differences between values and goes well in the limits of measurement uncertainty (Tyler and Darlington 2004), but it still confuses the user and alters the results. Although the guidance for doing that is given in a note, it is hard to conclude if this procedure is recommended or not. There are no studies or references which confirm if exclusion of any values is valid.

The standard refers to annex C for more information on evaluating comfort and perception. However for comfort the annex does not give any new information. It actually limits the usability even more by stating that comfort feeling changes based on the circumstances and many other factors. Even though the standard has twice stated that there is no conclusive evidence of any time dependency of vibration on comfort, it gives an equation to evaluate it. For methods for assessment when the crest factor limit is exceeded the annex refers back to the main part of the standard. The annex gives also the subjective response scales for evaluating the results. However the scales overlap, thus human reaction to comfort cannot be exclusively evaluated. There has been no research or solutions to solve this problem (Wyllie and Griffin 2007).

Criticism of the standard has increased over the years, because many studies have found inconsistencies regarding the frequency weighting curves and averaging methods (Griffin 1998). The frequency weighting curves have been based on the perception studies. There are several problems with them as the curves have been extrapolated based on only a few frequencies and linear response has been assumed, which is not consistent with some studies. For evaluating comfort the problem is also that the weightings are statistical, thus they give no individualised effect (i.e. no personal information is regarded in the analysis). There is also an indication that W_k, the vertical frequency weighting curve, underestimates subjective feeling of lower frequencies (Mansfield and Maeda 2005b).

2.6.1.4 Important changes to earlier versions

The evolution of ISO 2631 has been significant from the early version to the current. Earlier studies have shown that first draft did not include a concept of forming a single numerical value to determine effects from vibration exposure (Miwa and Yonekawa 1974). The biggest change has been from the 1985 version to the current 1997 version. More specific frequency weightings and evaluation methods were implemented and new definitions applied. More restrictions to the usage of the standard were also applied, based on the new information. Originally it was considered only to evaluate the worst frequency component of the worst axis (ISO 1974 and 1978). Later it was changed to taking the r.s.s. for the 1985 version. The main method in the early standards was 'single-axis 1/3-octaveband analysis', but additionally 'single-axis frequency weighted r.m.s. value' and 'the sum of vector frequency weighted r.m.s. value' was proposed as secondary methods (Wikstroem, et al 1991). The methods in the early versions of the standard were not considered valid or reliable (Griffin 1978).

2.6.2 BS 6841 (1987)

2.6.2.1 History

Although the UK voted against the first version of ISO 2631-1 standard (Griffin 1998), they produced their own standard with very similar content. The standard is broader in defining its scope and resembles more ISO 2631-1 (1997) than the earlier versions. One cause for publishing BS 6841 was the growing interest towards vibration problems in industry and the slowness of the international forum to produce a new ISO standard (Griffin 1998). The role of BS 6841 has been significant since its introduction and for the creation of ISO 2631-1 (1997).

2.6.2.2 Content of the standard

The basic method in BS 6841 is also the r.m.s. method (Equation 4). Frequency weightings are applied in the same way as in ISO 2631-1, except for vertical direction where weighting curve W_b is used instead of W_k. For using the full 12-axis measurement procedure for comfort evaluation BS 6841 has the same multiplying factors as in ISO 2631-1. The crest factor is calculated exactly as in ISO 2631-1, although BS 6841 uses a lower crest factor limit (6) when referring to additional methods.

With the exception of the crest factor limit the rest of the process is almost identical to ISO 2631-1 for calculating PVTVs and OVTV. The only exception is that BS 6841 does not exclude any PVTVs like ISO 2631-1 does if 25 % margin is exceeded. Only when calculating PVTV, then BS 6841 has the same guidance to exclude axes based on the 25 % margin.

If the crest factor limit is exceeded, then the analysis procedure changes from the one in ISO 2631-1. The standard recommends of using either root mean quad (r.m.q) or VDV as an additional method. R.m.q and VDV are both fourth power methods, so basically either one can be used (but r.m.q. is implied). VDV is recommended to be used if two or more events of different duration are needed to be analysed together. After calculating either the r.m.q. or VDV values the standard does not refer back to usage of the r.m.s. values, thus the values from r.m.q. or VDV calculations should be reported (Figure 21).

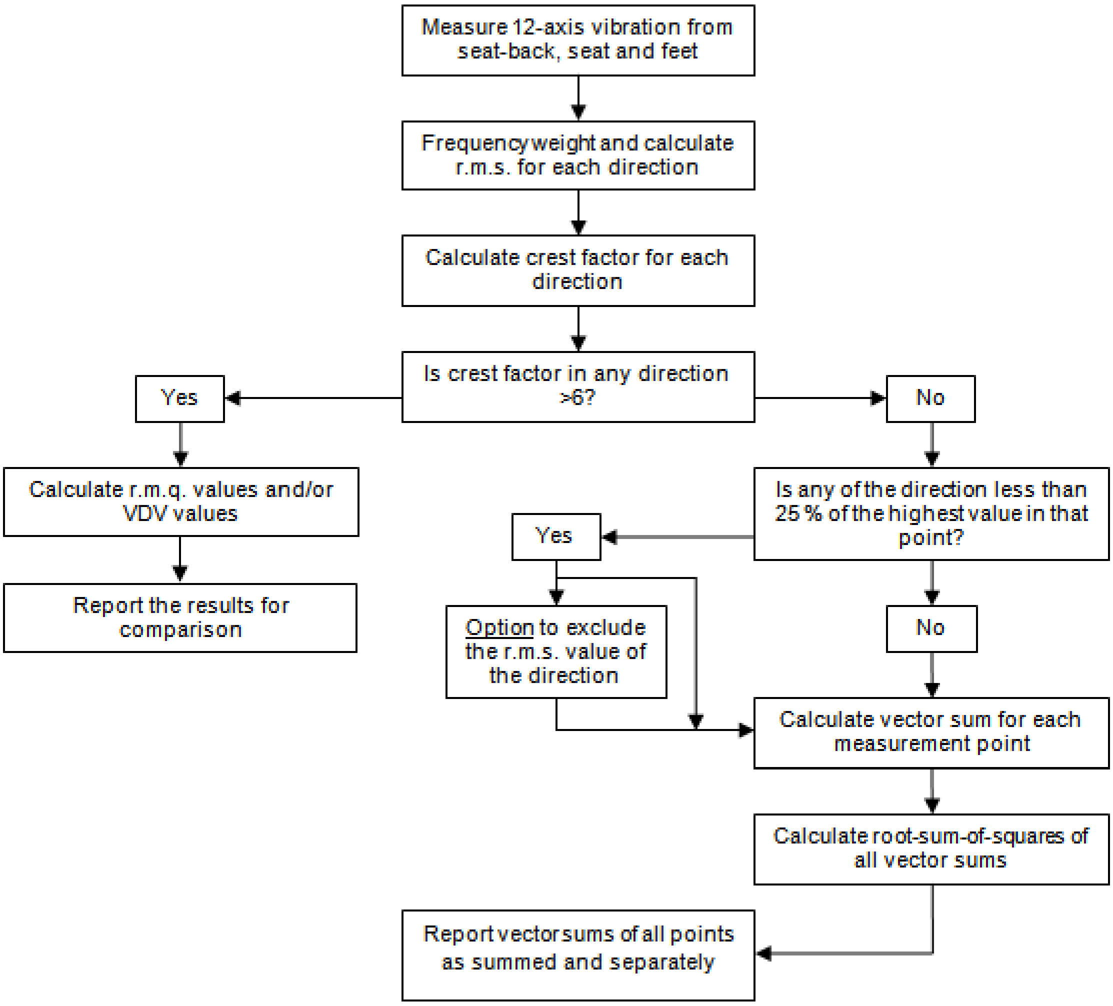

Figure 21. Measurement and analysis procedure of BS 6841 for evaluating comfort of seated persons from whole-body vibration.

2.6.2.3 Interpretation of BS 6841

The discomfort is defined in the standard as *"sensations arising directly from the vibration"*. It defines a method for comparing the effects of multi-directional vibrations, but reminds that the effects are related to specific environments. In a note about human variability the standard states that:

"People differ in their response to vibration and individuals may have different reactions at different times. Thus two motions, which are assessed as equally severe by the recommended evaluation procedures, may have noticeably different effects."

The statement indicates that the methodology in use is derived from statistical studies that have averaged the results of many people, which can contain larger variations, thus this method might give wrong results if a single person is considered.

An interesting note is presented about the frequency weighting:

“Weightings for rotational vibration are therefore only considered necessary below 10 Hz. However the weightings are given for higher frequencies for consistency.”

There is an indication that rotational vibrations above 10 Hz are perceived as translational, but the analysis method still uses the rotational axes (i.e. frequency weightings) above 10 Hz. The standard implies that defining the crest factor is important when evaluating comfort and it should be below 6 (or even lower) for more accurate analysis. The standard refers to alternative methods in the appendix C if crest factor of 6 is exceeded.

As ISO 2631-1 also BS 6841 guides to exclude any direction that has 25 % lower value, but only for calculating PVTVs:

“if a weighted value determined in any axis is less than 25 % of the maximum value determined at the same point, but in another axis it need not to be included in the above calculations.”

For the measurement procedure the standard states the same 12-axis procedure as in ISO 2631-1 (1997) for seated postures. For standing and recumbent postures the method is also the same 3-axis procedure from the seat, than in ISO 2631. Frequency weighting curves are given to all axes with multiplying factors.

In an appendix C, where discomfort is further explained the standard states the same things about variability in humans and environments. For vibration containing a high crest factor (>6) the standard suggests:

“For these situations the root-mean-quad value will be more likely to predict accurately the relative discomfort of motions of similar duration than r.m.s. value.”

It further goes on to give even another possibility:

“If vibration exposures consist of periods of high and low vibration throughout variable periods of time, the vibration dose value may be determined as described in the appendix A.”

The r.m.q. and VDV are fourth power methods, which are given as an option, although no other information about the usability of the methods is given. The standard then gives a guideline for comparing the r.m.s. values for subjective opinion. In a note the standard states:

“The procedure specified in this standard is based upon laboratory research and field surveys.”

BS 6841 standard also emphasises only three translational axes from the seat and states in a note the same thing as ISO 2631-1:

“In some environments the comfort of a seated person is affected by rotational vibration on the seat, by vibration of the backrest or by vibration at feet.”

After that it gives in smaller print the rest of the multiplying factors and frequency weightings for other axes.

2.6.3 Comparison of ISO 2631-1 and BS 6841 standards

A quick look at the standards makes them seem very similar. The primary method in both is the calculation of the frequency weighted r.m.s. values for each of the twelve axes. The multiplying factors are the same as using the crest factor to evaluate applicability of the r.m.s. method. There are differences in the vertical frequency weighting curve W_b of BS 6841 to W_k ISO 2631-1, but they are marginal (other frequency weightings are exactly the same). BS 6841 uses lower crest factor limit than ISO 2631-1 for recommending using of additional methods (the same as ISO 2631-1:1985 uses), but this can also be stated as a small difference (although the usability of the r.m.s. method itself is greatly lowered).

The biggest differences between the standards are when the crest factor limit is exceeded and additional methods are required. ISO 2631-1 refers to the running r.m.s., MTVV and VDV methods, but actually only instructs to use them to find out if the r.m.s. method is correct (there is no indication of how to interpret the values themselves). Even though the r.m.s. method is said to underestimate the vibration ISO 2631-1 instructs to always report it as well. BS 6841 on the other hand refers to the r.m.q. or VDV methods as an option, but only indicates that the methods will “more likely” predict the relative discomfort. Both standards give no guidance on how to interpret to results of the additional methods, thus their usage does not give any useful information. Especially for the r.m.q. method where there is no additional information in the standard. Only a few publications have used the r.m.q. method since its existence (Boileau, et al 1989, Fairley 1995, Monsees, et al 1988), thus not enough information on usability and its relation to comfort exists. The standard has only additional information about VDV relating to health.

In general BS 6841 is simpler and more understandable than ISO 2631-1, as it does not have that many notes that only confuse the reader. The problem with both standards is that they rely on a method that underestimates even relatively low shocks and spikes, thus they have to spend time on describing limitations for the usability and introduce additional methods, which have insufficient guidance and no greater scientific proof than the default method.

Another issue is that there is no time dependence for comfort. Basically one minute of vibration exposure can be concluded to be as comfortable as 10 hour exposure if the r.m.s. or r.m.q. method is used. Only the usage of VDV incorporates time dependency, but there is no conclusive knowledge on how duration affects comfort feeling. Certainly there are no tables for assessing discomfort for the VDV values.

Both standards also give the possibility of not measuring rotational axes or backrest and floor. They only loosely state that if other axes or locations have an effect on comfort then they should be considered. The guidance on how to assess if they are needed is not given, thus it is easy to exclude them and just use the current commercial seat pad with three axes for comfort measurements. The 12-axis measurement procedure of the standard is optional, not mandatory, and is only given as an informative reference as there is no real evidence of the method to be able to estimate comfort in practice. If no better guidance is given, then it is assumed that all of the twelve axes should be measured for the best accuracy.

The methods in both standards are based on the knowledge gathered from studies that have used single-axis or dual-axis vibration exposure. There is a reason to assume that multi-axis vibration exposure will have a different effect than combinations of single-axis exposures. There is a difference in biodynamic response of multi-axis versus single-axis (Holmlund and Lundström 2001). This could indicate that also comfort opinion will change in multi-axis environments.

It is clear that the possibility of different variations of procedure, limitations of the basic method, lack of guidance of additional methods, small printed notes and scattered information make the standards very hard to use in a systematic manner (or even properly). Depending on the user the procedure can show different results. This has been concluded already for the health evaluation procedure (Griffin 1998), but it is more evident for both standards in comfort evaluation procedure.

For any method or procedure to be practically used it should not have a possibility for differing interpretation. It should clearly define the methods and limitations to every situation. It seems that the only practical procedure to measure and analyse comfort based on the standard is to always measure the 12-axis vibration, calculate frequency weighted r.m.s. values, calculate the crest factor values, and calculate additional methods and report all of them separately for each axis.

2.6.4 Additional standards

2.6.4.1 ISO 10326

The standard specifies: *"basic requirements for the laboratory testing of vibration transmission through a vehicle seat to the occupant"*. The standard has a description for a 3-axis seat pad (Figure 22) and installation locations for floor, backrest and seat surface used in whole-body vibration measurements. The measures for the 3-axis seat pad can be considered as a basis for designing the 6-axis seat pad's mechanical housing. The standard also introduces the SEAT value and equation.

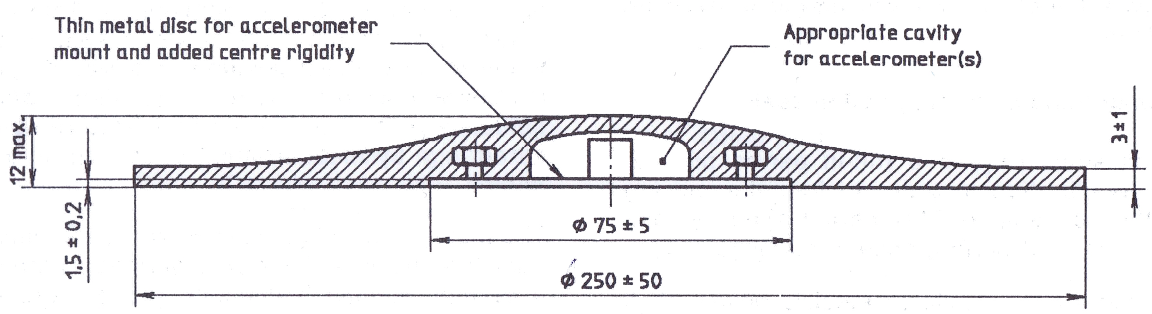

Figure 22. Seat pad sensor measures according to ISO 10326 (1992).

2.6.4.2 ISO 8041

ISO 8041 defines the test procedure, tolerances and technical information for equipment used in whole-body vibration measurements. There are no direct specifications concerning 12-axis equipment or 6-axis seat pad sensor, but most of the specification intended for the 3-axis equipment can be used directly, such as tolerances for the frequency weightings, r.m.s. values, and so on. The requirements are not considered here in detail, but they are used when developing the equipment in Chapter 4.

2.6.5 European legislation

The European Union accepted and ratified a new directive (2002), which mandates minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration). The directive sets limit values in form of r.m.s. and VDV values that dictates the vibration a worker can be exposed to during an eight-hour work day. The directive sets certain requirements that the employer must follow to reduce the vibration affecting the worker.

The directive does not refer to comfort evaluation or to any problems regarding comfort and working ability. Because of that, the directive is not related to this thesis directly, but it is still useful to understand the basics of the directive and how to relate the results based on the directive to comfort evaluation.

There are two limit values that are used: 1) daily exposure limit value and 2) daily action value. The daily exposure limit value (1.15 m/s^2) can never be exceeded in the standard eight-hour working day. The daily action value (0.5 m/s^2) sets a limit as to when an employer should start a program to reduce the vibration level. The directive lists basic measures that the employer should do when the vibration levels are too high. Although the directive sets limit values to act upon, the directive also instructs and expects the employer to reduce and evaluate the vibration in any case. From the measurements only the highest value of the three axes (x, y and z) from the seat is used to assess the vibration exposure.

2.6.6 Guidelines for assessing discomfort from vibration

There is no practical guidance for comfort assessment as there is for health (EN 14253 2003). The guidance does not have any information on assessing comfort from vibration. It only refers to comfort of seat and other ergonomic factors, not on how to evaluate vibration related to comfort using the standardised method.

2.6.7 Summary

Based on the review of the standards and their guidance on measuring and evaluating the health of seated persons, it is evident that there are difficulties in using them. The author has not been able to find any previous publications, which have critically evaluated the comfort evaluation procedure of ISO 2631-1 and the procedure for validating it using the full method and field-like stimuli. Some field studies have been made, but the results have not been confirmed in a laboratory environment. Also rarely have all twelve axes been measured.

For any method or procedure to be practical it should not have a possibility for differing interpretation. It should clearly define the methods and limitations to every situation. Based on the review of the standard and publications it is clear that the guidance gives a possibility for large differences in the final results even though it has been properly followed.

The comfort evaluation method has not been validated as a whole. The method is based on separate studies, which have all used only one or two axes simultaneously or a limited setup (Maeda and Mansfield 2006a). There are no known publications or research, which have validated the overall procedure in a multi-axis environment. It is evident that research on validating the whole method is needed and this includes more measurements in field and in the laboratory. Additionally even though it has been shown to work reasonably well for stationary vibrations (e.g. sinusoidal), the applicability in the field with and without high shocks has been questioned (Wikstroem, et al 1991).

Even if the standard method is valid the problem of confusing guidance and lack of practical instrumentation still hinders its usage. More practical and affordable equipment should be developed to enable wider usage of the standard. The standards describe the equations, sensor directions and locations, frequency weightings, multiplying factors and general guidance to measure and interpret the values for analysing discomfort. They do not give any technical details or references on how to build the necessary instrumentation, nor detailed information on the installation procedure.

2.7 Conclusions

Although there is evidence of negative effects of vibration to health and comfort, the details of the reasons are still mainly unknown. The modern belief is that vibration is just one of the many factors that contribute to comfort and health problems (Hostens 2004, Hoy, et al 2005). Still health and comfort problems seem to appear more likely with professional drivers than any other groups (Agius, et al 1988, Boshuizen, et al 1990, Bovenzi and Betta 1994).

This review has shown the effects and importance of understanding vibration. It is shown that the link between vibration characteristics and discomfort is not yet completely understood and is complex. Based on the review there is a need to improve understanding of the standard method for predicting discomfort from whole-body vibration. The process of validating the standard method requires the development of more accessible technical equipment, which allows research in the field and laboratory and gives possibility to validate the standard procedure and to further improve it.

3 Chapter 3 – Planning and selecting general methods for validating and improving the ISO 2631-1 method

3.1 Introduction

Based on the literature review it was evident that validation of the ISO 2631-1 (1997) standard method is necessary in a multi-axis environment and using field-like stimuli. Most of the studies have been conducted in a laboratory using single or dual-axis stimuli and using sinusoidal or narrow-band random stationary excitations. Typically exposures have been short (i.e. a few seconds) and judgments have been acquired using methods more suitable for the laboratory. The studies which have been conducted in the field, have shown conflicting results, have rarely used all twelve axes and have mainly used test tracks with shock type stimuli.

To introduce new results and validation of the standard it is necessary to conduct trials which are closer to real world circumstances. Thus methods, which can be used in field environments, are needed for acquiring and analysing judgments. Methods used in the previous studies are not practical in the field or for long exposures as they only include one judgment per stimulus and might need a reference stimulus (Maeda 2005). The judgment of time variant vibration (i.e. random vibration) has been shown to be problematic using traditional methods (Maeda 2005).

Even though field trials will include more variability, it is important to validate results of laboratory studies in the field, otherwise there is no link to practicality. There is a clear need to improve testing of seat comfort in the field and methodology to analyse the results (Kolich 2008).

3.2 Research plan and goals of the thesis

The purpose of the thesis work is to validate the applicability of the current ISO 2631-1 standard in laboratory and field environments using multi-axis field-like stimuli. Depending on the results the second goal is to improve the predictability of the discomfort from whole-body vibration either by optimising the current standard method or by suggesting a completely new method. The first priority is to optimise the current standard method, as this would comply better with the current equipment and guidance.

To limit factors and scope of the work a seated passenger exposed to whole-body vibration while not conducting any specific task is regarded as the study case. This allows more detailed study of the relative effects of axes and correlation of discomfort and vibration characteristics.

Thus based on the problems with the current standard guidance and its usability it becomes clear that the task for generating more research in this area, is to suggest more logical evaluation procedure, develop more practical equipment and improve guidance for comfort assessment. Based on the conclusion the following steps must be taken, which will be the goals of this thesis:

- Develop practical equipment for measuring 12-axis vibration in the field and laboratory;
- Validate the developed equipment using laboratory experiments;
- Measure and evaluate 12-axis vibration from the field from different machines;
- Evaluate correlation of discomfort to vibration using six axis test bench in a laboratory;
- Optimise ISO 2631-1 discomfort model based on laboratory results;
- Evaluate correlation of discomfort to vibration using a real vehicle in the field;
- Optimise ISO 2631-1 discomfort model based on field results;
- Suggest more practical guidance based on the results.

3.2.1 Goals for developing and validating equipment

The literature review showed that commercial equipment for measuring all twelve axes of vibration are expensive and difficult to obtain. For a researcher to build their own measurement system requires understanding of electronics, sensors, signal processing and software programming. A simple and inexpensive, yet accurate, system for measuring all twelve axes was considered necessary. This will include a six-axis seat sensor and two tri-axis sensors for backrest and floor. Also software for calculating translational and rotational axes will be developed. The equipment should allow long measurement periods (several minutes) of raw acceleration data. The equipment is developed to be commercial quality, thus allowing other researchers to purchase the equipment and software. Two experiments will be conducted to validate the equipment in a multi-axis test bench and in the field.

3.2.2 Goals of the 12-axis field measurements

Based on the literature review there were only a few 12-axis measurements available publicly (Griffin 1990, Maeda 2004). It was concluded necessary to conduct additional field measurements from typical work environments to have more confidence in the analysis. The goal of the field measurements is to obtain enough data to analyse relative contribution of the twelve axes in normal work environments. The results are compared to other publications and concluded how many axes have practical contribution to the overall vibration total value, does contribution change for different machines and environments, and to provide guidance which axes are sufficient for a full discomfort evaluation and the number of axes which can be excluded based on the '25% contribution' criteria.

3.2.3 Goals of the trials

Studies which have claimed or introduced a new method to predict discomfort or health, have been based on either laboratory or field trials. Laboratory studies have normally a very narrow scope of stimuli and an artificial environment. On the other hand assumptions made in field studies can be inappropriate and error margins too large (Griffin 2007). It is necessary to incorporate both research environments for testing and evaluating methods in laboratory and validating them in the field, thus this thesis uses both approaches.

3.2.3.1 Laboratory trial

The goal of the laboratory trial is to validate the standard method for predicting discomfort from whole-body vibration and to analyse how frequency weighting, multiplying factors and averaging methods affect the results in a multi-axis environment using non-stationary stimuli. The trial will conclude how many and which axes are necessary for predicting discomfort and how correlation between discomfort and vibration varies amongst subjects. The trial results will also be used to try to optimise the standard method based on the analyses of effects of different parts of the methods.

3.2.3.2 Field trial

The goal of the field trial is to validate and test the standard and improved method in practice. The field trial will introduce several variables, which are not present in a laboratory. It is important to test the method in the field as it shows how practical the standard method is. Several subjects will be measured simultaneously as no permanent test track (i.e. highly repeatable vibration exposure characteristics) is used. This requires a simple method and equipment to acquire judgment data.

3.3 Selecting general methods for conducting the research

3.3.1 Calculating vibration magnitudes

Vibration magnitudes for each axis are calculated based on the measured acceleration data in m/s^2. The calculations are performed using the guidance from the main standards (ISO 2631-1 and BS 6841). Because of the nature of the thesis the magnitudes are calculated using several different approaches, where some magnitudes are calculated without applying parts of the standard method. Table 7 summarises different approaches of calculating the vibration magnitudes that is used in this thesis.

Table 7. Different approaches used in the thesis to calculate vibration magnitudes for each axis. Frequency weighting and multiplying factors are applied based on the ISO 2631-1 standard. Averaging methods are applied based on the ISO 2631-1 and BS 6841 standards. Point and overall vibration total values are calculated for all setups.

Setup	Frequency weighting	Averaging method	Multiplying factors
1	Yes	r.m.s.	Yes
2	Yes	r.m.q.	Yes
3	Yes	r.m.s.	No
4	Yes	r.m.q.	No
5	No	r.m.s.	No
6	No	r.m.q.	No

3.3.2 Acquiring and calculating subjective judgments

Normally trials include a short stimulus and an overall judgment is made for each stimulus. This is possible if the stimuli are relatively short (i.e. less than 15 seconds). However for longer stimuli the overall judgment will most likely be unreliable as subjects need to memorise the feeling during the exposure (Kuwano and Namba 1985). Thus a method which can be used for more real-time judgment is a necessary requirement.

Based on the requirements and aims of the analyses it was decided to use the continuous judgment method of line length to acquire judgment data simultaneously with vibration data (see Chapter 2 Section 2.3.2.6 for details of the method).

3.3.3 Statistical analysis

Because of the stimuli types, measurement environments and chosen judgment method the correlation needs to be calculated and analysed using a ranking method, as normal distribution cannot be assumed. A Spearman rho (r and r^2) is selected as the primary method for calculating correlation, because it is a widely used method and simple to calculate. Additionally Kendall's tau (t) is calculated for the most important results for giving a better insight for the understanding of the relationship and confidence on the results. In most cases both methods will lead to the same conclusions (Crichton 1999).

A Wilcoxon signed-rank test is used to evaluate statistical differences amongst two sets of matched data (e.g. differences of correlations for each subject). A Friedman test is used to evaluate if the number of dependent results have any statistical differences. A Friedman test can be applied to multiple data sets. A Mann-Whitney U-test is conducted when the two data sets are independent. The significance of the results is evaluated based on the p-value (two-tail) and null hypotheses are introduced for each case.

3.4 Conclusions

Based on the literature review in Chapter 2 it was found that ISO 2631-1 needs to be validated and possibly improved for comfort evaluation in the field. A number of experiments, trials and field measurements were planned, which require robust and simple methods to analyse the results. Several approaches are used to calculate vibration magnitudes and a number of statistical methods are used for analysing correlation between subjective judgments and objective results.

4 Chapter 4 - Developing and validating equipment for measuring 12-axis vibration in a field and laboratory

4.1 Introduction

There are only few publications, which have used the full discomfort evaluation method of ISO 2631-1 (1997) or BS 6841 standards (Griffin 1990, Maeda 2004). This is partly because of lack of practical equipment and the complexity of the standardised method**.** In Chapter 2 there was an analysis of the current discomfort evaluation procedure of the standard and the required work to validate it. Based on the review the development of more practical and less expensive equipment for 12-axis measurements was concluded. Currently there is no feasible commercial equipment to allow wider usage of the 12-axis comfort method in practical field measurements, because the equipment is expensive and not actively sold. Without proper equipment it is not possible to increase the knowledge on how to evaluate discomfort in practice.

Based on the previous publications it has been found that the standard does not give an explicit guidance on the 12-axis measurements for comfort evaluation. There is a possibility for interpretation when analysing the measurement results. The full method requires measurements from a seat, backrest and floor. The measurements from floor and backrest can be done using traditional 3-axis accelerometers that record translational accelerations, but the measurements from the seat needs also rotational accelerations. There is a doubt how many axes are needed for assessing discomfort of a seated person. These problems have hindered the usage of the comfort method.

4.2 Goals of the development of equipment

New measurement equipment was to be designed, developed and validated for allowing practical 12-axis field measurements. The purpose was to realise the measurement instrumentation so that it is practical and simple for field measurements and made from affordable components. The equipment will be validated in laboratory experiments and a commercial partner will be searched for producing the equipment for open market.

The development was focussed on a 6-axis seat pad sensor, which included detection of both translational and rotational axes. Additionally the data acquisition and signal processing hardware was designed as well as software for analysing the measurement data.

4.3 Developing and validating measurement equipment

4.3.1 Components and methods for acquiring and detecting translational and rotational axes

4.3.1.1 Acceleration MEMS sensors

The sensor system was chosen to be based on MEMS technology. The advantage of the MEMS sensor (i.e. capacitive sensor) compared to a piezoelectric sensor is a simpler design and needs very few extra components before digitizing the signal. The sensitivity and noise levels are well within the technical requirements of the standard (ISO 8041 2005). MEMS sensors have typically voltage in – voltage out operation. In practice the sensors only require low noise voltage source (e.g. 5V) and proper anti-aliasing components, and an A/D sampling circuit. The sensors also detect gravity, not like piezoelectric sensors, so in practice the measurements can be made up to a DC (i.e. 0 Hz) level. The challenge is to minimise the noise levels and to optimise the sensor's whole dynamic range, which is less than with piezoelectric sensors. For whole-body vibration measurements this can be achieved if the measurement accuracy is specified to ±0.01 m/s^2, which is well enough for practical field measurements.

Table 8 shows typical technical specifications of a MEMS acceleration sensor. Range is typically from 1.5 to 8 g, which is directly related to the resolution of the sensitivity of the sensor. For measuring whole-body vibration from a seat a 2 g range is sufficient. For a floor a higher range is suggested.

Table 8. Technical specifications of the MEMS sensor selected for the 12-axis measurement system.

Parameters	Units	Values
Range	g	1.5 to 6.0
Sensitivity	mV/g	560
Noise	$\mu V/\sqrt{Hz}$	175 typical
Bandwidth	Hz	0-3300 (vertical), 0-1700 (horizontal)
Cross-axis Sensitivity	%	±2.0 typical
Operating temperature	C	-40 to +85

4.3.1.2 Data acquisition

Any analog signal that is digitized will require an analog-to-digital (A/D) conversion. The resolution of the conversion is based on the A/D characteristics (i.e. number of bits it can use to digitize the analog signal). For an example when a 24 bit A/D sampling resolution is used, the maximum theoretical sensitivity of the measurement device for a certain voltage span can be calculated. The maximum 24 bit sampling resolution (R_{max}) and maximum theoretical sensitivity (S_{max}) using a voltage span of 5 V is:

$$R_{\max} = \frac{5V}{2^{24}} = 2.98 \cdot 10^{-7} V = 0.000298 mV \tag{15}$$

If an analog acceleration sensor, with a sensitivity of 560 mV/g, is used in conjunction with the A/D converter, the maximum sensitivity (i.e. resolution) of the measurement system will be:

$$S_{\max} = \frac{0.000298 mv}{560 mv/g} = 5.32 \cdot 10^{-7} g = 5.32 \cdot 10^{-6} m/s^2 \tag{16}$$

Thus the better resolution of the A/D conversion the greater theoretical accuracy it is possible to achieve.

4.3.1.3 Accuracy of an acceleration signal

The practical sensitivity of any system is affected by the noise characteristics of all components and the sensitivity of the accelerometer. There are many noise sources that affect the measurement results, but the most important ones are the noise characteristics of the sensor and the A/D component. They will affect the accuracy of the analog-to-digital conversion.

Based on the result of Equation 16 a conclusion can be made that the noise and sensitivity characteristics of the accelerometer, its circuit board and cabling are the limiting factors. There are also noise sources from the environment affecting the accuracy of the system. So even though all the necessary information about the MEMS sensor and other electronic components are given in the technical specifications, in practice the whole system (including the cabling) has to be tested and validated on a test bench.

4.3.1.4 Method for calculating rotational accelerations

For measuring rotational components of vibration a design having three sensors in three corners of the plate (A_0, A_1 and A_2) for calculating rotational axes, and a single 3-axis sensor in the middle (A_4) for translational axes is selected (Figure 23). Calculated rotational accelerations are based on the relationships of the sensors' directions and the distances between them (Equations 17-19). The additional 3-axis sensor in the middle is redundant, as all six axes could be calculated based on the corner sensors. However, for maximal accuracy of the translational axes and to simplify the calculation process, the middle sensor was used.

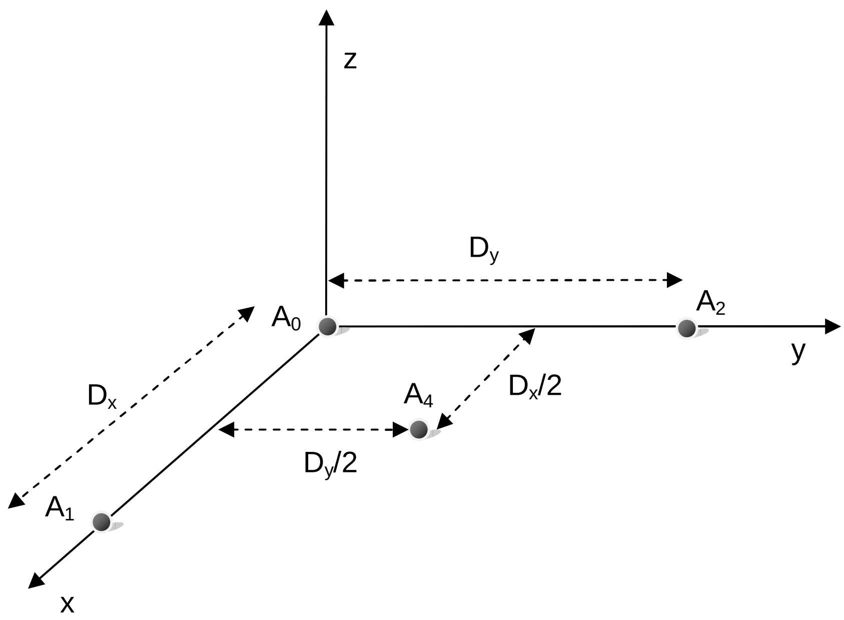

Figure 23. Sensor locations and orientations for calculating 6-axis vibration using 6-axis accelerometers at points A0, A1, A2 and A4.

$$\text{Roll: } a_{P,rx} = \frac{a_{z2} - a_{z0}}{D_y} \quad (17)$$

$$\text{Pitch: } a_{P,ry} = \frac{a_{z1} - a_{z0}}{D_x} \quad (18)$$

$$\text{Yaw: } a_{P,rz} = \frac{a_{y1} - a_{y0}}{D_x} \quad (19)$$

where a_{zo}, a_{z1}, a_{z2}, a_{y0}, and a_{y1} are acceleration (m/s^2) for directions x, y and z at locations A_0, A_1 and A_2, D_y and D_x are distances in metres between locations A_0, A_1 and A_2 (Figure 23).

4.3.2 Prototype I: Experiment for validating sensor configuration for measuring 12-axis vibration

4.3.2.1 Purpose

The goal of the first prototype was to test the chosen MEMS sensor type and configuration for measuring 6-axis vibration. An analog ±2.0g version (560 mV/g) of the sensor was chosen.

4.3.2.2 Technical details

The 12-axis sensor system requires a measurement device for recording the signals, which includes A/D-channels, anti-aliasing filters, processor, software and memory, among other components (e.g. voltage regulation). The first prototype for recording the sensor information was realised using a commercial development kit and a developed I/O card including two 24 bit 8-channel A/D converters. A development kit from Altera (Stratix II) was used in this study. The measurement device sampled at 260 Hz each channel and saved the raw acceleration data to memory and the analysis process (including the frequency weighting) was done afterwards using a Matlab environment. Figure 24 shows the first prototype of the measurement device.

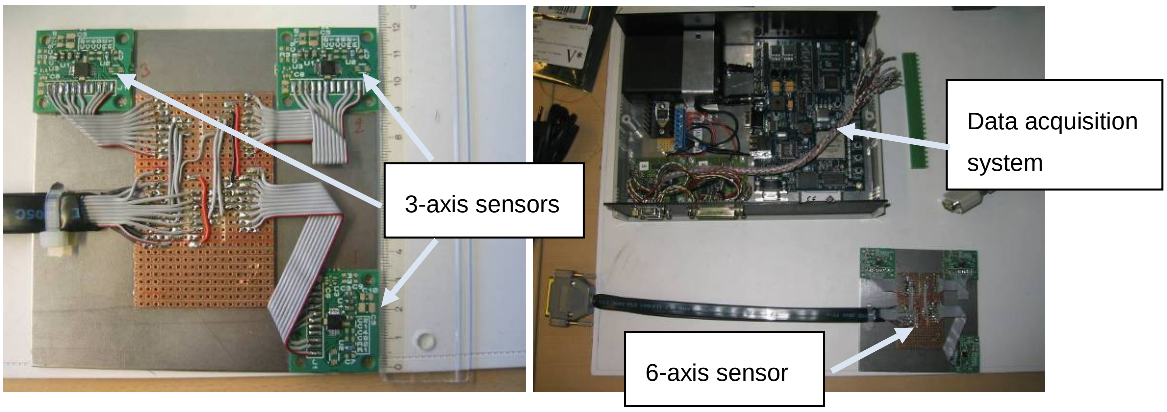

Figure 24. The 6-axis sensor configuration for measuring translational and rotational axes from seat (left) and the measurement system to acquire measurement data (right).

4.3.2.3 Validation of the accuracy of the equipment

The prototype measurements system was tested using a 6-axis test bench at Japan NIOSH, Kawasaki, Japan (Figure 25 left). The purpose was to evaluate and validate the developed measurement equipment and the 6-axis MEMS sensor configuration (later called MEMS) against a 12-axis measurement system made by IMV Corporation (later called IMV).

The sensors were installed on the floor of the test bench (Figure 25 right). The MEMS sensor plate was installed on the top of the IMV sensor to be as close as possible to the same position. Two other tri-axial MEMS sensors were installed for comparison test as well, which were designed for floor and backrest measurements.

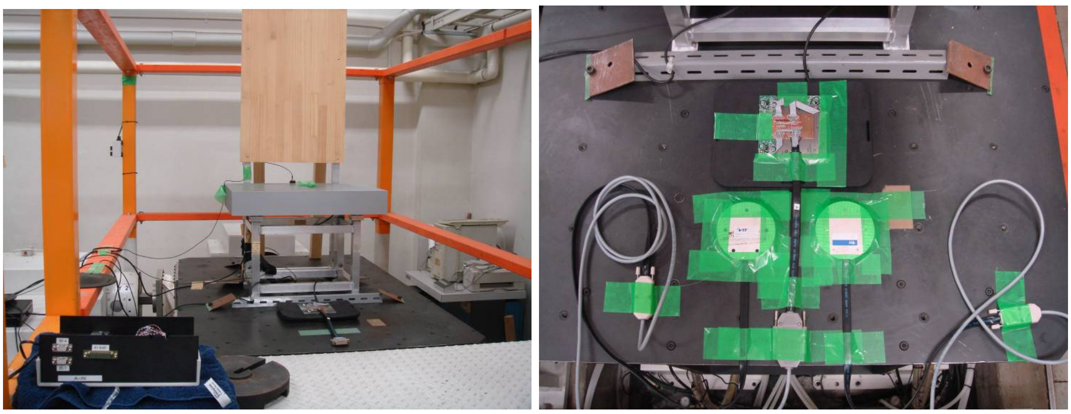

Figure 25. Japan NIOSH 6-axis test bench (left) and installed sensors (right). The MEMS and IMV sensors were installed to the same location to compare results.

Tests were made to validate the measurement equipment: 1) for determining the practical sensitivity and noise characteristics of the system, 2) for determining the sensor configuration to detect rotational vibrations (Table 9). Also a comparison of the r.m.s. values was made to determine the practical error margin when analysing comfort.

Tests consisted of stimuli having different amplitudes and frequencies separately for each axis (fore-and-aft, lateral, vertical, roll, pitch and yaw) and for combination of one translational and one rotational axis. Based on these tests the basic characteristics of the sensor and measurement device (e.g. sensitivity and noise) was concluded and the sensor configuration for calculating rotational directions was evaluated. Not all possible combinations were tested, but at least two different amplitudes and frequencies for all possible combinations of axes were used.

Table 9. Summary of the test stimuli conducted for evaluating the accuracy of the developed sensor configuration. At least two frequencies and amplitudes were used for all possible combinations of axes (all six axes separately and combination of one translational and rotational axis).

Excitation signals	Axes	Amplitudes
1, 4, 8, 16, 40 and 80 Hz (sinusoidal), 0-20 Hz (random)	Fore-and-aft, lateral, vertical, roll, pitch and yaw	0.25, 0.5, 1.0 and 2.0 m/s^2

The analysis included comparison of the sensor signals in time and frequency domain and the differences of the frequency weighted r.m.s. values. The most important goal was to evaluate the error margin of the r.m.s. values, because that in practice defines the usability of the equipment.

Time domain analysis was not the most convenient way to compare signals, but showed visually any discrepancies (e.g. Figure 26 left). A more efficient way was using the frequency domain, in this case power spectral density (PSD) (e.g. Figure 26 right). The results showed that both sensors corresponded well to the stimulus. Because IMV had 1024 Hz sampling rate and the developed prototype equipment had 260 Hz sampling rate, the signal from IMV was resampled to 260 Hz. The resampling process was not exact so small differences can be seen in the time domain. However, the resampled signals corresponded to each other very well and no significant differences were found based on the time and frequency domain analyses. IMV had better noise ratio, which was expected, because the prototype equipment did not yet include efficient noise reduction, and because IMV has low noise piezoelectric sensors. The noise of the developed equipment was due to a noisy power source (i.e. 50 Hz peak in the spectrum) and because the sensor is ratiometric the output signal is influenced by the noise of the input voltage. This issue was known and can be solved by introducing a high precision voltage regulator.

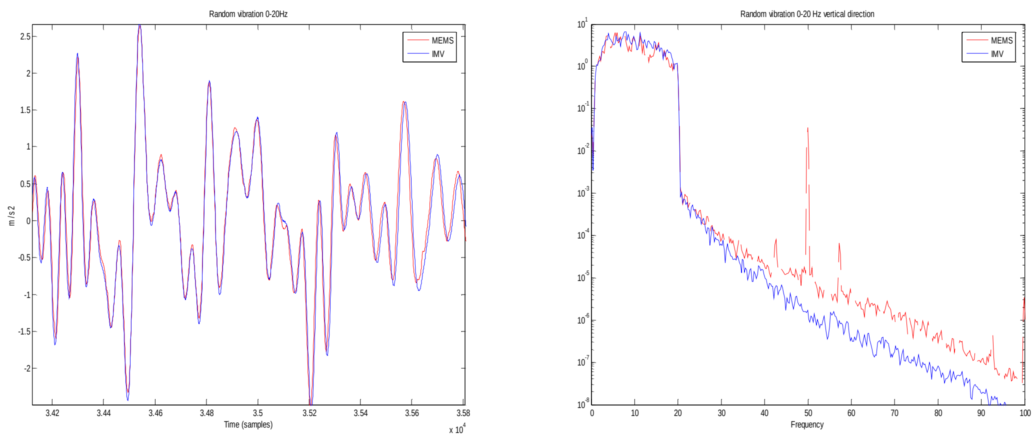

Figure 26. Random vibration in time domain (left) and frequency domain (right) from the test bench for MEMS and IMV.

Based on the frequency domain information, a transfer function estimate was calculated to provide frequency response information between the two sensors (Figure 27). Between 0 and 20 Hz the signals from the sensors had highest differences in 10 Hz area (+8 % to -4 %). In other areas the difference was much smaller. In the 0 to 20 Hz area the mean ratio was 1.0091 and standard deviation 0.029.

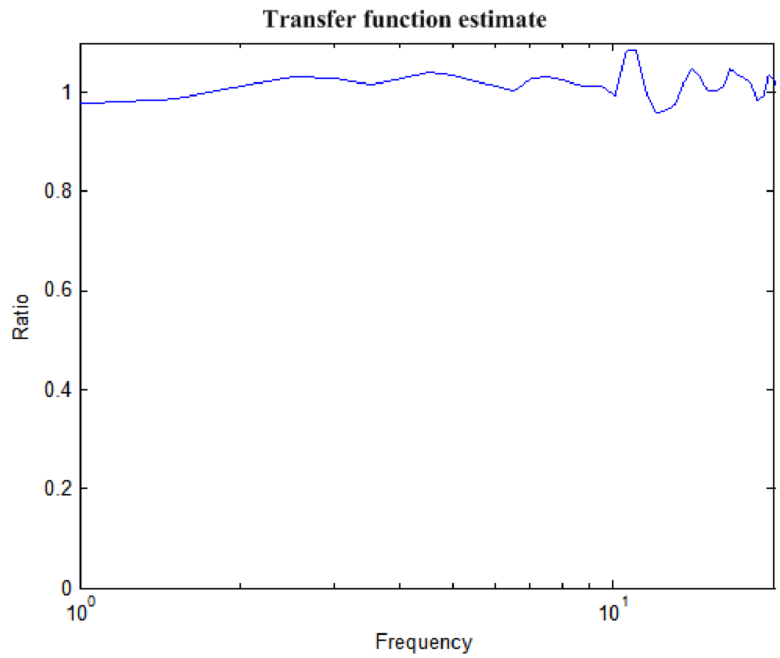

Figure 27. A transfer function estimate comparing MEMS to IMV for vertical axis. Same analysis was made for all axes for each stimulus.

The last procedure was to calculate frequency weighted r.m.s. values and to compare the differences between them (Figure 28). For the example stimulus the MEMS sensor showed 0.661 m/s^2 and IMV 0.694 m/s^2 for vertical direction. The difference was less than 5 %. The same procedure was conducted for all analysed stimuli. A linear trendline of the r.m.s. values shows that in general IMV gives 5.9 % higher values than MEMS.

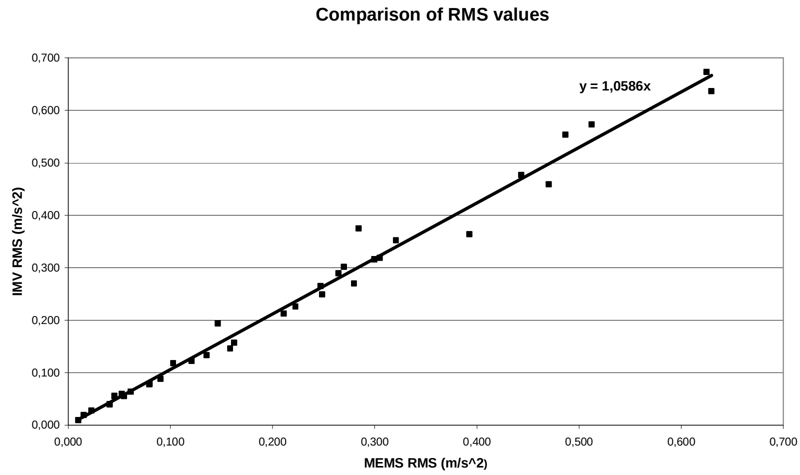

Figure 28. Comparison of the r.m.s. values of IMV and MEMS for all analysed stimuli. R.m.s. values are calculated for combining three translational and three rotational axes based on the overall vibration total value of the ISO 2631-1 standard.

The error margins found comparing to the commercial equipment were small (< 5 %) and can be considered as sufficient for practical measurements, because other error factors in field measurements are much higher. The technical specifications in ISO 8041 alone allow errors from ±10% to even up to ±27% (Mansfield 2003). Although the commercial measurement equipment should give systematic results, in a study the difference between measurement systems were concluded to be even 25% of each other (Tyler and Darlington 2004). The accuracy was within the required limits even at very small amplitudes (e.g. 0.06 m/s^2).

4.3.2.4 Summary

A 6-axis seat pad was designed, constructed and validated using a 6-axis test bench at JNIOSH, Kawasaki, Japan, and by comparing results to those obtained using a commercially available system, compliant with ISO 8041. Small tri-axial MEMS-sensors were used. A circuit board was designed including also anti-aliasing filters.

The developed prototype was the first test version and thus did not include all the necessary components of commercial measurement equipment. Because the purpose was mainly to show the usability of less expensive sensors for practical measurements, a commercial development kit was used for data recording. The results showed that using simple and less expensive components it is possible to realise a 12-axis measurement system. The next step was to further develop the current equipment for enabling practical field measurements.

4.3.3 Prototype II: Experiment for validating equipment for field measurements

4.3.3.1 Purpose

The equipment of the first prototype was still impractical and the sensor signals needed to be noise controlled. Thus a second prototype was needed. The goal for the second prototype was to allow practical field measurements, so the equipment was designed to be simple and small.

4.3.3.2 Technical details

A digital version of the same MEMS sensor (prototype I) was chosen to minimise the noise and need for additional components. The resolution of the digital version is dependent on the chosen amplitude range and the performance of the noise reduction. The internal A/D conversion resolution of the sensor is 12 bits, thus the maximum theoretical resolution is 1/4096 of the amplitude range (in reality the sensor does not use the whole A/D-range optimally, so the practical sensitivity is lower). There were four possible amplitude ranges to choose from (Table 10). Using the maximum digital resolution an optimal sensitivity was calculated. The ±1.5 g versions were chosen for the seat pad and ±3.0 g for the floor and backrest, because it is rare to exceed 10 m/s^2 acceleration on the seat, but floor vibrations can be much higher. The amplitude range for the backrest sensor was chosen to be same as for the floor sensor for practical purposes.

Table 10. The theoretical sensitivity (i.e. smallest detectable change in vibration amplitude) for different amplitude ranges of the selected MEMS sensor.

Amplitude range (g)	Amplitude range (m/s^2)	Sensitivity (m/s^2)
±1.5	29.43	0.0072
±2.0	39.24	0.0096
±3.0	58.86	0.0144
±6.0	117.72	0.0287

The sensors and the sensor configuration were designed based on the experience of the first prototype. This time all sensors of the seat pad were integrated in to the same circuit board, which also included all the other components of the device (Figure 29). Only floor and backrest sensors had separate housings.

The sensors used in the second prototype were digital, thus no separate A/D component was included as the sensors provided a digital signal directly. The digital signals from the six 3-axis sensors were recorded using an FPGA chip, which sampled at 400 Hz frequency. The raw acceleration data was saved to four 64 Mbit memory chips. This meant that the equipment could save up to 24 minutes of raw acceleration data from six 3-axis sensors at 400 Hz sampling rate without the need for external data acquision.

The measurement procedure was designed to be very simple: while the device is powered it is measuring and recording data. After the measurement the data is downloaded from the device to PC using a terminal program and RS-232 port.

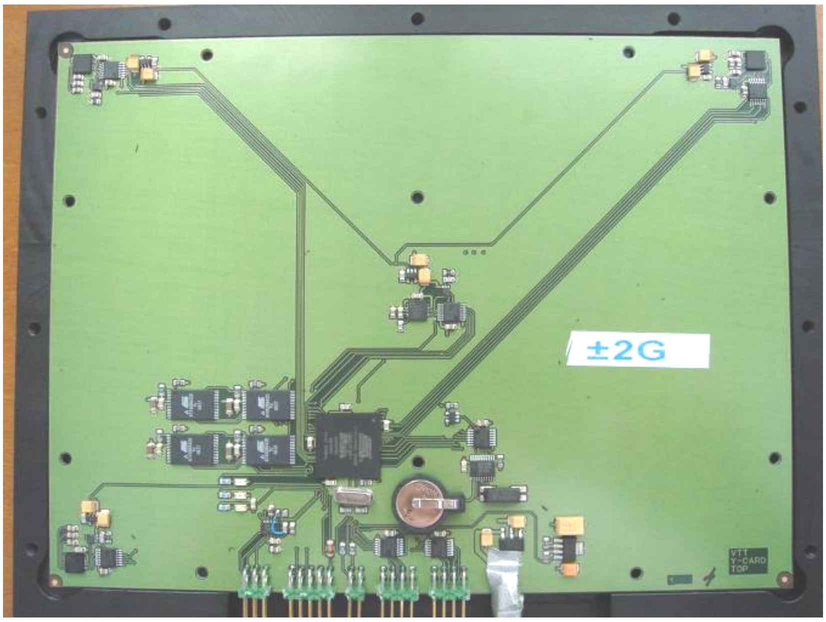

Figure 29. The 6-axis seat sensor and data acquisition system, which includes also memory and processor for acquiring and calculating sensor data.

4.3.3.3 Validation of the accuracy of the equipment

As the sensor configuration was tested previously, the calibration procedure of the second prototype focused on the accuracy of the whole equipment. The experiments were conducted in a laboratory in Finland. Three tests were conducted; 1) noise, 2) sensitivity and 3) sensor calibration test. The noise test was conducted when the sensors were resting on a table. The results showed that the noise was less than the smallest resolution of the values (< 0.01 m/s^2).

Sensitivity was tested and calibrated using the gravity effect. The sensors are capacitive, so they detect the earth's gravity. When the sensor is turned around its axis, the signal value changes based on the gravity, thus the effect of gravitation can be used to calculate the sensor's practical sensitivity and to conduct static calibration (Table 11). Because the information from the sensor was digital, the sensitivity in this case means the same thing as resolution, and the values are in 12 bit integer.

Table 11. The sensitivity of prototype II for all sensors and axes based on the gravity test.

Sensor	Axis	Value (+g)	Value (-g)	Span (value)	Span (gravity)	Sensitivity (m/s2)
1	x	2044.5	1222.8	821.6	+0.5g...-0.5g	0.0119
1	y	2124.1	1298.2	825.9	+0.5g...-0.5g	0.0119
1	z	2963.6	1297.2	1666.4	+g...-g	0.0118
2	x	2056.6	1218.2	838.4	+0.5g...-0.5g	0.0117
2	y	2078.8	1287.8	791.0	+0.5g...-0.5g	0.0124
2	z	2921.3	1286.6	1634.7	+g...-g	0.0120
3	x	2027.9	1194.8	833.1	+0.5g...-0.5g	0.0118
3	y	2266.3	1464.9	801.4	+0.5g...-0.5g	0.0122
3	z	3102.9	1465.4	1637.4	+g...-g	0.0120
4	x	2052.5	1225.2	827.3	+0.5g...-0.5g	0.0119
4	y	2168.0	1357.5	810.5	+0.5g...-0.5g	0.0121
4	z	2996.2	1354.6	1641.6	+g...-g	0.0120
5	x	2033.0	1497.3	535.6	+0.5g...-0.5g	0.0183
5	y	2562.3	1487.5	1074.8	+g...-g	0.0183
5	z	2519.3	1433.7	1085.5	+g...-g	0.0181
6	x	2040.1	1473.3	566.8	+0.5g...-0.5g	0.0173
6	y	2602.8	1518.6	1084.3	+g...-g	0.0181
6	z	2581.2	1493.9	1087.3	+g...-g	0.0180

Figure 30 shows the gravitation test in time domain for one of the sensors for vertical direction. The average value of the stabilised signal was calculated for both positions. The smaller value was then subtracted from the larger one and the result was divided by the gravity span.

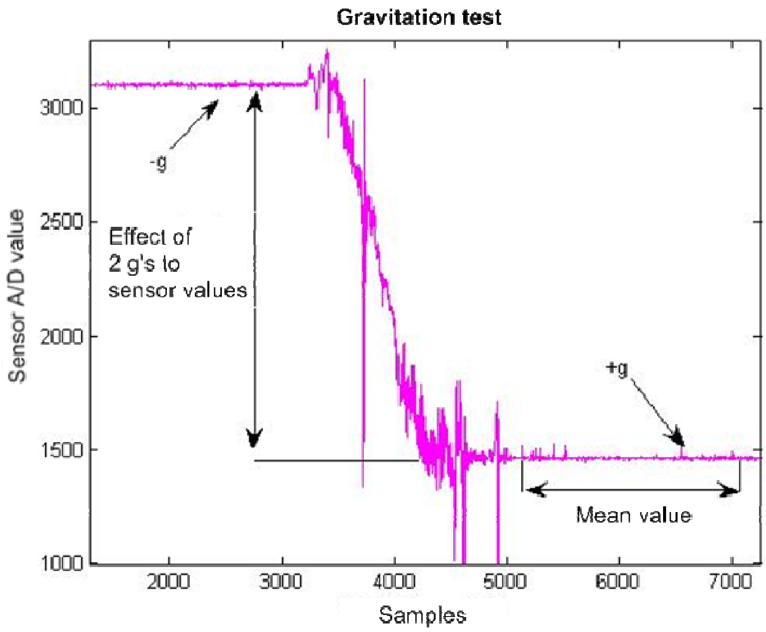

Figure 30. Validation of sensitivity of prototype II by using gravitation test for a vertical axis of one of the sensors.

4.3.3.4 Summary

The second prototype was developed for field measurements requiring minimal components. The tests were conducted to determine the validity of the equipment for whole-body vibration analysis. The results showed that the practical resolution of the system including noise characteristics (less than 0.02 m/s^2) was well enough for analysing the discomfort in reasonable accuracy, and that the equipment can be used for field measurements.

4.3.4 Commercial version

4.3.4.1 Purpose

It was previously concluded that there were no twelve axes measurement systems commercially available in practice. One of the goals of the thesis work was to develop measurement equipment supporting the full method, which would be commercially viable. The purpose was to use the knowledge from the prototypes to produce a commercial version of the measurement equipment. This version was developed with a Finnish technology company Vibsolas, which is specialised in motion sensors and applications (http://www.vibsolas.com).

4.3.4.2 Technical details

The version is based on the same sensor type and configuration used in prototype II, but it was decided to make a more universal sensor system, thus an interface to a general data acquisition system was made. V12SP sensor system comprises from three sensor boards:

- Seat pad sensor (V6SP) including four 3-axis accelerometers (Figure 31);
    - o Can detect translational and rotational acceleration ranges up to 6 g;
- Backrest sensor (V3SP) including one 3-axis sensor (Figure 32);
    - o Detects translational acceleration;
- Floor sensor (V3SP) including one 3 axis sensor (Figure 32);
    - o Detects translational acceleration.

The sensor configuration was designed for calculating translational and rotational accelerations from the seat and translational accelerations from the backrest and floor. The rotational accelerations are detected based on the sensor configuration selected earlier.

Figure 31. The commercial 6-axis seat sensor V6SP board and mechanical housing.

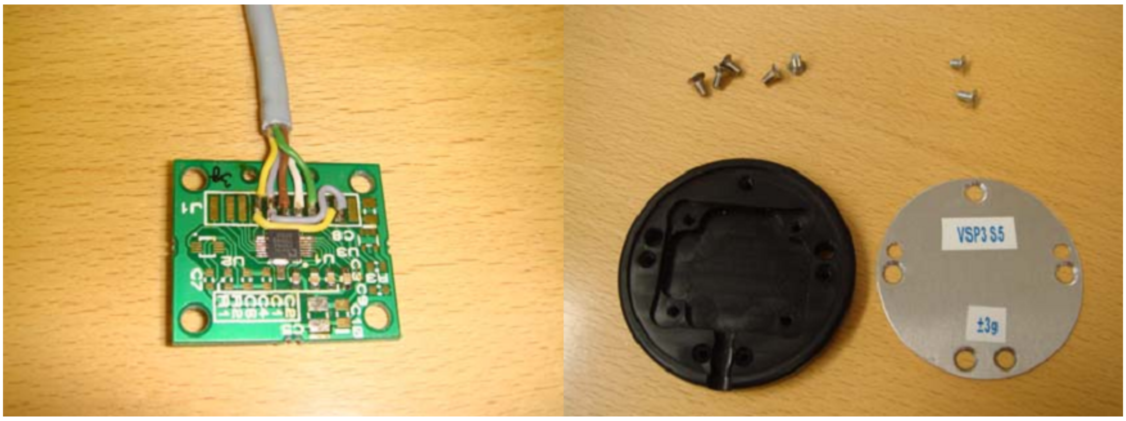

Figure 32. The commercial 3-axis backrest and floor sensor V3SP (left: electronic board, right: mechanical housing).

The analog outputs from the sensors are anti-alias filtered using 100 Hz single pole filter. Recommended sampling rate is 10-20 times the cut-off frequency.

4.3.4.3 Improvements for the second prototype

V12SP was developed for whole-body vibration discomfort analyses and to comply with ISO 2631-1 (1997) requirements. It was designed to use with any data acquisition system (DAQ) that can process analog signals between 0-5 Volts.

4.3.4.4 Validation of the accuracy of the equipment

Table 12 shows the sensitivities of the V6SP sensors (1.5 g and 3.0 g versions). The sensitivities were calibrated using a gravity test with National Instruments NI-DAQ system (power supply 12V, A/D input range 0-5V). The sensitivities might not be similar in another data acquisition system.

Table 12. The sensitivities of the commercial V6SP sensor for 1.5 and 3.0 g versions using National Instruments NI-DAQ system with 5 V input.

Sensor	Axis	Sensitivity 1.5 g (V/g)	Sensitivity 3.0 g (V/g)
A1	x	1.34461	0.62034
A1	y	1.33249	0.66061
A1	z	1.32970	0.67333
A2	x	1.33230	0.64181
A2	y	1.32400	0.67069
A2	z	1.33387	0.65580
A3	x	1.32690	0.64603
A3	y	1.33668	0.66508
A3	z	1.34603	0.66251
A4	x	1.34174	0.62246
A4	y	1.35110	0.66326
A4	Z	1.34132	0.66335

4.3.4.5 Summary

A commercial version of the 12-axis sensor system was developed and validated. The system can be used with any data acquisition system with A/D inputs from 0 to 5 V. The equipment can be bought through the company website at a reasonable price.

4.4 Developing and validating analysis software

The process of measuring and analysing the 12-axis vibration for discomfort evaluation is described in Figure 33. The whole process involves several steps from acquiring the raw acceleration signal to the calculation of the final value. Some of the steps are done in the measurement equipment, such as detecting the acceleration signals, anti-aliasing the signals, A/D converting and recording them in the memory. After downloading the data to a computer it needs to be unit converted, rotational directions calculated, frequency weighted, r.m.s. and CSF (Crest Factor; r.m.s. peak value) values calculated, multiplying factors applied, and finally the point vibration total value and overall vibration total value calculated. The final version of the analysis program was made using a Python development environment.

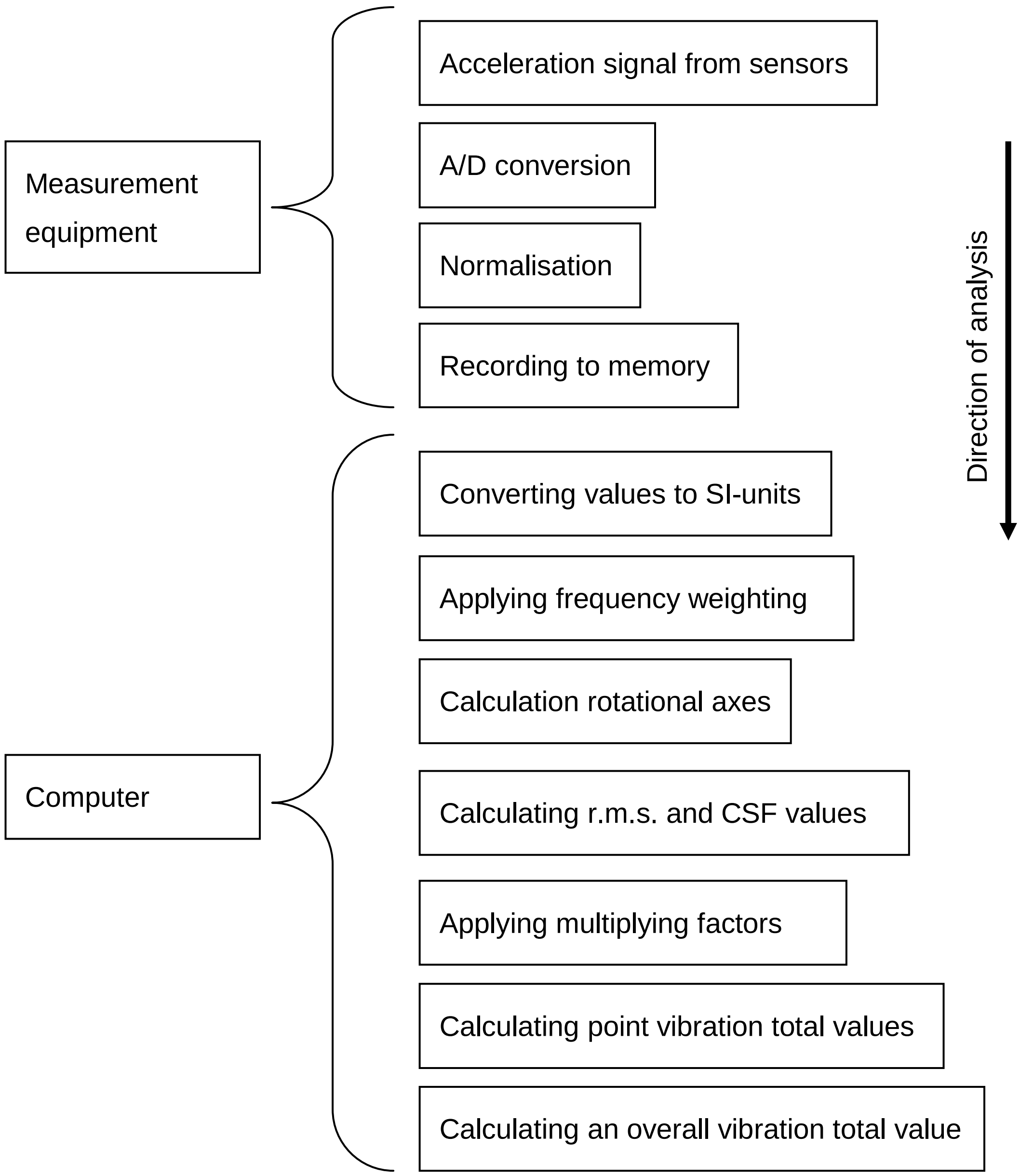

Figure 33. The analysis procedure of the developed measurement equipment and software for measuring, calculating and evaluating discomfort from whole-body vibration using the full method of ISO 2631-1.

4.4.1 Converting to SI-units

Each sensor has a sensitivity range, which is noted in relation to the digital value and acceleration (e.g. 864 counts/g for digital sensors and 560 mV/g for analog sensors). The values from the sensor need to be converted to represent acceleration values using this information. In the Table 11 there are calculated sensitivity values for each of the sensor directions used in this study, based on the gravity test. The conversion is done using equation 20, where the sensor value S_{sensor} is multiplied by the sensitivity value:

$$R_{SI} = S_{sensor} \cdot Sensitivity \tag{20}$$

Figure 34 shows the change in the signal after unit conversion. At this point the data has not been filtered yet.

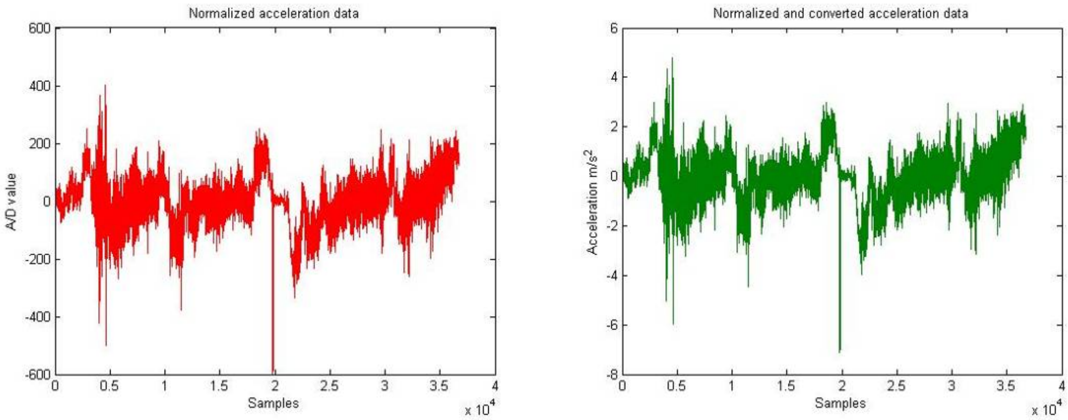

Figure 34. Converting the raw acceleration data from A/D values to SI units (m/s^2) (left: before and right: after).

4.4.2 Frequency weighting

Each axis has a defined frequency weighting curve (i.e. filter). The standard gives the values to create the filtering algorithms to represent the frequency weightings. There are different methods to realise the filters. In this case the filters were developed in a Python environment using digital IIR-filter design.

The developed filters can be validated in several ways. At first the evaluation can be done by plotting developed and the standardized filters in the frequency domain. Secondly weighting values at each 1/3 octave band can be compared and for third r.m.s. and crest factor values can be calculated for the reference stimulus in the standard (ISO 8041 2005). The developed filters are visually identical to the standard's filters (Figure 35 and Figure 36).

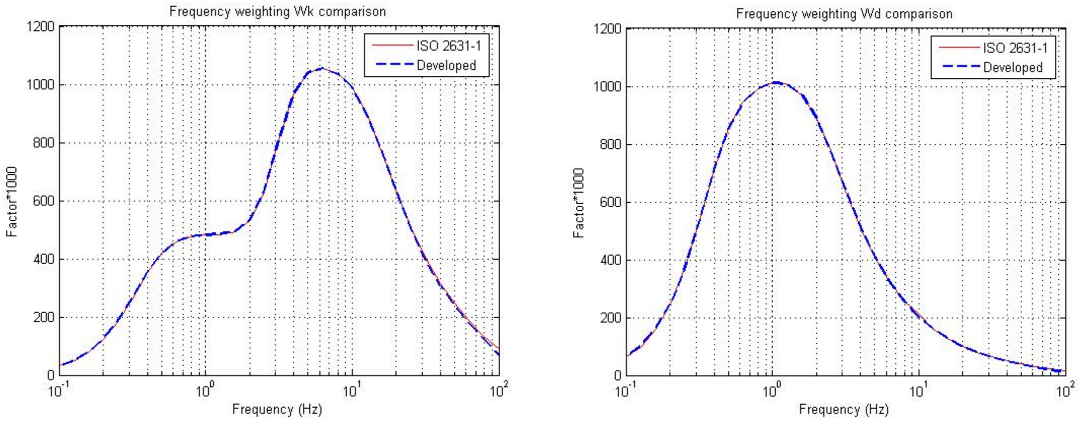

Figure 35. Frequency weighting curves Wk (left) and Wd (right) for both developed and standard's filters in frequency domain.

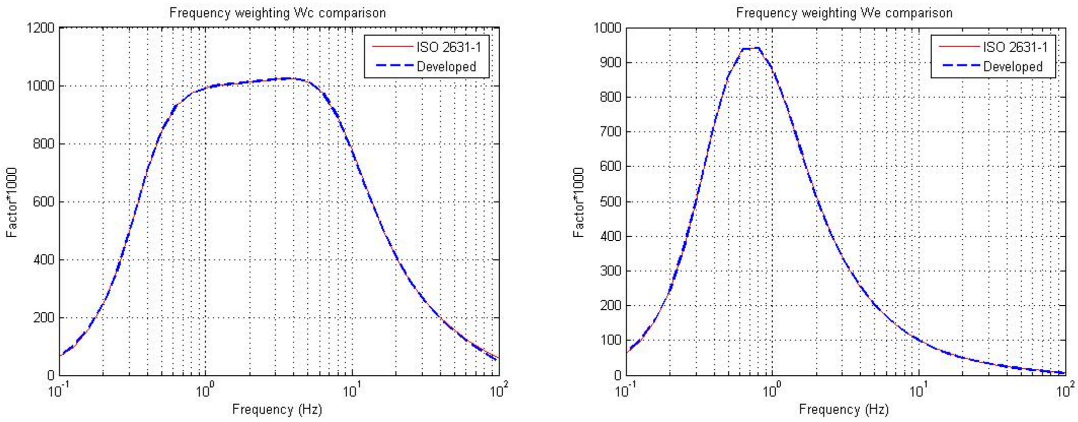

Figure 36. Frequency weighting curves Wc (left) and We (right) for both developed and standard's filters in frequency domain.

The developed filters comply with the tolerance requirements of ISO 8041 standard up to 100 Hz (Table 13). The software uses sampled data up to 100 Hz and rest of the data is cut-off by resampling process.

Table 13. Weighing values for the standard and developed weighting curves and errors (%) between them at each $^{1}/_{3}$ octave frequency.

	Developed filter				ISO 2631-1 Standard				Error (%)			
Freq (Hz)	W_k	W_d	W_c	W_e	W_k	W_d	W_c	W_e	W_k	W_d	W_c	W_e
0.100	31.5	63.1	63.0	63.2	31.2	62.4	62.4	62.5	1.0	1.1	1.0	1.1
0.125	50.3	100.7	100.6	101.0	48.6	97.3	97.2	97.5	3.5	3.5	3.5	3.6
0.160	80.2	160.6	160.3	161.3	79.0	158.0	158.0	159.0	1.5	1.6	1.5	1.5
0.200	121.5	243.7	243.2	245.3	121.0	243.0	243.0	245.0	0.4	0.3	0.1	0.1
0.250	181.8	365.3	364.0	368.5	182.0	365.0	364.0	368.0	-0.1	0.1	0.0	0.1
0.315	262.1	528.5	525.7	534.9	263.0	530.0	527.0	536.0	-0.3	-0.3	-0.2	-0.2
0.400	351.3	711.6	705.9	721.6	352.0	713.0	708.0	723.0	-0.2	-0.2	-0.3	-0.2
0.500	417.6	851.5	841.7	860.8	418.0	853.0	843.0	862.0	-0.1	-0.2	-0.2	-0.1
0.630	458.5	943.5	928.5	938.3	459.0	944.0	929.0	939.0	-0.1	-0.1	-0.1	-0.1
0.800	476.9	992.1	972.2	940.8	477.0	992.0	972.0	941.0	0.0	0.0	0.0	0.0
1.000	482.4	1010.9	990.9	879.6	482.0	1011.0	991.0	880.0	0.1	0.0	0.0	0.0
1.250	484.6	1007.5	1000.2	772.2	484.0	1008.0	1000.0	772.0	0.1	0.0	0.0	0.0
1.600	494.3	968.3	1006.6	631.8	494.0	968.0	1007.0	632.0	0.1	0.0	0.0	0.0
2.000	531.4	890.2	1011.7	511.5	531.0	890.0	1012.0	512.0	0.1	0.0	0.0	-0.1
2.500	630.6	775.9	1017.1	409.0	631.0	776.0	1017.0	409.0	-0.1	0.0	0.0	0.0
3.150	804.1	641.9	1022.5	323.0	804.0	642.0	1022.0	323.0	0.0	0.0	0.0	0.0
4.000	967.3	511.8	1023.8	253.0	967.0	512.0	1024.0	253.0	0.0	0.0	0.0	0.0
5.000	1038.9	408.9	1012.8	201.6	1039.0	409.0	1013.0	202.0	0.0	0.0	0.0	-0.2
6.300	1054.4	322.9	974.1	159.5	1054.0	323.0	974.0	160.0	0.0	0.0	0.0	-0.3
8.000	1036.2	252.8	890.4	125.3	1036.0	253.0	891.0	125.0	0.0	-0.1	-0.1	0.2
10.00	987.8	201.3	775.0	100.0	988.0	212.0	776.0	100.0	0.0	-5.0	-0.1	0.0
12.50	900.9	160.4	644.8	79.9	902.0	161.0	647.0	80.1	-0.1	-0.4	-0.3	-0.3
16.00	765.7	124.8	509.2	62.2	768.0	125.0	512.0	62.5	-0.3	-0.2	-0.5	-0.4
20.00	631.4	99.4	405.6	49.6	636.0	100.0	409.0	50.0	-0.7	-0.6	-0.8	-0.8
25.00	506.7	79.0	321.2	39.5	513.0	80.0	325.0	39.9	-1.2	-1.3	-1.2	-1.1
31.50	397.4	62.1	251.3	31.0	405.0	63.2	256.0	31.6	-1.9	-1.7	-1.8	-1.8
40.00	305.9	48.1	193.9	24.0	314.0	49.4	199.0	24.7	-2.6	-2.6	-2.6	-2.7
50.00	236.5	37.4	150.3	18.7	246.0	38.8	156.0	19.4	-3.9	-3.6	-3.7	-3.7
63.00	176.0	28.0	112.2	14.0	186.0	29.5	118.0	14.8	-5.4	-5.1	-4.9	-5.6
80.00	120.0	19.1	76.6	9.6	132.0	21.1	84.4	10.5	-9.1	-9.5	-9.2	-9.0
100.0	69.6	11.1	44.5	5.6	88.7	14.1	56.7	7.1	-21.5	-21.3	-21.5	-21.4

The values for reference signal from ISO 8041 show practically same results for the developed software (Table 14). This is the official test based on the standard to validate the frequency weightings. Results show less than 1 % error for each test.

Table 14. Calculated r.m.s. values for the standard and developed frequency weightings using guided reference frequencies.

Application	Weighting	Reference frequency	Reference amplitude	ISO 2631-1 filter	Developed filter
Whole-body vibration	W_c	15.915 Hz	1.0 m/s^2	0.5145	0.5144
	W_d			0.1261	0.1261
	W_e			0.06287	0.06286
	W_k			0.7718	0.7716

Figure 37 shows the acceleration signal before and after the frequency weighting. Because the standard's filtering emphasises only lower frequencies the characteristics of the signal can change significantly in the time domain.

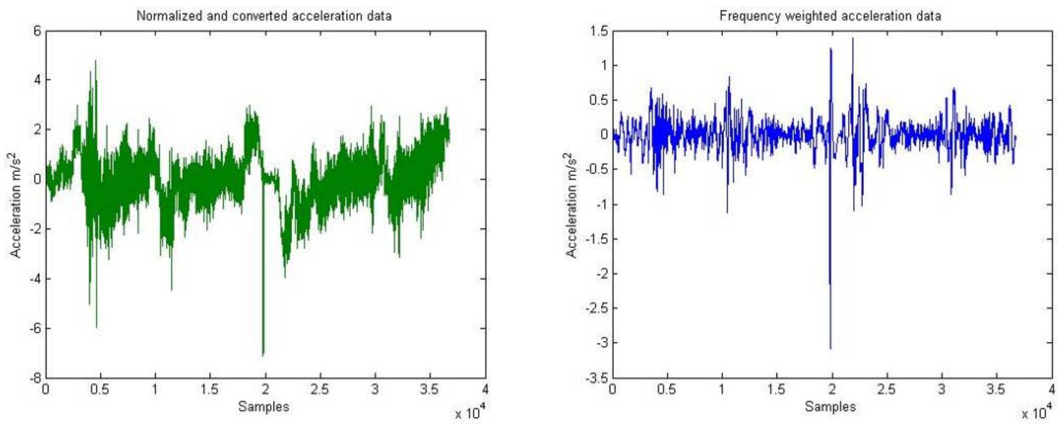

Figure 37. An example of the effect of frequency weighting w_d for the acceleration data in time domain (left: before and right: after).

4.4.3 Root mean square values and crest factors

The r.m.s. calculation can be validated using reference signals. In this case the reference signal was 1 Hz and 1 m/s^2 sine wave (Table 15). In this case the r.m.s. value should be 0.707 and the CSF should be 1.4142. The results showed a very good match to ideal values, thus the software functions can be concluded to work properly.

Table 15. Validating the r.m.s. and CSF calculations using a reference signal.

Reference freq.	Reference amplitude	Theoretical r.m.s.	Theoretical CSF	Calculated r.m.s.	Calculated CSF
1 Hz	1 m/s^2	0.707 m/s^2	1.414	0.707 m/s^2	1.414

4.4.4 Point and overall vibration total values

Validating the functions, which calculate point and overall vibration total values (Equations 13 and 14) is simple. The results were tested using Microsoft Excel function for vector sum and comparison to the developed Python function. Results from the calculations can be verified and determined that programmed functions work (Table 16).

Table 16. Reference values to validate if programmed algorithms to calculate point and overall vibration total values work. Both values are calculated using a vector sum principle (Equation 13).

	Results	
Reference values for x, y, and z	**Excel**	**Python**
1,2,3	3.741657	3.741657
4,5,6	8.774964	8.774964
7,8,9	13.92839	13.92839
10,11,12	19.10497	19.10497

4.4.5 Calculating rotational axes

Because the chosen solution for recording rotational accelerations is based on translational accelerometers, the rotational directions need to be calculated based on at least two sensors. The rotational directions can be calculated using Equations 17-19. There is a reference publication that has already validated the method (Yamashita and Maeda 2003). The data from experiment I was used to validate the software.

4.4.6 Software development

The analysis software was first developed and tested. It was further developed using Python programming language, thus a commercial and license free software was produced (PyHuman package).

4.4.7 Summary

The validation of the analysis process and software was found to comply with the standard. The frequency weighting curves were nominally identical up to 100 Hz, which is the effective range of the system and exceeds the 80 Hz upper limit described in ISO 2631-1. Also the r.m.s. and CSF equations gave practically identical results compared to ISO 8041 requirements. Based on the test it was concluded that the analysis is accurate and complies with the standards' requirements.

4.5 Conclusions

12-axis measurement equipment and analysis software were developed and validated. The tests showed compliance with the standards' requirements. The standards do not include guidance on how to build and test the 6-axis seat pad sensor, but another reference was used to realise it (Yamashita and Maeda 2003). Based on the results it was concluded that the equipment and the software are accurate enough to be used for the full discomfort evaluation based on ISO 2631-1 standard.

5 Chapter 5 - Field measurements: contribution of twelve axes according to the ISO 2631-1 method

5.1 Introduction

Because of the lack of usable measurement equipment and the confusing guidance of the standardised method, there have been very few studies that have used the standard ISO 2631-1 method to evaluate discomfort from whole-body vibration and even fewer that have measured and analysed all twelve axes in the field. Thus there has not been enough data to evaluate how the twelve axes are present in the field and which measurement locations are important.

Typically 3-axis sensors are used for measuring vibration in the field, thus in practice there is more interest in evaluating how many locations need to be measured, instead of the individual axes. As rotational axes require more complex measurement configuration, it is of interest to conclude if rotational axes can be completely neglected. However, because of lack of publications analysing the effects of the axes in the field, the relative importance of individual axes are also needed to be analysed, as well as the effects of frequency weighting and multiplying factors for emphasising the axes and locations. Additionally the usability of the r.m.s. method (i.e. crest factor values) and possibilities to compensate missing locations using multiplying factors need clarification.

Based on the literature review in Chapter 2, only two adequate publications were found to have 12 axis data (Griffin 1990, Maeda 2004). However, it was found that neither publication gave enough information to conduct all the necessary analyses to conclude the relative effects of the axes. Also the data sets in the publications were relatively small, thus additional measurements were considered necessary. The literature review in Chapter 2 found also another 12-axis measurement study (Parsons and Griffin 1983), but the method they used is not the same as in the standard.

The relative importance of the axes is affected by the frequency weighting curves, the multiplying factors and the root-sum-of-squares (r.s.s.) method for combining the axes to point and overall vibration total values (PVTV and OVTV). The frequency weighting models the response of the body in the frequency domain and the multiplying factors define the relative importance of the axes in the same location when calculating

PVTVs. The differences between locations are emphasised when PVTVs are combined to OVTV as PVTVs are multiplied to the second power (i.e. highest PVTV is emphasised). Thus, the standard procedure might affect the results so that certain axes and locations will always be most dominant (i.e. there is no need to measure some axes in any environment). This needs to be verified.

The standard’s recommendation to use 1.4 multiplying factors for horizontal axes when using only translational axes from the seat has no reference. There are no papers that have validated the factors. The purpose of the factors is not clear, but it is assumed that they are used to compensate for the missing backrest axes (i.e. OVTV using the seat translational axes or seat and backrest translational axes should give similar values). It needs to be validated for different work environments. It is also noted that no compensating factors are provided for floor translational or seat rotational axes. Similar factors should also be produced for them if they contribute to the OVTV.

For most work machines and vehicles the seat has a relatively rigid frame, thus vibration measured from the seat surface should correlate to backrest vibration. Also floor vibration can have a correlation to seat vibration. Depending on the suspension and cushion type, the correlation may vary significantly. If comparison of OVTVs from different measurements is done, then the axes, which have not been used, should be compensated so that all results would equal the value using all axes. It would be easier to have a compensating factor for PVTVs instead of each axis. If PVTVs of locations have high correlation, then they can be compensated by a single multiplying factor.

The standard method assumes that the weighting procedure will produce a value that is linked to the discomfort from vibration exposure. However, the frequency weighted r.m.s. method produces the averaged value of each axis for the whole frequency range from 0.5 to 80 Hz. It might be that an axis has dominant amplitude at a specific frequency range, but is not dominant if the whole range is averaged, such that the axis or PVTV could be neglected in the overall assessment. The discomfort might be more a sum of combination of axes, which are dominant at each frequency range, than based only on the dominant axis or location. It has been noted in previous studies that amplitudes and frequency characteristics change the discomfort depending on whether low or high frequencies dominate. This suggests that vibration has different effects depending on the frequency range.

The conclusions from the previous publications and the analysis of the standard weighting procedure lead to the following hypotheses:

- All twelve axes are not needed to be measured (i.e. not all measurement locations) (e.g. (Wikstroem, et al 1991));
    - Most likely at least rotational axes can be neglected;
- There is a correlation between some axes, thus their effect can be approximated based on the other measured axes (i.e. the effect of some measurement locations can be approximated by using a multiplying factor) (e.g. (ISO 2631-1 1997));
- Most dominant axes will be translational axes from the seat and backrest fore-and-aft (i.e. most dominant measurement location will be the seat surface) (e.g. (Maeda 2004));
- Different axes are dominant at low frequencies than high frequencies (i.e. weighting attenuates the axes differently);
- R.m.s. method is the best method to calculate vibration magnitudes of the axes and r.s.s. for combining the axes for evaluating discomfort (e.g. (Parsons and Griffin 1983)).

5.2 Goals of the field measurements

The goal is to analyse how the nine translational and three rotational axes, and the three measurement locations, which are set by the standard (ISO 2631-1 1997), have importance in real work environments. Based on the analyses, laboratory and field trials can be designed and conducted to find out the relative effects on discomfort.

The purpose of the analyses is to find answers to the following questions:

- What are the dominant and negligible axes and locations in practice?
- Are the dominant axes and locations similar in all machines or do they change between machines and environments?
- Does dominance in axes change for different frequency ranges?
- What are the effects of the ISO 2631-1 frequency weighting curves and multiplying factors for emphasising axes and locations?
- Can the r.m.s. method be used to evaluate the effects of vibration (i.e. is crest factor threshold exceeded)?

- Can vibration from another location be approximated by using a multiplying factor, thus simplifying the number of the measured locations (e.g. the standard suggests that the effect of seat backrest axes can be replaced by 1.4 multiplying factors for seat horizontal axes)?;
- Are results from the previous studies and the new field measurements similar enough to have more general conclusions from the results?

The new field measurements are conducted to extend the published data sets. The purpose is to measure 12-axis whole-body vibration exposure from typical mobile work machines (e.g. wheel loader) and transport equipment (e.g. bus) in normal working conditions. All new measurements are planned to be conducted in real working conditions with real machine operators. At least two different work phases of each machine and at least two repetitions of minimum of 3 minutes each is measured. If the measured task is shorter than 3 minutes, then it is repeated as long as the minimum measurement period is fulfilled.

5.3 Methods

5.3.1 Results from previous publications

The results of the 12-axis data found in the previous studies (Griffin 1990, Maeda 2004) were included in the analysis with the new field measurements. The frequency weighted r.m.s. values for each axis was used. Neither study reported unweighted r.m.s. values or crest factors, thus some analyses were not possible from the previous publications.

5.3.2 Measurement procedure

Although the measurement plan included the measured machine types, the machine model, manufacturing year, etc, were not chosen beforehand. These were determined by the availability of the machine to be measured. Some of the machines (a bus, train and car) were chosen because the other publications had measured them also. This was done for including overlapping data with previous measurements for direct comparison and reference.

Before the installation of the equipment, the information of the machine and environment was documented. Also the sensors were calibrated with a gravity test before each installation. The sensors were installed on a seat, backrest and floor using adhesive tape (Figure 38). The equipment with the same setup (i.e. sensor configuration) was used for all measurements. All measurements were recorded as raw acceleration data from six 3-axis sensors. Four 3-axis sensors were used to measure rotational and translational axes from the seat based on Figure 23, one 3-axis sensor recorded translational axes from the floor and one 3-axis sensor recorded translational axes from the backrest. The measurement procedure and purpose was explained to the machine operator. The measurement itself was automatic, so that the operator did not need to do anything except use the machine normally. Each operator signed a consent form.

Figure 38. The sensors were installed to the floor, seat surface and backrest based on the guidance of the ISO 2631-1 standard. The equipment used in the new field measurements were based on the second prototype version (Chapter 4).

During the measurements the additional information of the work phases, surface/terrain, speed, etc, were documented. Because the measurements for each machine were conducted in the period of a few hours, the environmental conditions (e.g. weather and surface) could not be chosen and are not comparable to other measurements. Based on the sensor information the 12-axis data was calculated in the developed PC environment (Chapter 4). The measurements were done in real working conditions comprising 1-7 repetitions of a single work phase for 3-10 minutes at one time (Table 17).

Table 17. *The measured machines and information from the new field measurements conducted in this thesis. Each machine and work phase was measured in an authentic environment, where the operator worked normally.*

Machine type	Machine model	Work phase	Speed	Repetitions	Duration per repetition (min to max)
Tractor #1	New Holland	Moving gravel road	43 km/h	4	3-5 mins
Tractor #2	New Holland	Moving asphalt road	43 km/h	4	3-5 mins
Tractor #3	New Holland	Cultivating in field	12 km/h	2	3-5 mins
Excavator #1	Volvo	Moving	5 km/h	2	3-5 mins
Excavator #1	Volvo	Digging	0 km/h	5	3-5 mins
Train #1	Pendolino	Moving	130 km/h	5	8-10 mins
Train #2	Pendolino	Slowing down	130-0 km/h	1	10 mins
Train #3	Pendolino	Accelerating	0-130 km/h	1	8 mins
Car #1	Volvo	Moving asphalt road	60 km/h	3	5-10 mins
Car #2	Volvo	Moving asphalt road	100 km/h	1	8 mins
Car #3	Volvo	Moving stone road	30 km/h	2	10 mins
Harvester #1	Ponsse	Moving in forest	3 km/h	6	5-10 mins
Harvester #2	Ponsse	Harvesting trees	0 km/h	1	5 mins
Bus #1	Volvo	Moving in city area	10-40 km/h	7	3-8 mins
Truck #1	Scania	Moving in city area	10-50 km/h	6	3-8 mins

5.3.3 Signal processing

The raw acceleration data from the sensors was bandpass filtered from 0.5 to 80 Hz as required in the standard, before the frequency weighting filters were applied. The rotational axes were calculated based on the vibration data from the seat pad sensor (see Figure 24 and Equations 17-19 in Chapter 4). The signal processing was conducted using the previously validated software.

5.3.4 Vibration magnitudes

Vibration magnitudes were calculated for each axis with and without frequency weightings using the r.m.s. method. Crest factors were determined for the weighted values to analyse the applicability of the r.m.s. method. R.s.s. (Equation 14) were used to combine axes from the same location to PVTVs and OVTVs with and without the documented multiplying factors. Translational and rotational axes were calculated separately from the seat surface as guided in the standard, thus creating four PVTVs:

1) seat translational axes (a_s), 2) backrest translational axes (a_b), 3) floor translational axes (a_f) and 4) seat rotational axes (a_r).

The four most likely measurement scenarios were created for calculating OVTVs: 1) only seat translational axes are measured (a_s), 2) seat and backrest translational axes are measured (a_{sb}), 3) seat, backrest and floor translational axes are measured (a_{sbf}) and 4) all twelve axes are measured (a_v). Scenario 1 represents a typical and simplest measurement scenario, where only seat translational axes are measured using a standard seat pad. Scenarios 2 and 3 are more difficult to realise, but still possible as many measurement systems support multiple sensor inputs (normally up to 16 input channels). Scenario 4 is the most difficult to realise, as it requires using also sensors for measuring rotational axes. However, it is the recommended scenario in ISO 2631-1 if there is no information on the importance of the axes in the environment.

It is also important to note that in most studies scenario 1 has been used without multiplying factors (i.e. 1.0) as described in the standard's main text. However, the standard notes that 1.4 multiplying factors should be used for seat horizontal axes, if the backrest axes are not measured. Based on the results from many studies it is clear that this note has not been considered and rarely have the multiplying factors been used when evaluating discomfort (the same multiplying factors are mandatory when evaluating the health effects). It is of interest to analyse to role of the compensating multiplying factors, thus two version from scenario 1 was created: $a_{s1.0}$ (no multiplying factors) and $a_{s1.4}$ (with 1.4 multiplying factors for horizontal axes). In other scenarios PVTV is calculated without the multiplying factors ($a_{s1.0}$) as they all include the backrest axes.

It is important to note that PVTV of seat translational axes will produce the same value as OVTV in scenario 1. In this case the 1.4 multiplying factors should always be used. Also the assumption is that if other locations are used then they include already locations from the previous scenarios, thus no measurement is made only from the backrest or floor.

5.3.5 Relative magnitude and contribution of the values

The relative magnitudes and contribution of all twelve axes and locations were analysed. The relative magnitude a_{ri} (in percentage) can be calculated as:

$$a_{ri} = \frac{a_i}{a_{\max}} \cdot 100\% \qquad (21)$$

where a_i is the r.m.s. value of a location (i.e. PVTV) or an axis i and a_{max} is the highest r.m.s. value of OVTV or the axes.

The relative contribution of a component to the OVTV a_{ci} (in percentage) can be calculated as:

$$a_{ci} = \left(\frac{a_i}{a_v} \right)^2 \cdot 100\% \tag{22}$$

where a_v is OVTV and a_i is the r.m.s. value of a PVTV or an axis i.

5.3.6 Dominant axis at different frequency range

The dominant axis at each 1/3 octave frequency was determined for each machine type for the new field measurements using three setups: 1) frequency weighting and multiplying factors, 2) frequency weighting without multiplying factors and 3) without frequency weighting and multiplying factors. The change in the dominant axis and the influence of frequency weighting and multiplying factors were evaluated. The evaluation was made by calculating the r.m.s. value for all twelve axes for each 1/3 octave frequency. The highest value was the dominant axis in that frequency.

5.3.7 Effects of frequency weighting and multiplying factors to the relative contribution of axes and locations

The relative magnitude and contribution of each axis and PVTV to OVTV was calculated with and without frequency weighting. Additionally the effect of multiplying factors were analysed based on comparing the relative contribution of PVTVs with and without the factors.

5.3.8 Effect of the 1.4 multiplying factors for seat horizontal axes to compensate backrest axes

The multiplying factors for seat horizontal axes were validated by calculating the factors, which would equalise a_s and a_{sb}:

$$a_{sb} = a_s \Rightarrow a_{sb} = \sqrt{k^2 \cdot a_{wx}^2 + k^2 \cdot a_{wy}^2 + a_{wz}^2} \Rightarrow k = \sqrt{\frac{a_{sb}^2 - a_{wz}^2}{a_{wx}^2 + a_{wy}^2}} \tag{23}$$

where a_{sb} is OVTV of seat and backrest translational axes, a_s is PVTV of seat axes with multiplying factors, a_{wx}, a_{wy} and a_{wz} are the frequency weighted r.m.s. values of seat translational axes x, y and z and k is the multiplying factor for horizontal axes.

5.3.9 Calculating compensating factors for overall vibration total values using a different number of axes

The analysis of correlation between number of included axes was conducted by comparing OVTVs of different scenarios by calculating Spearman rho (r^2). The purpose of this method was not to analyse the true correlation in frequency domain (i.e. coherence), but the practical correlation when using the standard method for selecting the appropriate number of axes for calculating OVTV. Additionally compensating multiplying factors were calculated for scenarios 1-3 that would equal a_v using the following principle:

$$a_v = k_i \cdot a_i \qquad (24)$$

Where k_i is a compensating factor for scenario i, and a_i is OVTV based on scenario i.

5.4 Results

5.4.1 Results from the previous publications

Two publications were found that reported data which was appropriate for the study. In this case only results from these two publications were taken, because no other well enough documented papers were found. Previous publications had partly similar machines and work environments. Griffin (1990) showed data from three machines, which were each measured for about 60 seconds. Maeda (2004) published results from seven machines. Maeda's measurements were from 10 to 120 minutes and 4-5 repetitions (Maeda 2007).

Some analyses were not possible from the results of the previous studies as they only reported the frequency weighted r.m.s. values.

5.4.2 Comparison of vibration magnitudes on different machines

OVTV (a_v) varied significantly based on the machine type and environment (Table 18). The smallest OVTVs occurred for the train and car. However, the car showed more variability between the values, because of different surface types. The train had fairly similar track conditions for all of the measurements; thus the values showed more consistency. The highest OVTVs were for the forklift and harvester. The harvester exhibited large variation in the values depending on whether it was moving (#1) or harvesting (#2). Moving in the forest caused three times higher values. In all machines the r.m.s. values from seat rotational and floor translational axes were relatively small compared to OVTV.

The frequency weighted r.m.s. values for each axis showed the highest magnitudes for seat vertical and backrest fore-and-aft axes (Tables 18 and 19). Vehicles driven on smooth surfaces (e.g. car, bus and train) showed small magnitudes for horizontal axes compared to the vertical axis. Vehicles driven on more uneven surfaces (e.g. work machines) had more equal magnitudes for all translational axes. Also rotational motions were significant for the aforementioned machines. The results show consistency amongst different studies.

Table 18. The frequency weighted point vibration total values (m/s^2) for seat translational axes with 1.0 multiplying factors ($a_{s1.0}$), backrest translational axes (a_b), floor translational axes (a_f) and seat rotational axes (a_r) with respective multiplying factors. The frequency weighted overall vibration total values (m/s^2) for seat translational axes with 1.4 multiplying factors ($a_{s1.4}$), seat and backrest translational axes (a_{sb}), seat, backrest and floor translational axes (a_{sbf}) and all axes (a_v) with respective multiplying factors for all measurements. Relative differences (%) are compared to the overall vibration total value using all axes (a_v).

		Point vibration total values				Overall vibration total values				Relative differences (%)			
Measurer	**Machine**	$a_{s1.0}$	a_b	a_f	a_r	$a_{s1.4}$	a_{sb}	a_{sbf}	a_v	$a_{s1.0}$	$a_{s1.4}$	a_{sb}	a_{fsb}
Maeda	Bus	0.537	0.265	0.364	0.155	0.558	0.648	0.667	0.717	75	78	90	93
Maeda	Taxi	0.280	0.115	0.205	0.094	0.300	0.347	0.359	0.377	74	79	92	95
Maeda	Bulldozer	0.999	0.565	1.147	0.355	1.261	1.521	1.561	1.661	60	76	92	94
Maeda	Excavator	0.574	0.205	0.602	0.196	0.750	0.832	0.855	0.879	65	85	95	97
Maeda	Tractor	0.801	0.315	0.562	0.232	0.915	0.979	1.006	1.055	76	87	93	95
Maeda	Combine	0.604	0.258	0.396	0.432	0.734	0.722	0.841	0.880	69	83	82	96
Maeda	Monorail	0.139	0.059	0.100	0.046	0.156	0.172	0.178	0.187	74	84	92	95
Maeda	Fork	1.378	0.399	0.934	0.449	1.454	1.665	1.724	1.770	78	82	94	97
Griffin	Bus	0.450	0.262	0.362	0.201	0.522	0.578	0.612	0.665	68	79	87	92
Griffin	Car	0.430	0.136	0.269	0.344	0.451	0.507	0.613	0.628	69	72	81	98
Griffin	Train	0.318	0.016	0.244	0.078	0.393	0.401	0.409	0.409	78	96	98	100
Marjanen	Car #1	0.235	0.078	0.175	0.124	0.267	0.293	0.318	0.327	72	82	89	97
Marjanen	Car #2	0.245	0.080	0.183	0.128	0.273	0.306	0.332	0.341	72	80	90	97
Marjanen	Car #3	0.619	0.267	0.426	0.332	0.684	0.751	0.821	0.863	72	79	87	95
Marjanen	Train #1	0.142	0.045	0.094	0.052	0.157	0.170	0.178	0.184	77	86	93	97
Marjanen	Train #2	0.117	0.038	0.074	0.039	0.127	0.139	0.144	0.149	79	85	93	97
Marjanen	Tractor #1	0.839	0.155	0.828	0.393	1.064	1.179	1.242	1.252	67	85	94	99
Marjanen	Tractor #2	0.527	0.057	0.453	0.130	0.693	0.695	0.707	0.710	74	98	98	100
Marjanen	Tractor #3	0.915	0.088	0.856	0.317	1.163	1.253	1.293	1.296	71	90	97	100
Marjanen	Excavator #1	0.638	0.162	0.642	0.377	0.772	0.905	0.981	0.994	64	78	91	99
Marjanen	Excavator #2	0.533	0.136	0.496	0.194	0.645	0.728	0.753	0.765	70	84	95	98
Marjanen	Harvester #1	1.242	0.182	1.123	0.211	1.626	1.675	1.688	1.698	73	96	99	99
Marjanen	Harvester #2	0.448	0.147	0.337	0.101	0.587	0.561	0.570	0.588	76	100	95	97
Marjanen	Bus #1	0.556	0.066	0.388	0.112	0.732	0.678	0.687	0.690	81	106	98	100
Marjanen	Truck #1	0.411	0.065	0.317	0.163	0.509	0.519	0.544	0.548	75	93	95	99

Table 19. The frequency weighted r.m.s. values (m/s^2 or rad/s^2) without multiplying factors for seat translational axes (Xs, Ys and Zs), seat rotational axes (Roll, Pitch and Yaw), backrest translational axes (Xb, Yb and Zb) and floor translational axes (Xf, Yf and Zf) for all measurements.

Measurer	Machine	Xs	Ys	Zs	Roll	Pitch	Yaw	Xb	Yb	Zb	Xf	Yf	Zf
Maeda	Bus	0.124	0.097	0.513	0.156	0.583	0.385	0.319	0.178	0.610	0.128	0.288	0.333
Maeda	Taxi	0.079	0.075	0.258	0.131	0.193	0.080	0.219	0.110	0.228	0.124	0.116	0.210
Maeda	Bulldozer	0.646	0.449	0.615	0.698	0.623	1.200	1.383	0.538	0.348	0.520	0.872	0.620
Maeda	Excavator	0.458	0.179	0.297	0.192	0.385	0.275	0.734	0.242	0.138	0.500	0.392	0.288
Maeda	Tractor	0.334	0.302	0.663	0.331	0.513	0.560	0.653	0.380	0.218	0.356	0.456	0.455
Maeda	Combine	0.353	0.240	0.427	0.328	0.353	0.255	0.458	0.226	0.255	0.776	1.264	0.553
Maeda	Monorail	0.036	0.063	0.119	0.033	0.128	0.100	0.093	0.084	0.133	0.056	0.124	0.078
Maeda	Fork	0.247	0.405	1.294	0.320	0.625	1.170	1.091	0.534	0.493	0.356	0.464	1.063
Griffin	Bus	0.161	0.218	0.359	0.334	0.375	0.075	0.379	0.216	0.418	0.192	0.156	0.478
Griffin	Car	0.080	0.114	0.407	0.166	0.213	0.055	0.265	0.174	0.350	0.360	0.372	0.798
Griffin	Train	0.082	0.221	0.214	0.025	0.008	0.005	0.246	0.236	0.208	0.080	0.112	0.175
Marjanen	Car #1	0.096	0.087	0.196	0.108	0.096	0.039	0.192	0.098	0.170	0.118	0.134	0.289
Marjanen	Car #2	0.088	0.085	0.213	0.100	0.120	0.037	0.207	0.092	0.159	0.096	0.144	0.301
Marjanen	Car #3	0.172	0.242	0.543	0.338	0.401	0.119	0.470	0.271	0.370	0.303	0.403	0.767
Marjanen	Train #1	0.026	0.064	0.124	0.057	0.065	0.031	0.105	0.060	0.076	0.079	0.078	0.109
Marjanen	Train #2	0.023	0.044	0.106	0.048	0.057	0.027	0.082	0.041	0.070	0.050	0.058	0.085
Marjanen	Tractor #1	0.413	0.526	0.506	0.195	0.235	0.057	0.884	0.745	0.538	0.479	0.838	0.775
Marjanen	Tractor #2	0.343	0.306	0.258	0.031	0.061	0.236	0.481	0.353	0.402	0.305	0.279	0.198
Marjanen	Tractor #3	0.596	0.426	0.548	0.019	0.086	0.403	0.923	0.524	0.867	0.955	0.595	0.367
Marjanen	Excavator #1	0.287	0.339	0.458	0.175	0.266	0.260	0.764	0.304	0.315	0.759	0.613	0.717
Marjanen	Excavator #2	0.240	0.283	0.382	0.179	0.176	0.149	0.529	0.426	0.363	0.368	0.343	0.369
Marjanen	Harvester #1	0.794	0.718	0.630	0.039	0.209	0.799	1.268	0.633	0.908	0.498	0.385	0.350
Marjanen	Harvester #2	0.284	0.263	0.225	0.212	0.147	0.061	0.308	0.412	0.254	0.183	0.191	0.192
Marjanen	Bus #1	0.345	0.343	0.270	0.080	0.092	0.103	0.400	0.366	0.301	0.229	0.230	0.193
Marjanen	Truck #1	0.247	0.183	0.273	0.080	0.093	0.076	0.332	0.271	0.273	0.322	0.268	0.314

5.4.3 Applicability of the r.m.s. method

If the crest factor value exceeds the threshold value of nine, the standard suggests that the r.m.s. method underestimates the effects of vibration on discomfort (because of high shocks). In almost all cases (11 out of 14) at least one axis showed crest factor higher than the threshold value (Table 20). The floor axes most commonly exceed the threshold. If only the seat and backrest axes were measured (Scenario 2) then 8 out of

14 showed crest factors over the threshold. If seat axes alone were used (Scenario 1) then 5 out of 14 exceeded the threshold. The analysis could be done only from the new field measurements as the crest factors were not available from the previous studies.

Table 20. The crest factor values for frequency weighted seat translational axes (Xs, Ys and Zs), seat rotational axes (Roll, Pitch and Yaw), backrest translational axes (Xb, Yb and Zb) and floor translational axes (Xf, Yf and Zf). Values exceeding the threshold limit 9 of ISO 2631-1 are highlighted.

Measurer	Machine	Xs	Ys	Zs	Roll	Pitch	Yaw	Xb	Yb	Zb	Xf	Yf	Zf
Marjanen	Car #1	6.1	4.8	4.9	4.8	4.4	4.6	5.4	5.4	4.5	5.9	6.4	5.5
Marjanen	Car #2	5.0	4.5	**9.2**	5.5	4.7	4.5	5.9	7.1	3.9	**9.8**	4.6	**11.6**
Marjanen	Car #3	6.0	6.2	7.1	5.9	5.5	8.7	5.5	4.8	6.4	**13.6**	7.4	7.5
Marjanen	Train #1	5.0	4.6	5.1	4.9	4.1	**9.9**	5.0	4.6	5.1	5.5	4.7	5.9
Marjanen	Train #2	**9.3**	5.1	6.1	5.2	4.6	4.0	4.9	5.1	5.9	6.4	6.2	5.9
Marjanen	Tractor #1	4.4	5.0	6.3	7.8	5.0	7.0	5.8	4.9	6.5	5.9	6.1	6.6
Marjanen	Tractor #2	5.5	6.0	6.6	5.9	8.6	5.8	7.0	5.1	4.9	6.9	8.1	6.6
Marjanen	Tractor #3	6.9	4.5	5.5	3.6	**9.9**	4.2	7.2	5.3	4.3	5.2	5.2	5.4
Marjanen	Excavator #1	5.7	5.3	6.6	7.3	5.3	6.8	6.5	7.0	7.8	7.6	7.4	**10.0**
Marjanen	Excavator #2	6.6	**10.5**	**9.0**	6.4	7.4	**9.9**	**12.0**	8.6	**9.0**	**16.9**	**14.8**	**16.9**
Marjanen	Harvester #1	6.8	5.4	**9.5**	7.6	6.0	6.5	7.7	6.0	8.3	**22.4**	**22.5**	**22.5**
Marjanen	Harvester #2	6.0	5.1	5.7	5.5	6.2	4.1	5.6	4.7	**11.5**	7.8	7.2	5.9
Marjanen	Bus #1	6.0	6.9	**12.2**	5.6	6.4	5.6	8.0	5.3	5.9	**9.5**	**10.7**	**12.5**
Marjanen	Truck #1	8.2	6.1	8.9	6.9	7.3	6.5	**9.6**	6.6	6.5	8.3	**10.7**	**9.9**
	Average	**6.2**	**5.7**	**7.3**	**5.9**	**6.1**	**6.3**	**6.9**	**5.7**	**6.4**	**9.4**	**8.7**	**9.5**

5.4.4 Relative magnitude and contribution of point vibration total values

For most of the measured machines PVTV from the seat translational axes were the highest (Table 21). PVTV of the backrest axes were dominant in few cases (3 out of 25), but the seat rotational and floor axes had no dominant PVTVs. In general they were less than 50 % of the dominant PVTV. In 7 out of 25 cases the seat rotational axes could have been neglected based on the standard recommendation (less than 25 % of the dominant PVTV can be neglected). For floor the translational axes 3 out of 25 PVTVs were below 25 % margin.

*Table 21. The relative magnitudes (%) of point vibration total values for seat translational axes (**$a_{s1.0}$**), backrest translational axes (a_b), floor translational axes (a_f) and seat rotational axes (a_r) with respective multiplying factors. The location which was the highest is treated as the most important point vibration total value (i.e. 100 %). The rest of the axes are compared to the most important point vibration total value (embolden). Underlined values are below 25 % of the highest value, thus could be neglected based on the standard guidance.*

Measurer	**Machine**	$a_{s1.0}$	a_b	a_r	a_f
Maeda	Bus	**100**	68	49	29
Maeda	Taxi	**100**	73	41	34
Maeda	Bulldozer	87	**100**	49	31
Maeda	Excavator	95	**100**	34	33
Maeda	Tractor	**100**	70	39	29
Maeda	Combine	**100**	66	43	71
Maeda	Monorail	**100**	72	42	33
Maeda	Fork	**100**	68	29	33
Griffin	Bus	**100**	81	58	45
Griffin	Car	**100**	62	32	80
Griffin	Train	**100**	77	<u>5</u>	<u>24</u>
Marjanen	Car #1	**100**	74	33	53
Marjanen	Car #2	**100**	75	32	52
Marjanen	Car #3	**100**	69	43	54
Marjanen	Train #1	**100**	67	32	36
Marjanen	Train #2	**100**	63	33	33
Marjanen	Tractor #1	**100**	99	<u>19</u>	47
Marjanen	Tractor #2	**100**	86	<u>11</u>	25
Marjanen	Tractor #3	**100**	94	<u>10</u>	35
Marjanen	Excavator #1	99	**100**	25	59
Marjanen	Excavator #2	**100**	93	26	36
Marjanen	Harvester #1	**100**	90	<u>15</u>	<u>17</u>
Marjanen	Harvester #2	**100**	75	33	23
Marjanen	Bus #1	**100**	70	<u>12</u>	<u>20</u>
Marjanen	Truck #1	**100**	77	<u>16</u>	40
	Average	**99**	**79**	**30**	**39**

The relative contribution of PVTVs to OVTV shows that the seat PVTV had the largest contribution on average (Table 22). It constituted on average about half of the contribution. From the rest of PVTVs only backrest axes have any significance.

Table 22. The relative contribution (%) of frequency weighted point vibration total values (m/s^2) for seat translational axes ($a_{s1.0}$), backrest translational axes (a_b), floor translational axes (a_f) and seat rotational axes (a_r) with respective multiplying factors to the overall vibration total value of all axes.

Measurer	**Machine**	$a_{s1.0}$	a_b	a_r	a_f
Maeda	Bus	56	26	14	5
Maeda	Taxi	55	29	9	6
Maeda	Bulldozer	36	48	12	5
Maeda	Excavator	43	47	5	5
Maeda	Tractor	58	28	9	5
Maeda	Combine	47	20	9	24
Maeda	Monorail	55	29	10	6
Maeda	Fork	61	28	5	6
Griffin	Bus	46	30	15	9
Griffin	Car	47	18	5	30
Griffin	Train	61	36	0	4
Marjanen	Car #1	51	28	6	14
Marjanen	Car #2	52	29	5	14
Marjanen	Car #3	51	24	10	15
Marjanen	Train #1	60	26	6	8
Marjanen	Train #2	62	25	7	7
Marjanen	Tractor #1	45	44	2	10
Marjanen	Tractor #2	55	41	1	3
Marjanen	Tractor #3	50	44	0	6
Marjanen	Excavator #1	41	42	3	14
Marjanen	Excavator #2	48	42	3	6
Marjanen	Harvester #1	54	44	1	2
Marjanen	Harvester #2	58	33	6	3
Marjanen	Bus #1	65	32	1	3
Marjanen	Truck #1	56	34	1	9
	Average	52	33	6	9

The effect of PVTV can be more clearly visualised from Figure 39. Seat and backrest translational PVTVs contribute 4/5th of OVTV. The results are consistent for all measurements.

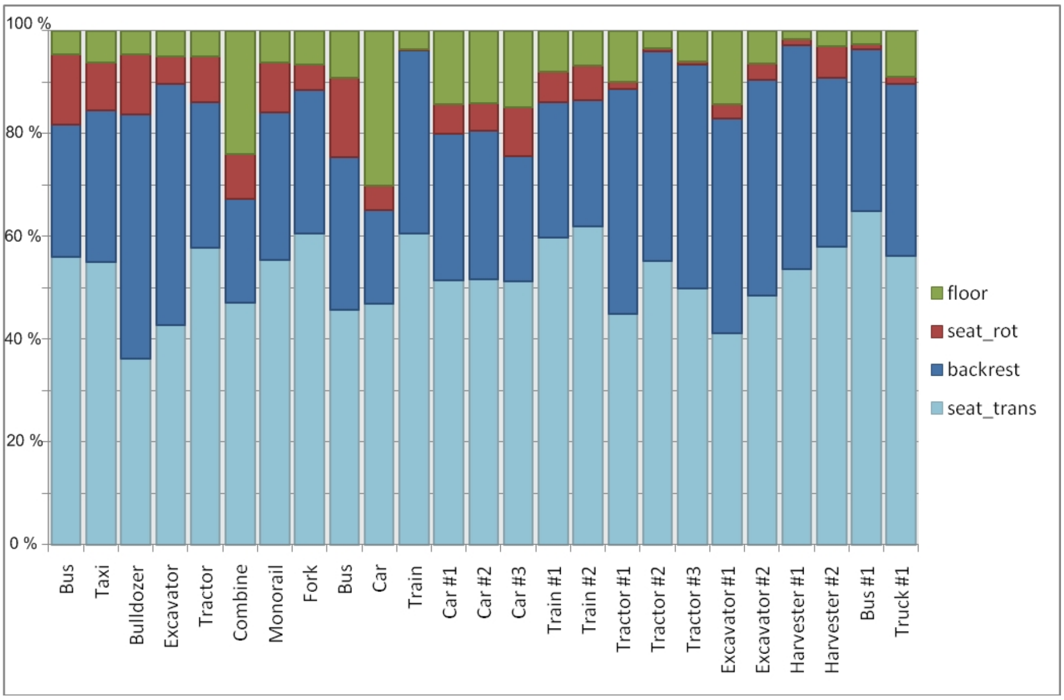

Figure 39. Relative contribution (%) of frequency weighted point vibration total values with respective multiplying factors to the overall vibration total value.

5.4.5 Relative magnitude and contribution of individual axes

The most dominant axis was the seat vertical for most of the environments (Table 23). The second most dominant was backrest fore-and-aft and for third both seat fore-and-aft and lateral axes had practically the same importance. The least important axis was seat yaw axis. The seat vertical was the most dominant for even surfaces and machines that are used in transportation, such as buses and cars. The few exceptions were tractor and combine (measured by Maeda). The backrest fore-and-aft was generally dominant in machines that were used on rough surfaces, such as the bulldozer, excavators, and harvesters.

Table 23. The relative magnitudes (%) of the frequency weighted seat translational axes (Xs, Ys and Zs), seat rotational axes (Roll, Pitch and Yaw), backrest translational axes (Xb, Yb and Zb) and floor translational axes (Xf, Yf and Zf) with multiplying factors. The axis which was the highest is treated as the most important axis (i.e. 100 %). The rest of the axes are compared to the most important axis (embolden).

Measurer	**Machine**	**Xs**	**Ys**	**Zs**	**Roll**	**Pitch**	**Yaw**	**Xb**	**Yb**	**Zb**	**Xf**	**Yf**	**Zf**
Maeda	Bus	24	19	**100**	19	45	15	50	17	48	6	14	26
Maeda	Taxi	31	29	**100**	33	30	6	68	21	35	12	11	33
Maeda	Bulldozer	58	41	56	40	23	22	**100**	24	13	12	20	22
Maeda	Excavator	78	30	51	21	26	9	**100**	21	9	21	17	20
Maeda	Tractor	50	46	**100**	32	31	17	79	29	13	13	17	27
Maeda	Combine	83	56	**100**	49	33	12	86	26	24	45	74	52
Maeda	Monorail	30	53	**100**	18	43	17	62	35	45	12	26	26
Maeda	Fork	19	31	**100**	16	19	18	67	21	15	7	9	33
Griffin	Bus	45	61	**100**	60	42	4	84	30	47	13	11	53
Griffin	Car	20	28	**100**	26	21	3	52	21	34	22	23	78
Griffin	Train	37	**100**	97	7	1	0	89	53	38	9	13	32
Marjanen	Car #1	49	45	**100**	35	20	4	78	25	35	15	17	59
Marjanen	Car #2	41	40	**100**	30	23	4	78	22	30	11	17	57
Marjanen	Car #3	32	45	**100**	39	30	4	69	25	27	14	19	57
Marjanen	Train #1	21	52	**100**	29	21	5	68	24	24	16	16	35
Marjanen	Train #2	21	41	**100**	29	21	5	62	19	26	12	14	32
Marjanen	Tractor #1	58	74	72	17	13	2	**100**	53	30	17	30	44
Marjanen	Tractor #2	89	80	67	5	6	12	**100**	46	42	20	18	21
Marjanen	Tractor #3	81	58	74	2	5	11	**100**	36	47	32	20	20
Marjanen	Excavator #1	47	55	75	18	17	9	**100**	25	21	31	25	47
Marjanen	Excavator #2	57	67	90	27	17	7	**100**	50	34	22	20	35
Marjanen	Harvester #1	78	71	62	2	8	16	**100**	31	36	12	9	14
Marjanen	Harvester #2	**100**	93	79	47	21	4	87	72	36	16	17	27
Marjanen	Bus #1	**100**	99	78	15	11	6	93	53	35	17	17	22
Marjanen	Truck #1	91	67	**100**	19	14	6	97	50	40	30	25	46
	Average	**54**	**55**	**88**	**25**	**22**	**9**	**83**	**33**	**31**	**18**	**20**	**37**

The vertical axis from the seat and fore-and-aft axis from the backrest showed significant contributions to OVTV on average (Table 24 and Figure 40). Horizontal axes from the seat showed also meaningful contribution, but the rest of the axes showed contribution of 6 % or less. Compared to relative magnitudes (Table 23) the dominant axis showed the same trend where the seat vertical is dominant for even surfaces and lighter machines, and the backrest fore-and-aft is dominant for rougher surfaces. Excavators and tractors showed highest dominance in the backrest fore-and-aft axis. In other machines the seat vertical was most likely the dominant axis. The seat rotational, backrest lateral and vertical, and floor translational axes had little or no significant contribution to OVTV.

Table 24. The relative contribution (%) of frequency weighted seat translational axes (Xs, Ys and Zs), seat rotational axes (Roll, Pitch and Yaw), backrest translational axes (Xb, Yb and Zb) and floor translational axes (Xf, Yf and Zf) to the overall vibration total value with respective multiplying factors.

Measurer	Machine	Xs	Ys	Zs	Roll	Pitch	Yaw	Xb	Yb	Zb	Xf	Yf	Zf	Most important axis
Maeda	Bus	3	2	51	2	11	1	13	2	12	0	1	3	Zs
Maeda	Taxi	4	4	47	5	4	0	21	2	6	1	1	5	Zs
Maeda	Bulldozer	15	7	14	7	2	2	44	3	1	1	2	2	Xb
Maeda	Excavator	27	4	11	2	3	0	45	2	0	2	1	2	Xb
Maeda	Tractor	10	8	40	4	4	1	25	3	1	1	1	3	Zs
Maeda	Combine	16	7	24	6	3	0	17	2	1	5	13	6	Zs
Maeda	Monorail	4	11	40	1	7	1	16	5	8	1	3	3	Zs
Maeda	Fork	2	5	53	1	2	2	24	2	1	0	0	6	Zs
Griffin	Bus	6	11	29	10	5	0	21	3	6	1	0	8	Zs
Griffin	Car	2	3	42	3	2	0	11	2	5	2	2	26	Zs
Griffin	Train	4	29	27	0	0	0	23	8	4	0	0	3	Zs
Marjanen	Car #1	9	7	35	4	1	0	22	2	4	1	1	12	Zs
Marjanen	Car #2	7	6	39	3	2	0	24	2	3	0	1	12	Zs
Marjanen	Car #3	4	8	39	6	3	0	19	3	3	1	1	13	Zs
Marjanen	Train #1	2	12	45	4	2	0	21	3	3	1	1	6	Zs
Marjanen	Train #2	2	9	51	4	2	0	19	2	4	1	1	5	Zs
Marjanen	Tractor #1	10	19	16	1	1	0	30	9	3	1	3	6	Xb
Marjanen	Tractor #2	23	19	13	0	0	1	29	7	5	1	1	1	Xb
Marjanen	Tractor #3	21	11	18	0	0	0	32	4	7	3	1	1	Xb
Marjanen	Excavator #1	9	11	21	2	1	0	36	3	2	4	2	9	Xb
Marjanen	Excavator #2	10	12	25	3	1	0	29	10	4	1	1	4	Xb
Marjanen	Harvester #1	22	18	14	0	0	1	36	3	5	1	0	1	Xb
Marjanen	Harvester #2	25	18	15	5	1	0	16	12	4	1	1	2	Xs
Marjanen	Bus #1	22	26	16	1	1	0	20	6	5	1	1	2	Ys
Marjanen	Truck #1	20	13	24	2	1	0	22	5	5	2	2	5	Zs
	Average	**11**	**11**	**30**	**3**	**2**	**0**	**25**	**4**	**4**	**1**	**2**	**6**	**Zs**

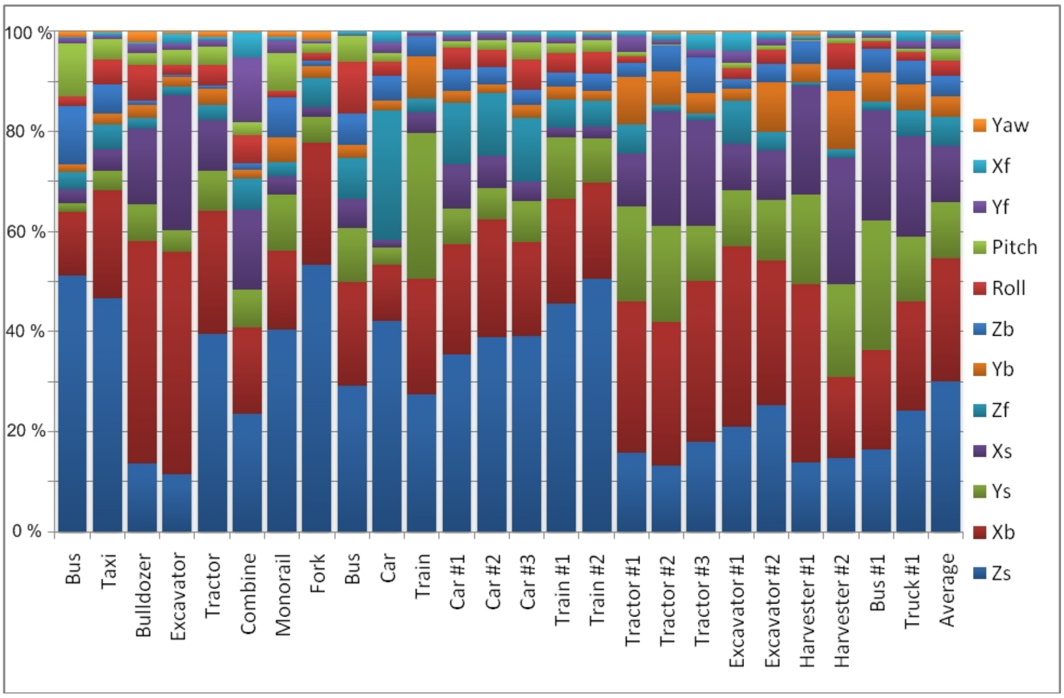

Figure 40. The relative contribution (%) of frequency weighted seat translational axes (Xs, Ys and Zs), seat rotational axes (Roll, Pitch and Yaw), backrest translational axes (Xb, Yb and Zb) and floor translational axes (Xf, Yf and Zf) to the overall vibration total value with respective multiplying factors.

5.4.6 Effect of frequency weighting to the contribution of axes

The results show that the weighted OVTV was on average 46 % of the unweighted value (Table 25). The influence of the frequency weighting was most significant for vehicles operating on smooth surfaces (e.g. car and train). Tractors and harvesters exhibited vibrations that were mostly present in the frequency range where attenuation is smallest, thus the unweighted and weighted values had the smallest difference.

For individual axes, the largest attenuation occurred for rotational axes (Table 25). The roll, pitch and yaw axes were less than 20 % of their unweighted values, while other axes were 50 to 70 %. The most unaffected axes to frequency weighting were backrest fore-and-aft (88 %) and seat vertical (71 %). Unweighted axes showed that roll and pitch axes are the most dominant without weighting.

Table 25. The relative difference ratios (%) of r.m.s. values with and without frequency weighting for seat translational axes (Xs, Ys and Zs), seat rotational axes (Roll, Pitch and Yaw), backrest translational axes (Xb, Yb and Zb) and floor translational axes (Xf, Yf and Zf), and for overall vibration total values for seat translational axes with 1.0 ($a_{s1.0}$), seat and backrest axes (a_{sb}), all translational axes (a_{fsb}), and to all twelve axes (a_v) The percentage is ratio of the weighted value to the unweighted value.

		Relative difference (%)															
Measurer	**Machine**	**Xs**	**Ys**	**Zs**	**Roll**	**Pitch**	**Yaw**	**Xb**	**Yb**	**Zb**	**Xf**	**Yf**	**Zf**	$a_{s1.0}$	a_{sb}	a_{fsb}	a_v
Marjanen	Car #1	38	26	69	12	8	6	87	36	51	55	47	69	41	51	56	27
Marjanen	Car #2	39	27	75	11	10	6	89	36	49	54	50	74	45	55	59	29
Marjanen	Car #3	32	32	76	15	17	10	92	42	46	66	64	76	46	55	62	34
Marjanen	Train #1	12	30	80	12	8	7	82	23	34	65	36	47	35	40	42	23
Marjanen	Train #2	11	33	77	13	8	7	76	25	35	49	34	50	35	42	42	20
Marjanen	Tractor #1	54	62	74	13	26	13	91	61	54	73	81	87	61	67	72	61
Marjanen	Tractor #2	76	78	65	17	15	27	91	69	73	63	71	50	75	76	73	61
Marjanen	Tractor #3	76	68	72	19	10	20	91	61	75	82	87	65	73	76	78	60
Marjanen	Excavator #1	39	37	78	16	8	12	83	33	36	71	59	72	44	53	60	34
Marjanen	Excavator #2	58	64	76	26	20	19	88	62	56	77	76	76	65	68	71	56
Marjanen	Harvester #1	86	86	55	35	19	44	93	85	78	67	66	57	78	81	79	67
Marjanen	Harvester #2	78	74	74	34	28	20	94	77	69	62	61	66	76	77	74	61
Marjanen	Bus #1	77	76	62	17	17	17	93	83	82	65	65	65	74	79	76	60
Marjanen	Truck #1	57	45	59	14	10	12	85	66	63	69	69	69	54	63	65	47
	Average	**52**	**53**	**71**	**18**	**15**	**16**	**88**	**54**	**57**	**66**	**62**	**66**	**57**	**63**	**65**	**46**

Power spectral densities from weighted and unweighted acceleration data are presented in Figure 41 and Figure 42. Both figures are from a car driven on a cobblestone road (two separate data sets). Figures show spectra of the two measurements (red) and an averaged spectrum (blue). The figures show that W_k and W_c frequency weighting curves have less attenuation on the frequency band, thus seat vertical, backrest fore-and-aft and floor translational axes are closer to unweighted spectra than other axes. Especially W_e show attenuation, which significantly changes the spectra of rotational axes. Because of the weighting the axes show most of the energy in low frequency area (i.e. below 10 Hz). For unweighted data the energy is spread in wider frequency range, especially for rotational axes.

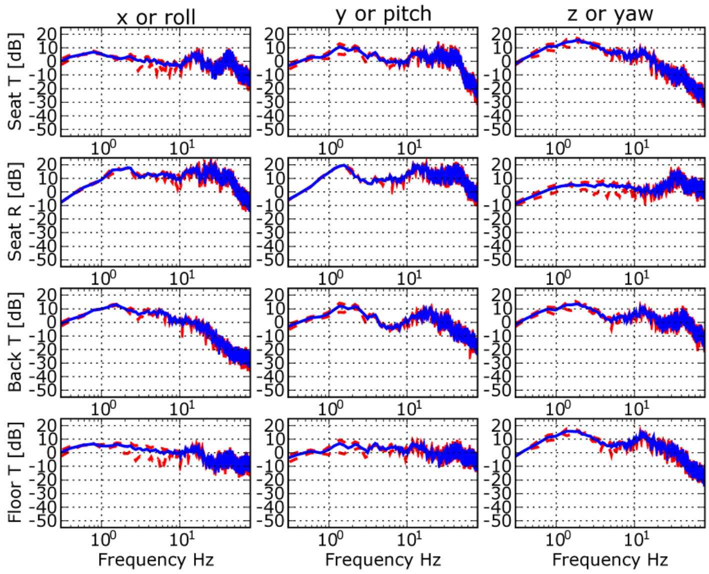

Figure 41. Frequency spectra (dBm/Hz) of twelve unweighted axes for a car driven on a cobblestone road (frequency range from 0 to 80 Hz). Blue line shows the mean spectra of two separate measurements (red lines).

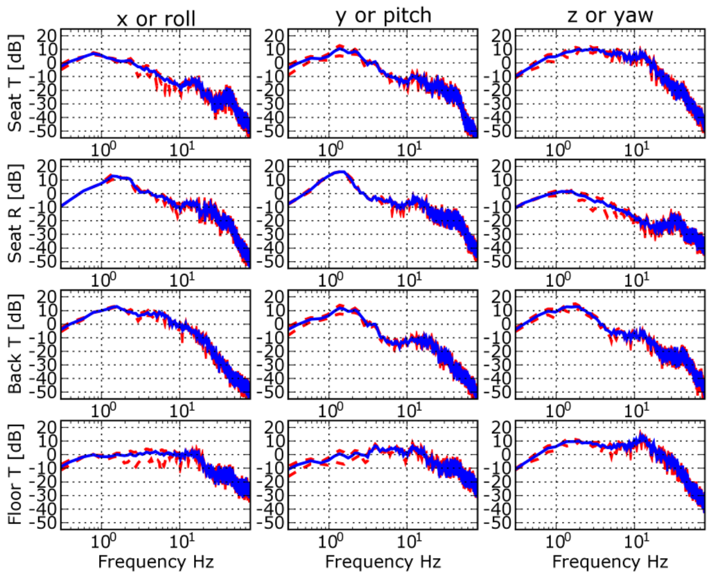

Figure 42. Frequency spectra (dBm/Hz) of twelve weighted axes for a car driven on a cobblestone road (frequency range from 0 to 80 Hz). Blue line shows the mean spectra of two separate measurements (red lines).

5.4.7 Effect of multiplying factors to the contribution of axes

PVTV from the seat (a_s) had smaller weighted r.m.s. value without multiplying factors, because of the 1.4 multiplication factors for horizontal axes (Table 26). For other combinations of axes OVTV was smaller with the multiplying factors (this is evident as all the factors for additional axes are less than one). The combined value (a_{sb}) of the seat and backrest was 81 % smaller. The seat, backrest and floor axes combined (a_{fsb}) were 67 % smaller and OVTV (a_v) 64 % smaller. It was clear that the multiplying factors attenuated rotational and floor axes significantly. This effect was systematic for all environments.

Table 26. Overall vibration total values of frequency weighted r.m.s. values (m/s^2) with and without multiplying factors, and relative differences of values with factors to without factors.

		With factors				**Without factors**				**Relative differences**			
Measurer	**Machine**	$a_{s1.4}$	a_{sb}	a_{fsb}	a_v	$a_{s1.0}$	a_{sb}	a_{fsb}	a_v	a_s	a_{sb}	a_{fsb}	a_v
Maeda	Bus	0.558	0.648	0.667	0.717	0.537	0.891	1.002	1.231	104 %	73 %	67 %	58 %
Maeda	Taxi	0.300	0.347	0.359	0.377	0.280	0.436	0.513	0.569	107 %	80 %	70 %	66 %
Maeda	Bulldozer	1.261	1.521	1.561	1.661	0.999	1.822	2.176	2.655	126 %	83 %	72 %	63 %
Maeda	Excavator	0.750	0.832	0.855	0.879	0.574	0.973	1.197	1.301	131 %	86 %	71 %	68 %
Maeda	Tractor	0.915	0.979	1.006	1.055	0.801	1.122	1.342	1.577	114 %	87 %	75 %	67 %
Maeda	Combine	0.734	0.722	0.841	0.880	0.604	0.831	1.787	1.869	122 %	87 %	47 %	47 %
Maeda	Monorail	0.156	0.172	0.178	0.187	0.139	0.229	0.278	0.323	112 %	75 %	64 %	58 %
Maeda	Fork	1.454	1.665	1.724	1.770	1.378	1.902	2.256	2.636	106 %	88 %	76 %	67 %
Griffin	Bus	0.522	0.578	0.612	0.665	0.450	0.753	0.925	1.055	116 %	77 %	66 %	63 %
Griffin	Car	0.451	0.507	0.613	0.628	0.430	0.639	1.145	1.178	105 %	79 %	54 %	53 %
Griffin	Train	0.393	0.401	0.409	0.409	0.318	0.511	0.557	0.558	124 %	79 %	73 %	73 %
Marjanen	Car #1	0.267	0.293	0.318	0.327	0.235	0.361	0.496	0.518	114 %	81 %	64 %	63 %
Marjanen	Car #2	0.273	0.306	0.332	0.341	0.245	0.370	0.507	0.532	111 %	83 %	65 %	64 %
Marjanen	Car #3	0.684	0.751	0.821	0.863	0.619	0.902	1.287	1.395	111 %	83 %	64 %	62 %
Marjanen	Train #1	0.157	0.170	0.178	0.184	0.142	0.201	0.254	0.270	111 %	85 %	70 %	68 %
Marjanen	Train #2	0.127	0.139	0.144	0.149	0.117	0.164	0.200	0.216	108 %	84 %	72 %	69 %
Marjanen	Tractor #1	1.064	1.179	1.242	1.252	0.839	1.526	1.965	1.990	127 %	77 %	63 %	63 %
Marjanen	Tractor #2	0.693	0.695	0.707	0.710	0.527	0.892	1.003	1.033	132 %	78 %	70 %	69 %
Marjanen	Tractor #3	1.163	1.253	1.293	1.296	0.915	1.647	2.029	2.070	127 %	76 %	64 %	63 %
Marjanen	Excavator #1	0.772	0.905	0.981	0.994	0.638	1.087	1.628	1.679	121 %	83 %	60 %	59 %
Marjanen	Excavator #2	0.645	0.728	0.753	0.765	0.533	0.937	1.125	1.163	121 %	78 %	67 %	66 %
Marjanen	Harvester #1	1.626	1.675	1.688	1.698	1.242	2.092	2.212	2.362	131 %	80 %	76 %	72 %
Marjanen	Harvester #2	0.587	0.561	0.570	0.588	0.448	0.728	0.798	0.841	131 %	77 %	71 %	70 %
Marjanen	Bus #1	0.732	0.678	0.687	0.690	0.556	0.833	0.915	0.929	132 %	81 %	75 %	74 %
Marjanen	Truck #1	0.509	0.519	0.544	0.548	0.411	0.653	0.837	0.849	124 %	79 %	65 %	65 %
	Average	**0.672**	**0.729**	**0.763**	**0.785**	**0.672**	**0.900**	**1.137**	**1.232**	**119 %**	**81 %**	**67 %**	**64 %**

A multiplying factor was calculated for the seat translational axes, which would produce the same OVTV compared to including the backrest axes. In ISO 2631-1 this value is defined as 1.4, but based on these results, the multiplying factor varied for different measurements from of 1.3 to 2.5 (Table 27). On average it was 1.693. For the combine (Maeda), the harvester (Marjanen) and the bus (Marjanen) the standard multiplying factor overestimated the effect and for the rest it underestimated it.

Table 27. Comparison of overall vibration total values (m/s^2) of seat translational axes with 1.4 multiplying factors ($a_{s1.4}$) and with seat and backrest translational axes (a_{sb}). and calculation of factor which would equal a_s and a_{sb}. Difference (%) is $a_{s1.4}$ to a_{sb}.

Measurer	Machine	$a_{s1.4}$	a_{sb}	Difference (%)	Factor
Maeda	Bus	0.558	0.648	86	2.52
Maeda	Taxi	0.300	0.347	86	2.13
Maeda	Bulldozer	1.261	1.521	83	1.77
Maeda	Excavator	0.750	0.832	90	1.58
Maeda	Tractor	0.915	0.979	93	1.60
Maeda	Combine	0.734	0.722	102	1.36
Maeda	Monorail	0.156	0.172	91	1.71
Maeda	Fork	1.454	1.665	87	2.21
Griffin	Bus	0.522	0.578	90	1.67
Griffin	Car	0.451	0.507	89	2.17
Griffin	Train	0.393	0.401	98	1.44
Marjanen	Car #1	0.267	0.293	91	1.68
Marjanen	Car #2	0.273	0.306	89	1.80
Marjanen	Car #3	0.684	0.751	91	1.75
Marjanen	Train #1	0.157	0.170	92	1.69
Marjanen	Train #2	0.127	0.139	92	1.80
Marjanen	Tractor #1	1.064	1.179	90	1.59
Marjanen	Tractor #2	0.693	0.695	100	1.40
Marjanen	Tractor #3	1.163	1.253	93	1.54
Marjanen	Excavator #1	0.772	0.905	85	1.76
Marjanen	Excavator #2	0.645	0.728	89	1.67
Marjanen	Harvester #1	1.626	1.675	97	1.45
Marjanen	Harvester #2	0.587	0.561	105	1.33
Marjanen	Bus #1	0.732	0.678	108	1.28
Marjanen	Truck #1	0.509	0.519	98	1.44
	Average	**0.672**	**0.729**	**93**	**1.69**

5.4.8 The dominant axis at different 1/3 octave frequencies

The results show that for a car the dominant axis in low frequencies, for weighted and multiplied data, varied between backrest fore-and-aft and seat vertical axis, while floor axes dominated over 10 Hz frequencies (Figure 43). If the same data was calculated without multiplying factors, then pitch axis was dominant in the low frequency range from 1-2 Hz and floor axes started to dominate already at 7 Hz. The unweighted data shows that rotational axes, especially roll, were the most dominant practically throughout the whole frequency range.

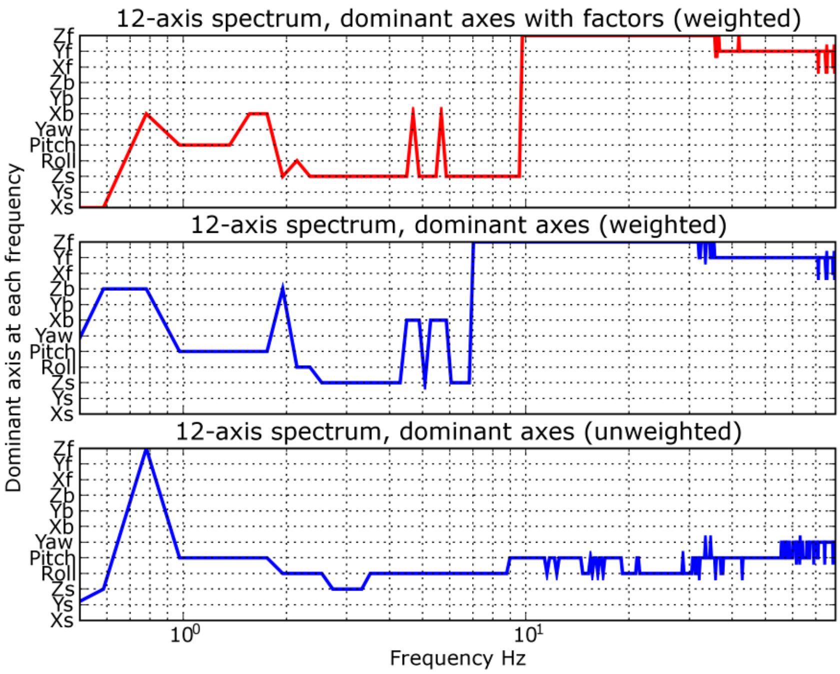

Figure 43. Dominant axes at each 1/3 octave frequency from a car driven on a cobblestone road. The top plot (red) represents frequency weighted acceleration data with multiplying factors, middle plot (blue) represents weighted data without multiplying factors and bottom plot (blue) unweighted data without multiplying factors.

If evaluating machines driven in fairly smooth environments (bus, car and train), they all show differing patterns for the dominant axis when using frequency weighting and multiplying factors (Figure 44). The only strong similarity was found with the unweighted data, where the rotational axes dominated practically in all frequencies. Seat and backrest axes dominated for all machines.

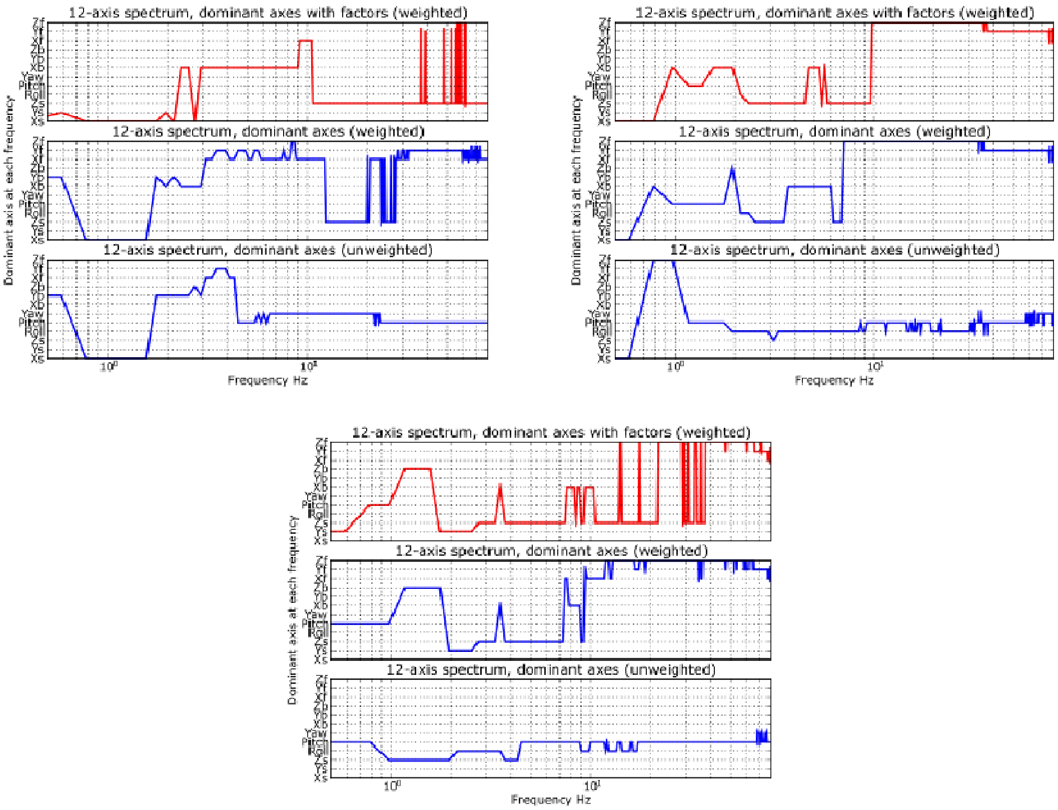

Figure 44. Dominant axes from bus (upper left), car (upper right) and train (below). The top plot (red) represents frequency weighted acceleration data with multiplying factors, middle plot (blue) represents weighted data without multiplying factors and bottom plot (blue) unweighted data without factors.

On the other hand, machines that were driven in rougher surfaces (excavator, harvester and tractor) had much stronger similarities than car, train and bus using the standard's weighting process (Figure 45). The backrest fore-and-aft axis dominated in most frequencies below 10 Hz, and the seat vertical dominated frequencies higher than 10 Hz. Again the rotational axes dominated for unweighted data.

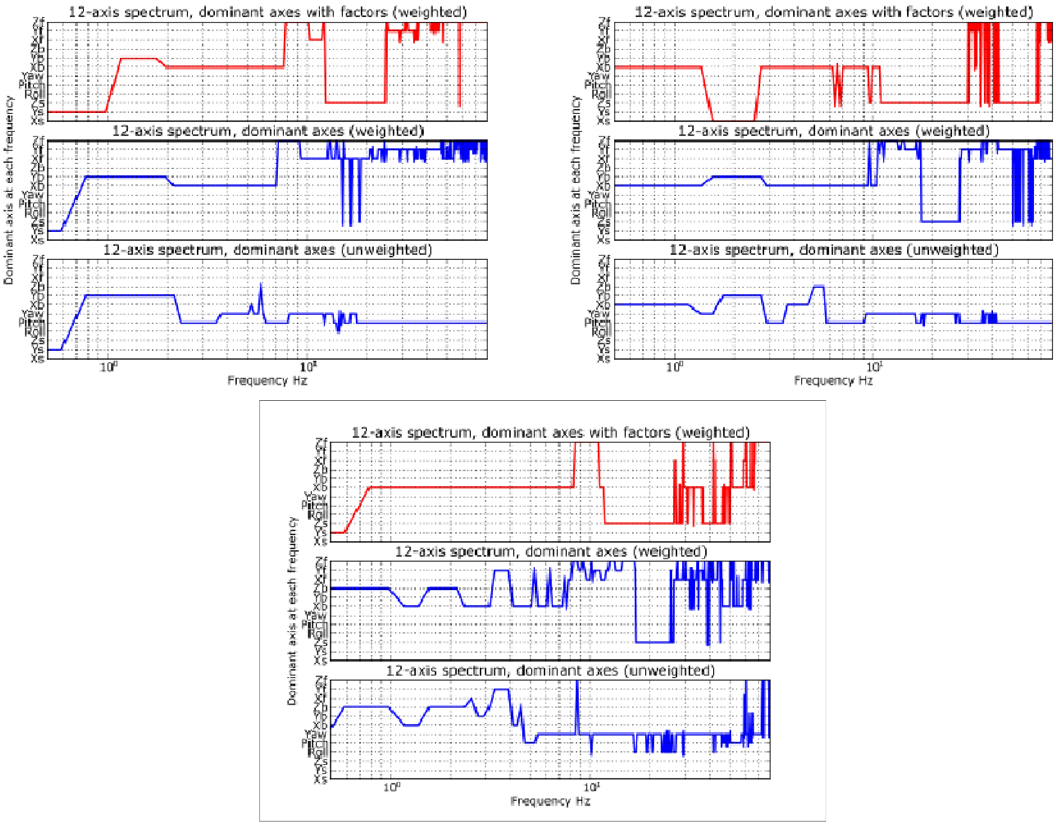

Figure 45. Dominant axes from excavator (upper left), harvester (upper right) and tractor (below). The top plot (red) represents frequency weighted acceleration data with multiplying factors, middle plot (blue) represents weighted data without multiplying factors and bottom plot (blue) unweighted data without factors.

5.4.9 Compensating factors for point vibration total values

Correlation between scenario 1 (a_s) and other scenarios were calculated. The correlation compared to scenario 2 (a_{sb}) was practically similar if 1.4 multiplying factors were used for seat horizontal axes (Figure 46: left) or were not used (Figure 46: right). Correlation was also calculated for comparing the effects of rotational and floor translational axes to the correlation of OVTVs (Figure 47). The results show that neither the floor axes (Figure 47: left) or the rotational axes (Figure 47: right) had a practical effect to correlation. The results are for all studies and no differences were found between the studies.

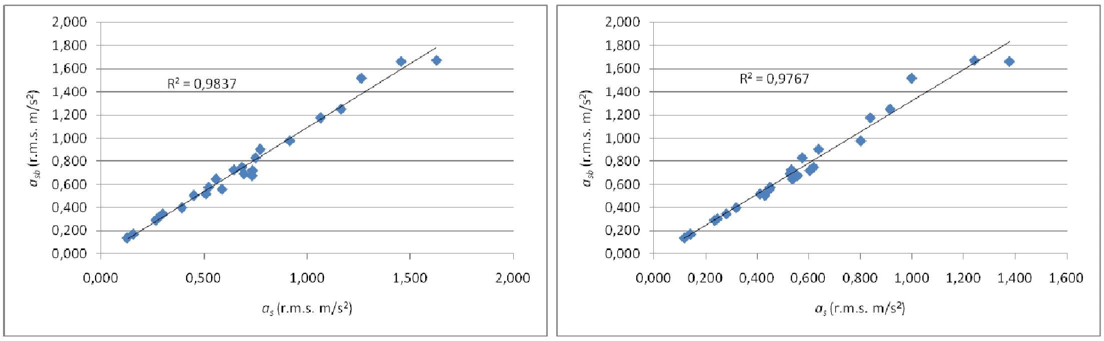

Figure 46. Correlation (Spearman R^2) between frequency weighted overall vibration total value of seat translational axes (a_s) (with 1.4 multiplying factors to seat horizontal axes is shown on left and without the multiplying factors on right) and seat and backrest translational axes (a_{sb}) with respective multiplying factors. The values are calculated based on the results from Maeda (2004), Griffin (1990) and the new field measurements.

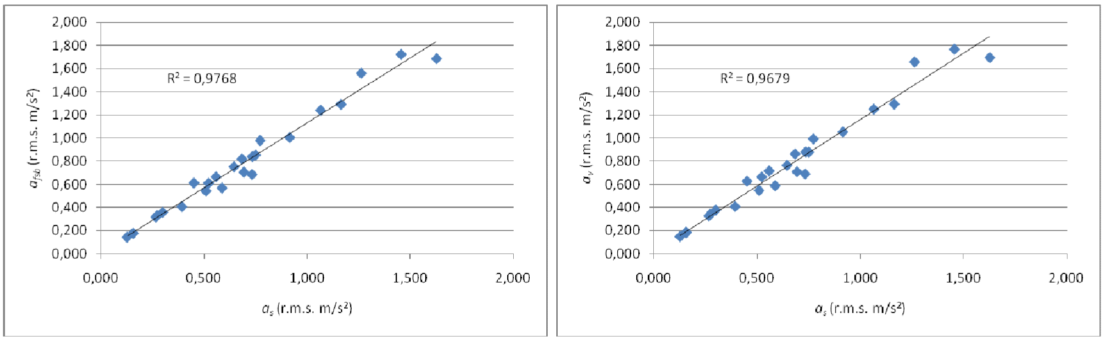

Figure 47. Correlation (Spearman R^2) between frequency weighted overall vibration total value of seat translational axes (a_s) with 1.4 multiplying factors to seat horizontal axes and seat, backrest and floor translational axes with respective multiplying factors (a_{fsb}) (left), and correlation for a_s and overall vibration total value using all twelve axes with respective multiplying factors (a_v) (right). The values are calculated based on the results from Maeda (2004), Griffin (1990) and the new field measurements.

As high correlation was found between scenario 1 and other scenarios, a compensating factor for the scenarios could be calculated in order to force the gradient of the regression line to 1 (Table 28). The factor is higher if less PVTVs are included. In this case it was assumed that the order of including axes will be the same as the order of the scenarios. For example if OVTV is calculated based on the seat translational axes, the calculated OVTV (including 1.4 multiplying factors for seat horizontal axes) is multiplied by 1.2 to compensate the effect of the other PVTVs.

Table 28. Compensating factors for different combinations of point vibration total values to compensate the effects of other point vibration total values. The factor is used to multiply the calculated overall vibration total value.

Compensation factor				
$a_{s1.0}$	$a_{s1.4}$	a_{sb}	a_{sbf}	a_v
1.4	1.2	1.1	1.03	1.0

5.5 Discussion

The purpose of the analyses was to determine the magnitude of the twelve axes of vibration present in field measurements. It is important to understand how the axes contribute in real work environment and how the standard methods emphasise the axes. Based on the standard guidance and previous literature there was not enough data for conducting the analyses, thus new measurements were made.

Despite the method for measuring 12-axis vibration being available since 1987, only two publications were found that had published 12-axis measurement results. Maeda's paper (Maeda 2004) was published in conference proceedings and Griffin's results were in his book "Handbook of Human Vibration" (Griffin 1990). This indicates that the full method is not used widely.

For 12-axis measurements, guidance provided in ISO 2631-1 is incomplete. There is substantial scope for interpretation which will affect OVTV result. If more axes are measured, the vibration total value will increase. Thus if not measuring all axes, then compensation factors should be created to estimate the overall exposure for the environment. The data presented here could be used for such a purpose, where the percentage contribution of typical exposures can be used to estimate the relative contribution from that axis.

The discomfort evaluation method is based on using the r.s.s. method for combining the values, which means that dominating axes are emphasized to the power of two. For this reason the standard gives a possibility to neglect values less than 25 % of the dominant value, because in reality their contribution will be small. For conducting measurements in the field it is feasible to optimise the number of accelerometers and channels used, thus it would be beneficial to have guidance on what axes are important (i.e. needed to be measured) in reality. This guidance is not available in the ISO 2631-1 (1997).

5.5.1 Relative contribution of locations and axes

The relative magnitudes and contribution analyses showed that the most important locations are the seat and backrest (translational axes). For individual axes the seat vertical and backrest fore-and-aft were the most important. The importance of the backrest fore-and-aft axis has been documented before, but it has not been noted to be more important than the other seat axes. In almost all cases the backrest fore-and-aft was at least the second most important axis. Normally the seat vertical was dominant for smoother surfaces and with machines that are used in relatively high speeds (e.g. car and train). The backrest fore-and-aft axis was dominant for rough surfaces and heavy work machines. In general both axes were among the three most dominant axes. The effect of seat rotational and floor translational axes was small.

The relative contribution of the twelve axes confirmed that the few dominant axes will determine OVTV. This was evident also for PVTVs. In all situations at least seat and backrest translational axes need to be included for calculating OVTV. It is however important to notice that OVTV can still be 10 to 20 % smaller when excluding the rotational and floor translational axes and in most cases all PVTVs were more than 25 % of the highest PVTV, thus they were not suggested to be neglected. In some cases this might lead to misleading conclusions of the discomfort level, especially if the value is close to two different categories, or if comparing data sets which have been produced using different combinations of accelerometers. This can be compensated for by using a factor depending on the number of PVTVs included.

5.5.2 Applicability of the r.m.s. method

Based on the interpretation of the ISO 2631-1 it was assumed that the r.m.s. method underestimates the effects of vibration even if only one axis exceeds the crest factor limit. In 11 out of 14 cases the crest factor limit was exceeded for at least one axis. The highest thresholds were for floor axes, which was expected, because in most cases the floor has the least damping (i.e. occurrence of high peaks are more common). In almost all cases only one or two axes exceeded the limit and in most cases it was the additional axis, thus if only seat translational axes were measured then the threshold would not have been exceeded for most measurements (5 out of 14). The crest factors showed that it is almost inevitable that at least one of the twelve axes will exceed the standard’s recommended limit value. The measurements showed that the crest factor easily exceeds the threshold value of 9. If it is exceeded the standard recommends calculating MTVV and/or VDV values, but there is no guidance on how to use them for comfort evaluation. Also the standard does not explicitly say if all axes should be under the limit for the r.m.s. method to work, or if just one axis exceeds the limit, even if this axis might hardly contribute to the OVTV. Certainly the limit value of BS 6841 standard (6) will be exdeeded in practically all cases.

These results indicate that the crest factor is not an effective method for evaluation of vibration. The factor is based only on one single peak from the whole measurement period, thus for similar vibration characteristics it is more likely to have a larger crest factor if a longer period is measured (i.e. likeliness of one high peak increases). Also it is more likely to have a high crest factor if a higher sampling rate is used for acquiring the acceleration signal. In this case higher peaks can be detected, but the r.m.s. value will be practically unaffected by the sampling rate. The frequency weighting somewhat compensates this, but still other factors than the true content of the vibration will have a significant effect on the factor. This has been also acknowledged by the international community as the new draft amendment for the ISO 2631-1 standard notes the same issue (ISO/TC 8/SC 4 2008).

5.5.3 Effects of frequency weighting

Frequency weightings significantly changed the relative emphasis of the frequencies for each axis. The impact was significant especially for rotational axes. The weighted rotational r.m.s. values were on average less than 20% of the unweighted values. The frequency weighting curve for rotational axes (W_e) emphasises only 0.5 to 1 Hz narrow frequency range. Frequencies over 1 Hz are significantly attenuated. For example at 10 Hz the weighting curve reduces the signal energy by 90%. The frequency spectra of the unweighted acceleration of rotational axes showed that on average the frequency range with vibration was higher than 1 Hz. The backrest fore-and-aft axis is weighted by W_c curve. The curve emphasises frequency up to 8 Hz and is much less progressive than W_e. Also W_d and W_k curves, which are used for the seat and floor translational axes and backrest horizontal axes have higher frequency range than W_e. Thus it was clear that the effect of the rotational axes was attenuated more than the other axes. Frequency weighting affected the backrest fore-aft axis the least where the weighted r.m.s. values were almost 90% of the unweighted value. The other axes were attenuated by approximately 40 to 50 %.

A more detailed analysis showed that within the frequency range of the standard (0.5 to 80 Hz), multiple axes were dominant at different frequencies. In most cases the seat or backrest translational axes were dominant below and the floor axes above 10 Hz.

However, the rotational axes were dominant for practically all environments in the absence of the frequency weighting and multiplying factors. This again shows how much the weighting influences the results.

Even though different machines exhibited different vibration values and relations, it was clear that the frequency weighting process almost always attenuated the axes so that either one of the seat translational or backrest fore-aft axis became dominant. Thus the effect of terrain and machine type or model was marginal. The rotational axes were not more dominant with machines that were driven on rougher surfaces or were larger (e.g. harvester). It can be assumed that the rotational motion in these machines is shown primarily as translational, as the point of measurement is at some distance above the centre of rotation.

5.5.4 Effect of multiplying factors

The multiplying factors change the relative effects of the frequency weighted r.m.s. values. For axes other than the seat translational the multiplication factors are less than 1. The backrest fore-and-aft factor is 0.8, but for the lateral and vertical axes the factors are 0.5 and 0.4 respectively. This means that in many cases the fore-and-aft axis will be the most dominant, even though it does not have the largest vibration magnitude. The same is true also for the rotational and floor translational axes, where roll and vertical axes have higher multiplying factors than other axes. Because of r.s.s. method for combining the axes, the differences in the factors have a second power effect, thus making the highest value even more significant. The axis with largest factor will most likely dominate the whole PVTV and the other axes will have insignificant meaning. The results showed that the axes with the highest multiplying factor were also the most dominant axes after weighting and scaling. The factors also further minimised the effects of rotational and floor axes.

The 1.4 multiplying factor used when only seat translational axes are measured is based on the assumption that the backrest axes will have an effect on the discomfort. No publications were found, which have validated the chosen factors and there is no reference in the standard where the factors have been derived. In fact BS 6841 does not have the 1.4 factors for replacing the backrest axes. It is not clear if the factor is supposed to be used for simulating the effect of backrest vibration to discomfort compared to without the backrest, or for simulating OVTV.

For the latter the results in the Table 27 showed that the multiplying factor that would produce similar results for a_s and a_{sb} should be about 1.7 and that it varies even for the same machine type for different surface or work phase. Thus there needs to be a study to evaluate and validate the multiplying factor based on the field measurements. There might be a different factor for certain types of work phases or machines. It is important to notice, that the calculation of the factor based on the backrest axes is related to the location of the sensor. Thus the installation will have an effect to the size of the factor. It would also be helpful for the purpose of the multiplying factor to be specified in the standard, such that comparisons between different measurement scenarios can be made.

5.5.5 Need for measuring additional axes

For conducting measurements in the field it is beneficial to optimise the number of measurement locations, thus it would be beneficial to have guidance on what axes are important contributors to the OVTV and those which can be ignored. For 12-axis measurements, guidance provided in ISO 2631-1 is incomplete. There is a substantial scope for interpretation which will affect OVTV result. If more axes are measured, OVTV will increase. Thus if not measuring all axes, then compensation factors should be applied to estimate the overall exposure for the environment. The data presented here could be used for such a purpose, where the percentage of contribution of typical exposures can be used to estimate the contribution from that axis.

Assuming that the standardised method of vibration assessment is correct, then the relative importance of the rotational axes from the seat and the translational axes from the floor has little or no significance to the subjective feeling based on the results in this paper, even though they are most likely larger than 25 % of the highest value. This eases the measurement process significantly.

5.5.6 Approximating point vibration total values using multiplying factors

The standard does not provide guidance on compensating OVTV depending on how many axes and locations are used. However, this has a direct effect on the size of the value and to the assessment, as the subjective tables are based on absolute values. Maeda (2004) noted that using just the seat translational axes will most likely produce a value that is interpreted as more comfortable than using all axes. This was also shown in this study. The seat translational axes alone produced OVTVs in average of 70 % of the value using all axes.

The different scenarios showed high correlation, thus a single value to compensate the missing PVTVs could be used to estimate OVTV of all axes. This will improve the comparison of values which are based on different number of axes and improve assessment of discomfort, which is based on the absolute values like in the ISO 2631-1 standard.

5.5.7 Differences and similarities of new and previous measurements

Relative magnitudes from the bus, car and train showed good agreement with the seat vertical being the most dominant and the backrest fore-and-aft being the second most dominant for all studies. Overall, good agreement was found for the seat, backrest and floor horizontal, and roll and yaw axes. Biggest disagreement was for the pitch axis, where Maeda's results showed fourth largest r.m.s. value and Griffin and Marjanen showed ninth largest. On the other hand Maeda showed smaller relative magnitude for the floor vertical than Griffin and Marjanen. For the relative contribution all sets showed similar trend than with the relative magnitude. The seat vertical and backrest fore-and-aft were clearly most dominant for the both sets. Also the same disagreements with the pitch and backrest and floor vertical axes were found with the bus, car and train. For the excavator and tractor the comparison between Maeda's and Marjanen's data show good agreement with the backrest fore-and-aft and seat translational axes. The biggest difference was for the roll, pitch, and backrest vertical axes. Also for the excavator and tractor, similar agreements and differences were found with the relative contributions.

Compared to an earlier study by Parsons and Griffin (1983), the results were similar for the ranking of most axes. The study used different cars and road types and concluded that seat vertical and floor vertical axes had highest contribution. The seat and backrest fore-and-aft axes were the next important, having thus similar findings than later studies. However, the study was conducted without multiplying factors and using weightings which were different from the standard.

5.5.8 Interpretation of the standard method for field measurements

The results showed that the three translational axes from the seat alone underestimated the total vibration value in almost all cases, if compared to using all twelve axes, even though the 1.4 multiplying factors were used. This will most likely underestimate one or two categories of the subjective feeling than using the 12-axis data. This has been indicated previously also (Maeda 2004). However, if the backrest axes were included the difference was on average less than 10 %. This was because the backrest fore-and-aft axis was either the most dominant or the second most dominant in all measurements. The rotational axes from the seat and translational axes from the floor had only marginal effect. In both cases the effect was only few percentages. So it is suggested to measure at least the seat and backrest translational axes.

5.5.9 Scope and limitations of the results

Even though the results presented in this paper are only from specific machines, which mean that the levels of r.m.s. values cannot be generalized, the relative importance of different axes can be considered to be representative of work machines in normal situations. However, there is still only a small body of data reporting 12-axis measurements. Some analysis could be made only from the new field measurements, thus limiting the number of measured environments.

5.5.10 Suggestion for further work

Assuming that the standardized method of vibration assessment is correct, then the relative importance of rotational axes from seat and translational axes from floor has little or no significance to the subjective feeling based on the results in this chapter. Thus it is most likely that they do not need to be measured. This eases the measurement process significantly. However, there is still only a small body of data reporting 12-axis measurements and so it is recommended that more 12-axis data is gathered and reported so that the relative importance of the axes in further practical environments can be determined.

The most recent study by Wyllie and Griffin (2007) suggests that the rotational axes have more effect on discomfort than the standard method implies. The standard also neglects the effect of phase between axes and this might emphasise the floor axes. Thus a laboratory study to confirm the effects of different axes in a multi-axis environment is needed.

5.6 Conclusions

The standardised method to evaluate discomfort from whole-body vibration emphasises the dominant axes. It was found that:

- The most dominant axes in field were from the seat (vertical) and backrest (fore-and-aft);
    - Thus dominant PVTVs were seat and backrest translational locations;

- Because of the standard's method, the effect of rotational and floor axes on the vibration total value were negligible;
    - And because of the weighting of frequency and axes, it is most likely that in any type of environment the rotational and floor axes have marginal effect, at least for the machine types measured here.
- The dominant axis changed for different frequency ranges, where the seat and backrest axes were dominant at low frequencies (< 10 Hz) and floor axes at high frequencies (> 10 Hz);
    - The effect of floor axes were higher without multiplying factors, and rotational axes were dominant without the frequency weighting;
- The crest factor limits the usability of the r.m.s. method, especially if all twelve axes are used, because it is likely that at least one axis will show high crest factor;
    - If less axes are used (e.g. seat translational axes), then the crest factor will be exceeded less often;
- Correlation analyses showed that a compensating factor can be produced to estimate the effect of PVTV of another location, thus all results could be directly compared even though different number of axes are included;
    - Higher multiplying factors than 1.4 should be used to compensate backrest axes, but the results showed large variation between environments, thus a factor for PVTV is suggested instead of individual axes;
- All studies showed similar results and trends, thus a more general notion can be concluded about the role of the axes and standard weighting process to the results.

The results suggested that there is no reason to measure the seat rotational and floor translational axes. However, there is limited information on how important the locations are for predicting discomfort of subjects. The relative contribution of axes to discomfort need to be validated in a laboratory using test subjects.

6 Chapter 6 - Laboratory trial part I: description and validation of trial procedure, methods and results

6.1 Introduction

The results from the field measurements in Chapter 5 suggested that if the standard method is correct, then the discomfort evaluation process can be simplified. Rotational axes from the seat and translational axes from the floor provided negligible contribution to overall vibration total value (OVTV) in all cases, because of the standard weighting process. However, there is very little information on how the axes contribute to the discomfort in practice. The studies conducted in a laboratory have normally used stationary sinusoidal or flat band random vibration stimuli and rarely more than one axis. The few studies, which have been conducted in the field, have used test tracks with short duration stimuli and emphasis on shocks (Fairley 1995). Only one study (Parsons and Griffin 1983) was found, which had measured all twelve axes and subjects' judgments, but the data was analysed using different weightings than in the standard and without using multiplying factors. There is a need for evaluating how well the full ISO 2631-1 method predicts discomfort in practice. This means non-stationary and field-like stimuli for long durations.

Based on the selected methods, stimuli, trial procedure and subjects, the results from a trial will have limitations. It is important to understand the limitations in relation to the goals of the trial. Before any conclusive conclusions can be made and new methods suggested, it is necessary to validate the results. The method selected for acquiring and evaluating judgment data (i.e. continuous judgment method) has no references in relation to vibration exposure, thus an analysis of the applicability of the method is needed before further conclusions can be made. The stimuli, which is based on field measurements, have uncontrolled frequency characteristics and non-stationary time signal. Thus, the results might be limited to similar environments. Depending on the selected trial procedure and guidance given to the subjects, and the characteristics of the subjects, the same trial can produce different results. It has been a norm to use students or laboratory staff in the trials, as they are easily available. However, there is a suspicion that people who have no experience or who do not have to consider the other aspects, such as costs of the trip, are not the best to evaluate discomfort for general public (Oborne 1976).

Even though there is a clear need for more information on the applicability of the standard method for evaluating discomfort, the results from the few related previous studies does provide indications for using the standard method:

- More axes will improve correlation to discomfort (Griffin, et al 1982, Parsons and Griffin 1983);
    - However, seat translational axes will have the highest effect (Fairley 1995);
- Using the r.m.q. method provides better correlation than the r.m.s. method for stimuli including shocks (Boileau, et al 1989);
- Higher multiplying factors for seat horizontal axes should be applied (i.e. frequency weightings for horizontal axes will underestimate the subjective discomfort judgment) (Maeda and Mansfield 2006b).

6.2 Goals of the trial

Based on the literature review in Chapter 2 and results from the field measurements a laboratory trial was planned. The trial should be conducted in a multi-axis environment using stimuli, which simulate vibration exposures experienced in the field, as there has not been this kind of study before. The results should seek to validate the conclusions from the previous studies and provide new information on the role of axes, frequency weighting, multiplying factors and averaging method for improving the correlation to discomfort in the field. The stimuli should include shocks, but also characteristics, which are more common in road transportation (i.e. non-stationary vibration).

The goals and analyses of the laboratory trial are divided into three separate phases:

1. Validate the chosen methods for acquiring and analysing discomfort judgments and the effects of stimuli and gender to the results (Chapter 6);
2. Validate the standard method (Chapter 7);
3. Improve the standard method (Chapter 8).

The first goal is to validate and verify that the chosen trial procedure, stimuli and judgment method provides results that can be used to validate and improve the standard. It is important to understand if the chosen stimuli order or subjects will affect the results. Based on the requirements of the latter goals the following questions were set for the validation of the trial methods (part I):

- Does the order of stimuli affect judgments?
- Do the characteristics of subjects affect judgments (i.e. weight, height, gender)?
- What is the best approach for averaging judgment value for best correlation?

6.3 Methods

6.3.1 Test environment

6.3.1.1 Multi-axis shaker

A 6 degrees-of-freedom shaker at Loughborough University was used to expose subjects to multi-axis vibration stimuli, which simulate vibration from field environments (Figure 48). The shaker can be excited using movement sampled at 50 Hz frequency. Each axis has a separate column of displacement values, thus six tab delimited columns comprise the data file. If acceleration or velocity data is to be used, a signal conversion (i.e. integration) and resampling is required to transform the data to displacement information.

Figure 48. Six-axis shaker at Loughborough University for conducting the multi-axis laboratory trial.

6.3.1.2 Sensor setup and data acquisition

Accelerometers were installed based on the standard guidance. Figure 49 shows the sensor layout for the shaker. A backrest sensor was installed half way up the backrest (270 mm from SIP). A floor sensor was installed below the seat at the same vertical axis as the seat sensor. The floor sensor was used to analyse the platform movement, but was not used for analysing the judgments. It was reasonable to assume that feet did not make any significant contribution to the judgment, and this was confirmed in pilot work (Bhalchandra 2008). Also it was previously concluded from the field measurements (Chapter 5) that the floor axes showed marginal contribution to the OVTV. The subject's feet rested on a footrest, which was adjusted based on the subject's height and did not move during the experiment.

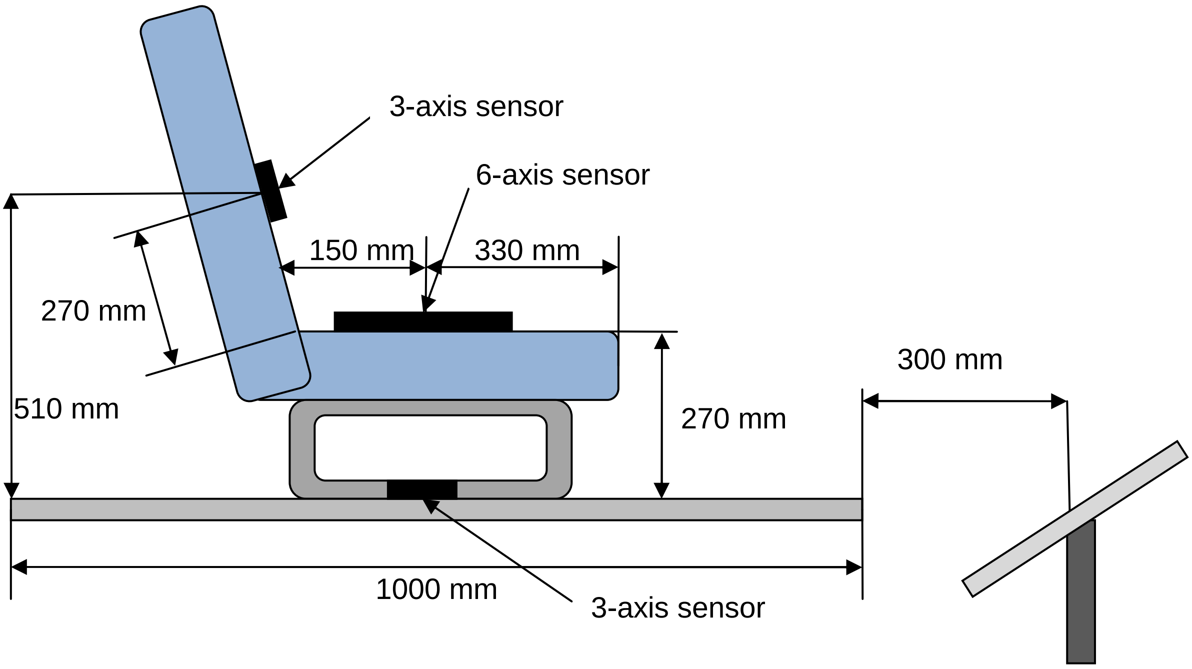

Figure 49. Shaker dimensions and sensor layout for the laboratory trial (side view).

The data was measured using a 12-axis sensor system produced by Vibsolas Ltd (the commercial version V12SP in Chapter 4) and National Instruments recording device. The recording and visualisation program was realised using a Labview 7.1 development environment. For each trial, the value of discomfort judgment and the twelve axes of the standard were recorded at sampling frequency of 1000 Hz. Six axes from the seat, including three translational and three rotational axes, three translational axes from the backrest and three translational axes from the floor were measured.

6.3.1.3 Stimuli

Stimuli were based on the acceleration data from the field measurements conducted in Chapter 5. The purpose was to create an environment that simulated frequencies and relative magnitudes of the axes that are present in the field, thus using an approach with high ecological validity. The stimuli were created taking the limitations of the shaker into account. This included band-pass filtering between 1 and 20 Hz. Each main stimulus was chosen so that as many as possible different frequency contents that are present in the field were covered (Table 29). A signal processing equalisation was conducted to the original measured 12-axis data, so that the stimuli represented similar characteristics to the original source.

Table 29. Main stimuli used in the trial to represent vibration from the field. Each stimulus was based on a selected data sample of the field measurements in Chapter 5. Each main stimulus lasted 15 seconds.

Main stimulus	Simulated machine	Work phase	Terrain	Speed
A	Car	Moving	Cobblestone road – city	30 km/h
B	Truck	Moving	Asphalt – city	30-60 km/h
C	Forestry harvester	Moving	Forest	3 km/h
D	Train	Moving	Rail track	140 km/h
E	Excavator	Digging	Gravel road	0 km/h

As signal noise and errors cause problems in the integration process, highpass filtering was applied for the converted acceleration data. In this case cut-off frequency for the highpass filter was 1 Hz using a 12th pole filter (Butterworth). A 20th pole low pass filter (Butterworth) at 20 Hz was also used, thus the controlled frequency range was between 1 and 20 Hz. However, due to friction and valve properties, additional frequencies above 20 Hz did exist (Figure 50). These frequencies could not be directly controlled, but they were considerably smaller in amplitude than the stimuli frequency characteristics. Frequencies below 10 Hz dominated the spectrum for each axis. For fore-and-aft axis the difference was over 15 dB, for lateral axis over 5 dB and for vertical axis over 10 dB.

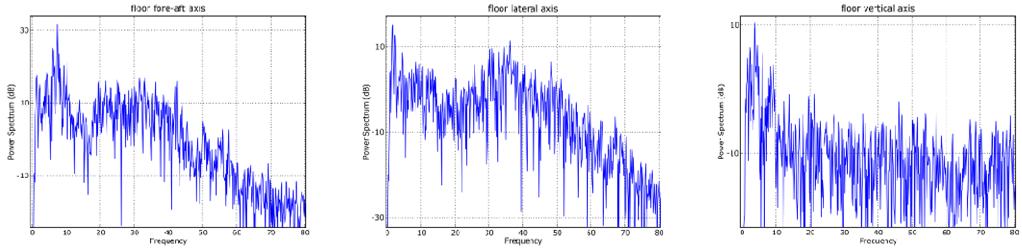

Figure 50. Power spectra from the multi-axis test bench of the floor translational axes for the train stimulus (left: fore-and-aft, middle: lateral and right: vertical axis).

Figures 50 - 54 show the frequency content of each main stimulus. The power spectra of the main stimuli represent the actual measured acceleration from the seat of the test bench. The spectra show that for translational axes the low frequencies (< 10 Hz) dominate. For rotational axes higher frequencies were noted as well, which is partly due to an interaction between the seat cushion and the sensor pad. All stimuli showed non-flat spectra and frequency characteristics, which are typically seen in the field.

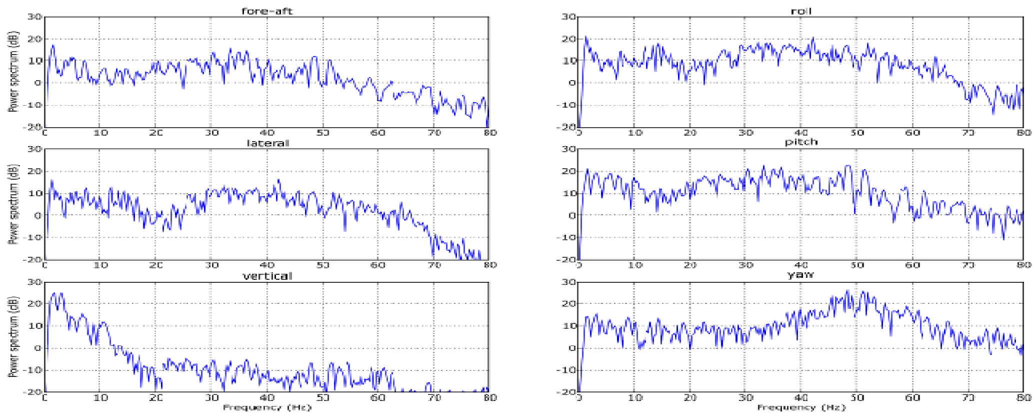

Figure 51. Unweighted power spectra of the main stimulus A (car) for each axis measured from the seat surface of the test bench.

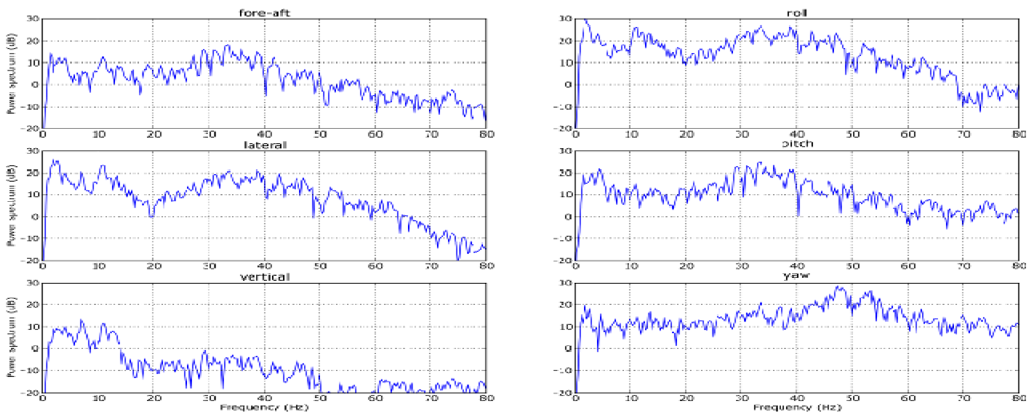

Figure 52. Unweighted power spectra of the main stimulus B (truck) for each axis measured from the seat surface of the test bench.

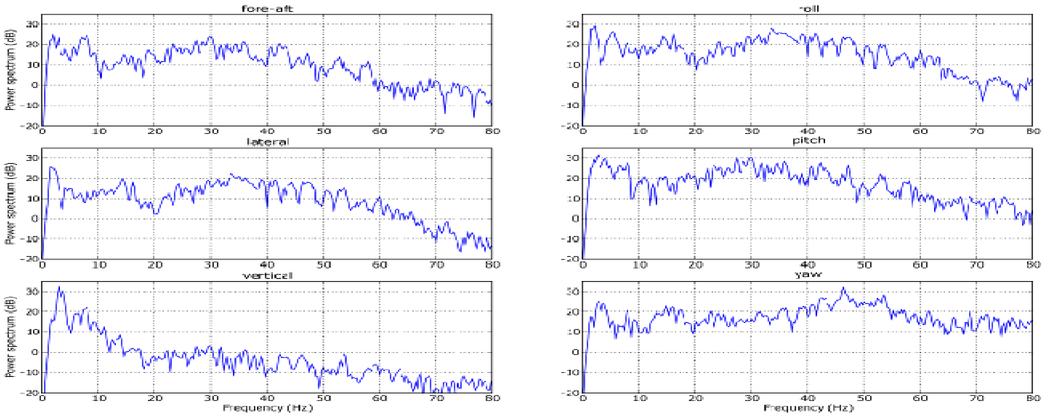

Figure 53. Unweighted power spectra of the main stimulus C (harvester) for each axis measured from the seat surface of the test bench.

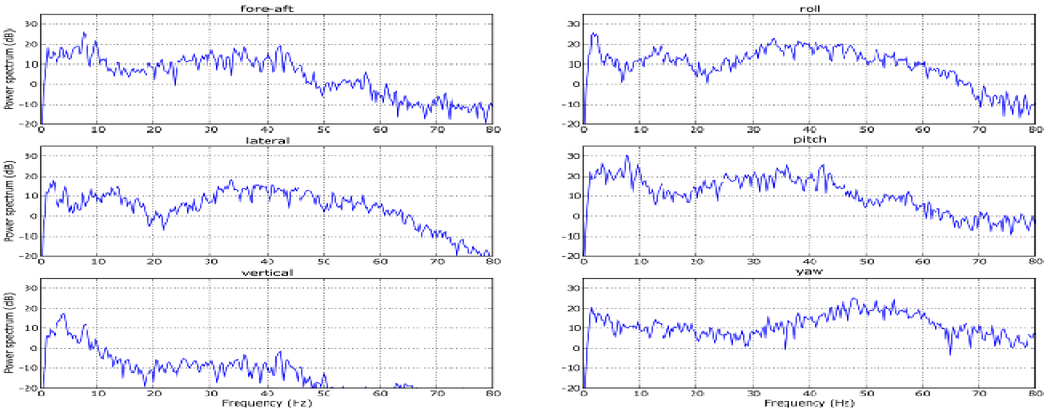

Figure 54. Unweighted power spectra of the main stimulus D (train) for each axis measured from the seat surface of the test bench.

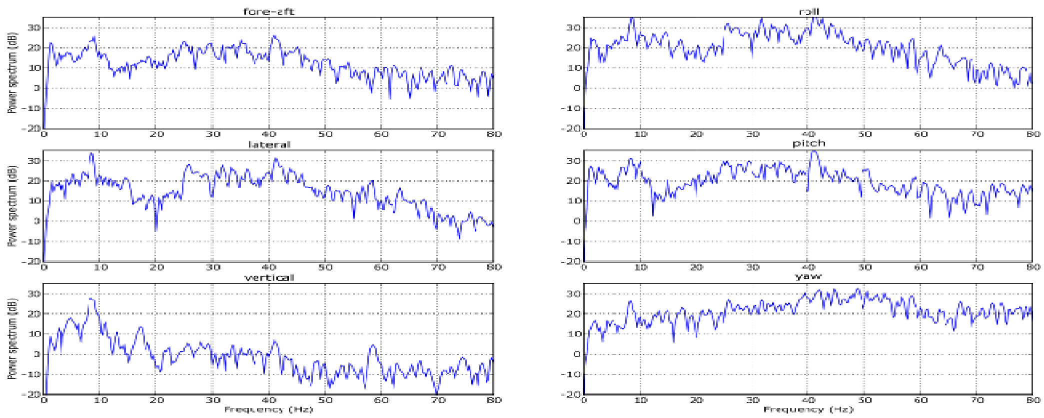

Figure 55. Unweighted power spectra of the main stimulus E (excavator) for each axis measured from the seat surface of the test bench.

For each main stimulus six variations were created that had different relative vibration magnitudes for the axes in order to test the ISO 2631-1 method. The variations can be used to analyse how discomfort is affected by the change of dominant axes, thus testing the effect of the multiplying factors. As each of the main stimuli had different frequency content, it was also possible to evaluate how similar OVTVs were perceived, if the frequency content was different, thus testing the effect of frequency weighting.

In total 30 different stimuli were created (Table 30). At least one variation of each main stimulus had little or no rotational vibration, but had similar OVTV than stimulus which had rotational vibration. All stimuli lasted 15 seconds.

Table 30. Stimuli and control factors for the test bench for all stimuli variations.

Main stimulus	Variation	Note	Control factors x	y	z	Roll	Pitch	Yaw
A	1	Car – original	1	1	1	1	1	1
A	2	Car - enhanced vertical	0.5	0.5	1	0.5	0.5	0.5
A	3	Car - w/o rotation	0.5	0.5	1	0	0	0
A	4	Car - enhanced rotation	1.5	1.5	1	1.5	1.5	1
A	5	Car - enhanced pitch	1.5	0.75	0.5	0.75	1.5	0.5
A	6	Car - enhanced fore-and-aft	1.5	0.75	0.5	0	0	0
B	1	Truck – original	0.9	1	0.6	1	0.8	1
B	2	Truck - enhanced lateral	0.45	1	0.3	0.5	0.5	0.5
B	3	Truck - enhanced lateral w/o rotation	0.45	1	0.3	0	0	0
B	4	Truck - enhanced vertical	0.9	0.5	1.2	1	0.8	1
B	5	Truck - enhanced vertical	0.45	0.25	1.2	0.5	0.4	0.5
B	6	Truck: w/o rotation	0.45	0.25	1.2	0	0	0
C	1	Harvester – original	1	1	1	1	1	1
C	2	Harvester - enhanced vertical	0.5	0.5	1	0.5	0.5	0.5
C	3	Harvester - enhanced vertical	0.5	0.5	1	0	0	0
C	4	Harvester - reduced all	0.5	0.5	0.5	0.5	0.5	0.5
C	5	Harvester - enhanced vertical	0.25	0.25	0.5	0.25	0.25	0.25
C	6	Harvester - w/o rotation	0.25	0.25	0.5	0	0	0
D	1	Train – original	0.5	0.5	0.5	1	1	1
D	2	Train - w/o rotation	0.5	0.5	0.5	0	0	0
D	3	Train - enhanced vertical w/o rotation	0.25	0.25	0.5	0	0	0
D	4	Train - enhanced pitch	0.6	0.25	0.25	0.5	1	1
D	5	Train - enhanced fore-and-aft	0.75	0.25	0.25	0	0	0
D	6	Train - enhanced fore-and-aft	0.75	0.125	0.125	0	0	0
E	1	Excavator – original	1	1	1	1	1	1
E	2	Excavator - enhanced vertical	0.5	0.5	1	0.5	0.5	0.5
E	3	Excavator - enhanced vertical	0.2	0.2	1	0.2	0.2	0.2
E	4	Excavator - enhanced fore-and-aft	1	0.2	0.2	0.2	0.2	0.2
E	5	Excavator - enhanced pitch	1	0.1	0.1	0.2	1.5	0.2
E	6	Excavator - enhanced rotation	1	0.1	0.1	1.5	0.2	0.2

6.3.2 Judgment method

Subjects evaluated discomfort of each stimulus using the continuous judgment method (Kuwano and Namba 1985). The trial was planned to be conducted using cross-modal matching of subjective judgment and visual line. Subjects were presented a discomfort line (Figure 56 left) that they could control in real-time using a rotary control (Figure 56 right). There was no numerical scale indicating the length of the line. The test subjects were asked to adjust the line so that it corresponded to discomfort judgment between “no discomfort” and “high discomfort”. The test subjects were guided to evaluate the instantaneous discomfort for each stimulus separately. At the end of each stimulus the test subjects reset the judgment by turning the indicator to “no discomfort” position.

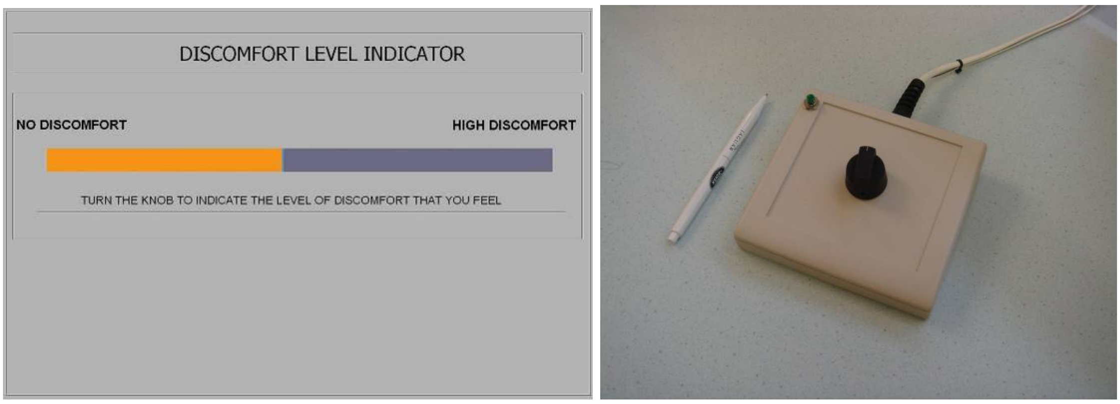

Figure 56. The visual information presented to participants to judge discomfort based on the continuous judgment of line length (left) and a rotary control for evaluating discomfort (right).

The continuous judgment method has not been commonly used in vibration research, but has been used in noise research. In the previous studies a delay between the stimulus and the response has been noted (see Chapter 2). There was also a suspicion that some seconds from the beginning of each stimulus should be neglected as the judgment started from “no discomfort” position, thus a visual inspection of the judgment data was considered necessary. An arithmetic mean of the judgment was calculated similarly as in the noise studies to produce a single judgment value for each stimulus.

6.3.3 Subjects

The experiment used 22 subjects (12 males and 10 females) (Table 31). The average age of the subjects was 22 years (three subjects were above 30 years). The average height was 181 cm for men and 164 cm for women. Average weight was 74.8 kg and 59.6 kg respectively. Each subject gave an informed consent to participate in the trial. The trial was approved by Loughborough University Ethical Advisory Committee.

Table 31. Information on the test subjects used in the trial. The stimuli were randomised and three sequences (a, b and c) were created. The order of sequence for each subject was changed.

Subject	Sequence order	Age (y)	Gender	Height (cm)	Weight (kg)
1	a,b,c	23	Male	178	60
2	b,c,a	22	Male	180	72
3	c,a,b	30	Male	175	85
4	a,c,b	36	Male	192	80
5	c,b,a	18	Female	160	57
6	b,a,c	24	Male	174	60
7	a,b,c	20	Male	186	85
8	b,c,a	31	Male	171	66
9	c,a,b	18	Male	180	84
10	a,c,b	18	Female	174	56
11	c,b,a	18	Female	163	65
12	b,a,c	20	Female	167	60
13	a,b,c	19	Female	155	46
14	b,c,a	18	Female	173	63
15	c,a,b	18	Male	182	71
16	a,c,b	18	Male	180	75
17	c,b,a	18	Male	194	79
18	b,a,c	18	Male	182	81
19	a,b,c	29	Female	153	47
20	b,c,a	18	Female	164	67
21	c,a,b	19	Female	165	65
22	a,c,b	22	Female	167	70
	Average	**22**		**173**	**68**

6.3.4 Study procedure

Before the trial, test subjects completed an instruction sheet, health screen questionnaire and consent form. The test subjects were instructed to sit on the seat in a comfortable upright posture and leaning against the backrest (Figure 57). A test sequence of five stimuli from the lowest vibration magnitude to the highest was used to familiarise subjects with the vibration before the trials began and to allow for training of controlling the judgment line on the screen. Each test subject was then exposed to three randomised sequences of all 30 stimuli (90 stimuli in total). Between sequences there was a break where the test subjects were asked to dismount from the seat and move around in the laboratory for five minutes, in order to minimise the effects of fatigue.

As each sequence took 10 minutes and there was a 5 minute break between the sequences, the trial procedure took 40 minutes for each subject. The subjects used a seat belt for safety purposes. The seat was adjusted to allow comfortable posture.

Figure 57. A test subject evaluating discomfort during the trial.

6.3.5 Vibration magnitudes

Vibration amplitudes were calculated using the standard's frequency weightings and multiplying factors, and r.m.s. averaging method. Point and OVTVs were calculated based on the standard guidance.

6.3.6 Effect of sequence type and order to judgments

As the test subjects were exposed to each stimulus three times in random order, it was necessary to validate that the judgment was not affected by the order of stimuli in a sequence or the order of sequences. An averaged judgement value for each sequence was calculated for the subjects based on the averaged values of each stimulus. The values were then tested for any statistical differences using Friedman test and Wilcoxon signed-rank test. The null hypothesis for Friedman test was that the distributions are same across the repeated measurements. The null hypothesis was rejected if p-value was low ($p < 0.05$). The null hypothesis for Wilcoxon test was that the distributions of the samples are symmetrical. The null hypothesis was rejected if p-value was low ($p < 0.05$).

6.3.7 Effect of subject characteristics to judgments

There have been indications in previous publications that men and women perceive vibration differently (Mansfield 2005). The differences can be related to the differences between physical or psychophysical characteristics (i.e. weight distribution, sensitivity, etc). Even though the goal of the study was not to evaluate differences between men and women, it was important to analyse any differences for improving the prediction of discomfort. If no statistical differences are found between men and women, then also the height or weight has most likely no effect to judgment, as clear differences in the physical characteristics were noted between the genders.

Mann-Whitney U test was used to analyse if there were statistical differences between the data samples. The test is used to show if two independent data sets come from the same distribution, thus have no statistical differences. The null hypothesis in the test was that the compared data samples come from identical populations, thus have same distribution. P- and z-values were calculated for testing the null hypotheses. The p-value was used to determine if the null hypothesis can be considered true.

6.4 Results

6.4.1 Vibration magnitudes

As rotational motion will always have translational components for the relevant axes, the translational axes were present in all scenarios (Table 32). However, stimuli without rotational components were well achieved. The table shows that in most cases the preferred effect of the factors was achieved (compare to Table 30). The frequency weighted r.m.s. values represented typical range of vibration levels in field environments. Vibration was measured over all 9-axes even where there was no driving signal, to include any cross-axis response of the seat dynamics. Highest magnitudes were for stimuli C1, E1 and E3. Crest factors were below 9 for all stimuli and axes.

Table 32. The frequency weighted r.m.s. values (m/s^2) with respective multiplying factors of each stimulus for each measured axis and overall vibration total value (OVTV) using seat translational and rotational axes and backrest translational axes.

		Seat translational			Seat rotational			Backrest translational			Floor translational			
Main stimulus	**Variation**	**x**	**y**	**z**	**Roll**	**Pitch**	**Yaw**	**x**	**y**	**z**	**x**	**y**	**z**	**OVTV**
A	1	0.308	0.284	0.702	0.224	0.136	0.029	0.580	0.168	0.251	0.080	0.086	0.259	1.080
A	2	0.192	0.162	0.701	0.117	0.077	0.026	0.419	0.095	0.246	0.063	0.063	0.257	0.906
A	3	0.154	0.107	0.704	0.062	0.059	0.026	0.387	0.059	0.242	0.062	0.059	0.258	0.867
A	4	0.429	0.401	0.706	0.318	0.197	0.030	0.756	0.242	0.255	0.100	0.108	0.260	1.296
A	5	0.404	0.215	0.297	0.165	0.185	0.018	0.686	0.135	0.135	0.074	0.057	0.106	0.931
A	6	0.149	0.108	0.273	0.054	0.037	0.012	0.220	0.056	0.116	0.059	0.047	0.100	0.422
B	1	0.250	0.803	0.349	0.452	0.128	0.052	0.511	0.434	0.078	0.088	0.237	0.146	1.230
B	2	0.163	0.705	0.158	0.381	0.084	0.041	0.355	0.354	0.043	0.053	0.205	0.065	0.979
B	3	0.082	0.659	0.133	0.308	0.043	0.023	0.199	0.316	0.034	0.047	0.190	0.060	0.836
B	4	0.270	0.554	0.765	0.374	0.139	0.047	0.564	0.338	0.149	0.123	0.171	0.347	1.259
B	5	0.153	0.272	0.718	0.185	0.080	0.026	0.390	0.167	0.137	0.081	0.086	0.328	0.925
B	6	0.103	0.199	0.728	0.091	0.055	0.017	0.365	0.103	0.136	0.082	0.083	0.329	0.869
C	1	0.741	0.803	1.197	0.528	0.381	0.073	1.303	0.472	0.251	0.248	0.149	0.380	2.250
C	2	0.400	0.417	1.126	0.287	0.197	0.043	0.874	0.244	0.232	0.148	0.094	0.364	1.615
C	3	0.302	0.238	1.135	0.126	0.122	0.031	0.792	0.116	0.223	0.150	0.078	0.358	1.471
C	4	0.335	0.389	0.458	0.262	0.157	0.030	0.625	0.227	0.102	0.093	0.068	0.142	1.010
C	5	0.171	0.208	0.432	0.138	0.076	0.018	0.382	0.123	0.093	0.056	0.050	0.133	0.674
C	6	0.123	0.130	0.437	0.064	0.038	0.011	0.308	0.064	0.090	0.060	0.045	0.132	0.580
D	1	0.472	0.435	0.331	0.361	0.233	0.058	0.883	0.284	0.092	0.236	0.106	0.100	1.257
D	2	0.225	0.323	0.297	0.161	0.084	0.012	0.375	0.158	0.083	0.198	0.089	0.091	0.671
D	3	0.111	0.171	0.257	0.081	0.043	0.008	0.225	0.085	0.068	0.090	0.052	0.078	0.423
D	4	0.473	0.246	0.240	0.194	0.224	0.052	0.845	0.164	0.077	0.256	0.068	0.056	1.086
D	5	0.351	0.163	0.287	0.083	0.124	0.011	0.479	0.078	0.084	0.319	0.049	0.067	0.705
D	6	0.341	0.087	0.277	0.050	0.118	0.010	0.460	0.040	0.077	0.310	0.032	0.059	0.661
E	1	0.620	0.915	1.461	0.498	0.286	0.070	1.009	0.565	0.239	0.477	0.523	0.668	2.258
E	2	0.349	0.461	1.371	0.255	0.146	0.039	0.647	0.274	0.201	0.300	0.281	0.638	1.687
E	3	0.211	0.210	1.389	0.117	0.093	0.028	0.599	0.119	0.181	0.188	0.144	0.634	1.566
E	4	0.296	0.147	0.317	0.082	0.094	0.014	0.336	0.086	0.081	0.229	0.056	0.103	0.594
E	5	0.660	0.216	0.243	0.098	0.353	0.022	1.205	0.123	0.098	0.221	0.103	0.077	1.468
E	6	0.352	0.550	0.286	0.406	0.105	0.030	0.473	0.403	0.082	0.241	0.094	0.075	1.040

Figures 58-60 show OVTVs using the seat translational and the rotational and the backrest translational axes for each stimulus in a sequence. Most notable difference is that sequence *a* had significantly higher amplitude for the first stimulus (E2) than sequences *b* and *c*.

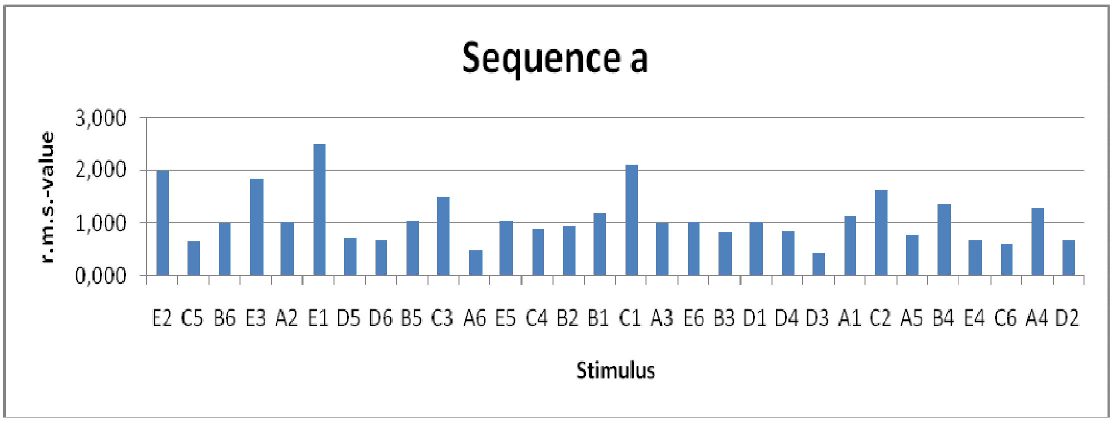

Figure 58. Sequence 'a' presented as the frequency weighted r.m.s. values (m/s^2) using the seat and the backrest translational and the seat rotational axes with the respective multiplying factors.

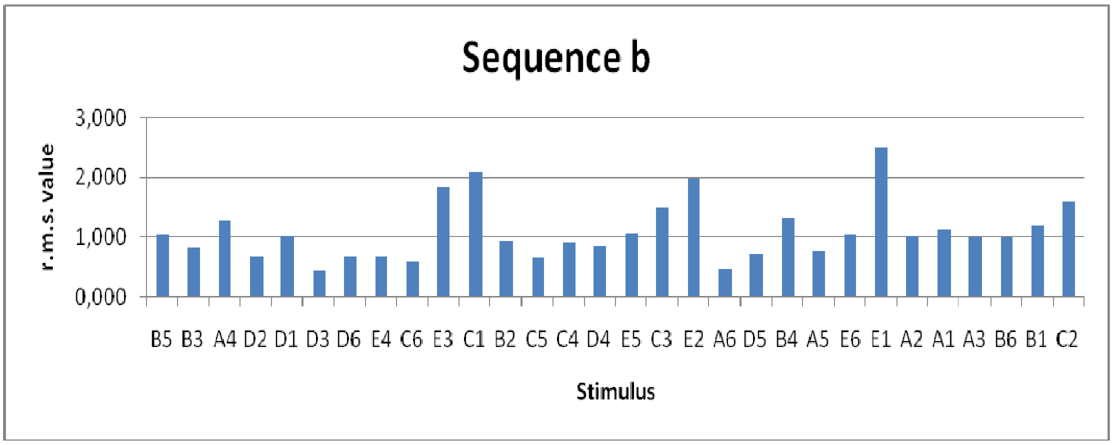

Figure 59. Sequence 'b' presented as the frequency weighted r.m.s. values (m/s^2) using the seat and the backrest translational and the seat rotational axes with the respective multiplying factors.

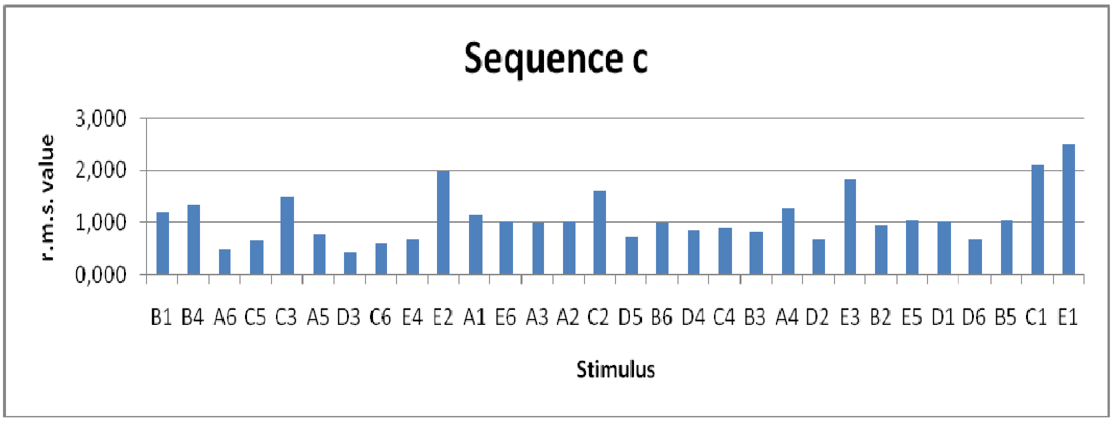

Figure 60. Sequence 'c' presented as the frequency weighted r.m.s. values (m/s^2) using the seat and the backrest translational and the seat rotational axes with the respective multiplying factors.

6.4.2 Judgment style and averaging period

Figure 61 shows an example of a continuous judgment of a stimulus. The judgment process was found to include three stages: 1) a delay for responding to vibration (2 seconds), 2) an adjustment period (3 seconds) and 3) a fine tuning period (10 seconds), where the final judgment was decided. A delay in average of 2 seconds was noted for responses to vibration during the trial. This was also found out previously in a pilot trial (Bhalchandra 2008). At the beginning of each stimulus also an adjustment period was noted, at which time the subject settled for the initial judgment level. In the last phase the subject changed the judgment relative to the initial level and vibration exposure (this included the 2 second response delay as well).

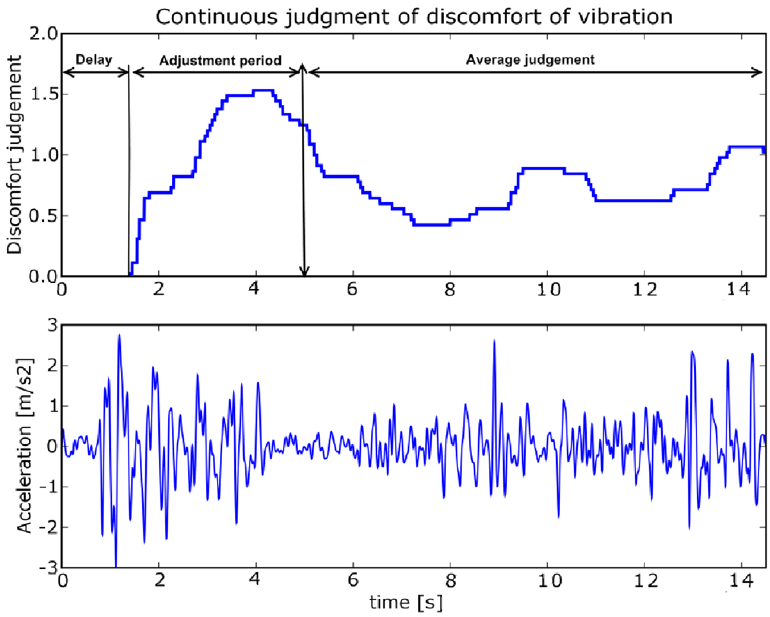

Figure 61. An example of continuous judgment of vibration (lower figure shows acceleration of seat vertical axis, above the discomfort judgment of the stimulus is shown).

Because of the response delay and the early adjustment period, first five seconds of the judgment of each stimulus was not included in the analyses (Figure 61). The last 10 seconds were averaged to produce a single numerical value of subject's discomfort using arithmetic averaging. The scale of the judgment was normalised between 0 and 2 in 16 bit resolution (i.e. zero means "no discomfort" and two means "high discomfort").

6.4.3 Judgment values

An averaged judgment value was calculated for each subject and sequence (Table 33). The averaged value included all averaged judgments from the stimuli. The subjects showed similar judgment levels for all sequences.

Table 33. Averaged judgment values for each sequence and test subject, and the order which the sequences were run for each subject.

	Stimuli sequences and mean judgments			
Test subject	***a***	***b***	***c***	**Sequence order (1,2,3)**
1	0.982	0.895	0.896	a,b,c
2	0.443	0.481	0.512	b,c,a
3	0.547	0.578	0.516	c,a,b
4	0.762	1.062	1.019	a,c,b
5	0.814	0.974	1.011	c,b,a
6	0.802	0.821	0.813	b,a,c
7	0.737	0.761	0.667	a,b,c
8	0.790	0.997	0.930	b,c,a
9	0.699	0.746	0.701	c,a,b
10	0.698	0.780	0.931	a,c,b
11	1.056	1.210	0.947	c,b,a
12	0.384	0.461	0.397	b,a,c
13	0.508	0.482	0.456	a,b,c
14	0.859	0.755	0.900	b,c,a
15	0.651	0.659	0.642	c,a,b
16	1.143	1.171	1.287	a,c,b
17	0.662	0.646	0.875	c,b,a
18	0.422	0.462	0.366	b,a,c
19	0.388	0.681	0.779	a,b,c
20	0.586	0.489	0.628	b,c,a
21	0.398	0.492	0.365	c,a,b
22	0.631	0.886	0.857	a,c,b

Averaged judgments for each stimulus variation were also calculated for all subjects, and for men and women separately (Figure 62). Men had slightly higher average values for most stimulus variations, but the differences were small.

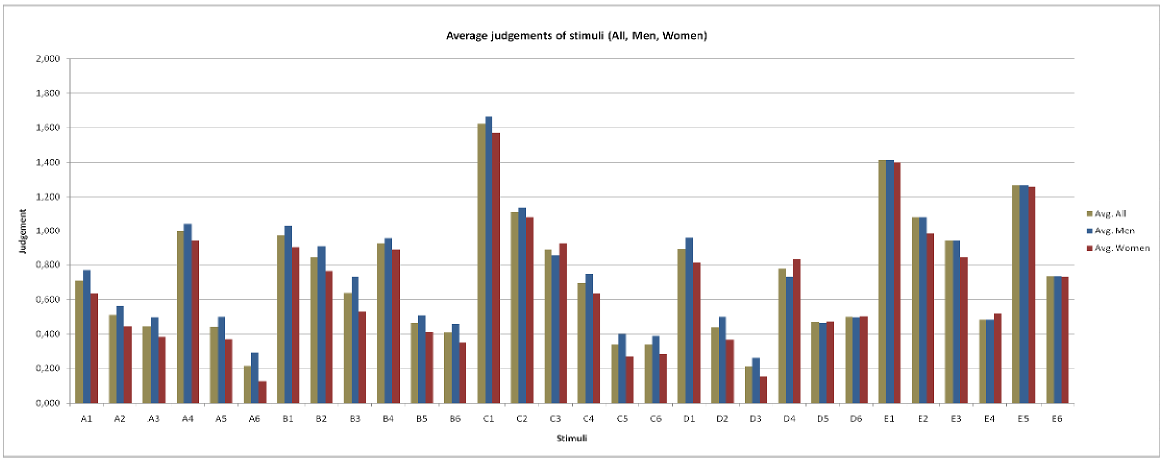

Figure 62. Averaged judgments for each stimulus for all subjects, and men and women separately.

6.4.4 Effect of sequence type and order to judgments

The order of stimuli in each three sequences was randomised, so there was a possibility that the judgment scale would change depending on sequence type and order of the sequences. This can be validated by comparing the averaged judgments for each sequence (Table 33).

For the effect of a sequence type to the judgment scale the Friedman Chi-Square value was 6.636 and p-value 0.0362. The results suggest that the null hypothesis should be rejected, thus there was a difference of judgment scale between sequence types. Using Wilcoxon rank-test it was found that there were differences ($p<0.05$) between sequences *a* and *b* (W=-151, z=-2.44, p=0.015). Between sequences *a* and *c* (W=-111, z=-1.79, p=0.074) and *b* and *c* there were no differences (W=7, z=0.11, p=0.912), although for a and c the p value was very close to 0.05.

For the effect of sequence order to the judgment scale the Friedman Chi-Square value was 0.636 and p-value 0.7275. The results suggest that the null hypothesis is correct, thus the order of sequences did not affect the judgments. This was confirmed using Wilcoxon rank-test between orders 1 and 2 (W=-89, z=-1.44, p=0.150) and 1 and 3 (W=-43, z=-0.69, p=0.490), and between orders 2 and 3 (W=82, z=1.32, p=0.187).

6.4.5 Effect of subject characteristics to judgments

Visual inspection of the results showed that the men evaluated each stimulus systematically slightly higher on average than the women (Figure 62). However in many cases the difference was marginal and similar trend was shown. The judgments of the men and the women were not significantly different (Table 34). Although the men tended to score slightly higher on average, the difference was not significant ($p>0.05$). Thus all further analyses were made without separating the subjects. The results also suggested that weight and height did not affect the judgments.

Table 34. Mann-Whitney U test for differences in judgment between men and women.

n_1	n_2	U	p (two-tailed)
30	30	381	0.315
Normal approx z =	-1.02013		0.308

6.5 Discussion

Based on the field measurements it was found that the rotational and floor axes had small contribution to OVTV, because of the standard's weighting. The effect of the different axes was needed to be validated in a multi-axis environment. Before validation of the standard procedure is possible, it was necessary to validate the chosen judgment method and effects of the study procedure to the results. This was a first known study which used non-stationary and field-like multi-axis stimuli for evaluating the correlation between discomfort and vibration exposure in a laboratory.

6.5.1 Vibration stimuli

The stimuli created for the laboratory trial was based on the field measurements in Chapter 5. The purpose was to simulate similar vibration characteristics that are found in typical work machines in the field. This was a different approach than in other laboratory studies where sinusoidal or random vibration stimuli have been used. The vibration amplitudes and frequency spectra showed typical vibration characteristics of work machines, where frequencies less than 10 Hz are dominant. The rotational axes were purposely emphasised for at least one of the main stimuli to evaluate if the rotational axes have any effect on discomfort. However, the frequency weighting and multiplying factors attenuated the rotational axes so that they were not dominant for any stimulus when calculating OVTVs.

Crest factors were below 9 for all axes and stimuli. This was somewhat expected as the test bench could produce vibration only between 1 and 20 Hz and the stimuli were created by integrating acceleration data, which included bandpass filtering. However, the magnitude levels of the stimuli were similar to the work machines they simulated.

6.5.2 Judgment style and values

The averaging using an arithmetic mean of the judgment values was based on the results from noise research. It was noted that it took the subjects about 5 seconds to find the initial discomfort level for each stimulus. For this reason the first 5 seconds from each judgement data was discarded and last 10 seconds were averaged as a single value.

The continuous judgment method allows more detailed analysis of the judgment style and reaction to vibration than other normally used methods, as the judgment is recorded at the same frequency as the stimulus.

6.5.3 Effects of procedure and method for results

There was an indication that the sequence types affected judgment scaling, where the averaged judgments of sequence *a* had statistical differences compared to the other sequence types (especially for sequence *b*). A closer look revealed that sequence *a* had higher vibration magnitude for the first stimulus than sequences *b* and *c*. It is likely that the first stimulus of a sequence influenced the scale for the judgments of rest of the stimuli, because no absolute categories were given to the subjects. However, the differences in the judgment values were small and because all subjects were exposed to all sequences, no normalisation was applied. There was no indication that the order of sequences affected the judgments.

There were no significant differences in the judgments between the men and women. This suggests that neither gender nor physical dimensions affected the discomfort judgment.

6.5.4 Scope of the results

The shaker used in the trial could produce movement between 0 and 20 Hz. In this case, because of the high pass filtering, the frequency range was in practice between 1 and 20 Hz. However as most of the energy in mobile work machines are within this frequency range, the shaker could be used to simulate vibration present in the field. Even though the study design and shaker caused limitations to the usability of the data, they were not considered critical considering the goals.

The standardised method includes twelve axes, but in this trial the floor axes were not used in the analyses, thus only nine axes were analysed. This was because the subjects kept their feet on a non-moving platform. This was done in order to reduce the number of variables in this laboratory study. It was reasonable to assume that feet did not make any significant contribution to the judgment (Bhalchandra 2008). However there might be a change in correlation between vibration and discomfort if feet would be included as well. This should be verified in future studies.

There are inconsistent or non-existent results for time-dependency between vibration and discomfort (see Chapter 2). Even though this is an important issue, it was not considered in this study, as the goal was to validate the standard's method, which does not require time dependency for making relative judgments. The duration of a stimulus used in this trial (15 seconds) was not long enough to evaluate time dependency. The effect of the length of the study procedure was minimised by having small breaks between the sequences. No statistical differences were found for the judgments of the first sequence to the last sequence.

The trial was limited to using subjects in a seated posture and leaning against a backrest using a European small-car seat, which had previously been run-in. The results might not accurately predict responses in a work machine seat, which has a different design and results in occupants adopting a different posture. However stimuli from the mobile work machines were used in the study, along with those from other road and off-road vehicles.

As the trial was conducted in a laboratory, the subjects did not see any road or could not predict or change the forthcoming movement. It has been shown that additional information (e.g. noise and visual sight) can change the response of a single variable (e.g. vibration) (Sato, et al 2007). Thus, the results might not be similar in a field environment where other factors have more presence.

6.6 Conclusions

A laboratory trial was conducted to provide data for validating the standardised method in a multi-axis environment. It was verified that the continuous judgment method can be used to evaluate discomfort of subjects to vibration amplitudes:

- The effect of stimuli and sequence order was minimised by changing the order of sequences for each subject and repeating each stimuli in random order for three times for each subject;
- Small effects of stimuli order were found, but they did not affect the overall results as judgment values were averaged;
- No statistical differences were found for the gender and physical characteristics;
- When using continuous judgment method, the first 5 seconds from the judgment values should be neglected, because of the adjustment period and delay of response.

Based on the validation of the data it was concluded that it can be used for analysing the correlation between vibration and discomfort and to validate and optimise the ISO 2631-1 method.

7 Chapter 7 - Laboratory trial part II: validating the ISO 2631-1 method

7.1 Introduction

The method in ISO 2631-1 can be used to evaluate and assess discomfort from whole-body vibration. However, the standard includes very little information on the assessment and guidance on how to interpret the results, or even how to choose the proper axes. The standard allows different interpretations, because it does not explicitly define the use of certain combinations of axes. However, it is strongly implied that at least the seat translational axes should be used in the analyses. Depending on circumstances, the backrest and floor axes should be included in the analyses. In addition there is a possible need to include the rotational axes from the seat as well. The full 12-axis method requires complex equipment which is not available to most practitioners. It would be beneficial if as few axes as possible could be used for the assessments, as this reduces complexity and cost, but currently there are no estimates of how much this reduced data set compromises the accuracy of the discomfort assessment. In many cases this has led to studies where only the seat translational axes have been measured.

The results from previous publications have indicated that the standard ISO 2631-1 method might not be valid. Evaluations of vibration are affected by the axes measured, frequency weighting curves, the multiplying factors and the averaging method. The frequency weighting models the response of the body in the frequency domain and the multiplying factors define the relative importance between the different axes. The averaging method emphasises the frequency characteristics of the vibration (i.e. effect of shocks compared to an average amplitude). Even though these methods have significant effects on the evaluation, they have not been validated in a practical multi-axis environment. It has been suggested that the current method does not provide accurate results which are comparable between environments (Mansfield and Maeda 2005b). It is necessary to investigate their role to understand how the standard method could be improved.

The frequency weighting curves have had considerable research and validation since late 1960's. The results show that the current frequency weightings for a seated person (W_d and W_k) have been successful in predicting both human body transmissibility and subjective response. The other frequency weighting curves (W_c and W_e) have not been subject to such thorough validation, but currently there are no conclusive results to support changing them. As the current instrumentation supports the weighting filters and they have an evidence base, there is no reason to prioritise changing them at this point. Thus the only practical option is to use them or not use them (i.e. no new weightings should be proposed).

The multiplying factors for the axes have had less research and validation than the frequency weighting curves despite their potential large modifying effects on vibration values. The purpose of the factors is to emphasise different axes and measurement locations. However there have been only few studies that have measured all twelve axes and considered their effects on discomfort (Griffin 1990, Maeda 2004). The current factors in ISO 2631-1 have no direct reference, thus the scope of the factors are not referenceable in the literature. It can be assumed that the multiplying factors are based on the results from Griffin et al. (1982), where it was found that comfort contours for each axis had different magnitude level (See Figure 8 in Chapter 2). However, the author has not found a publication where this has been replicated. Because it is easy to apply a different set of multiplying factors without changing the instrumentation, the validation of the factors should be considered.

The main averaging method to evaluate discomfort is to use the frequency weighted r.m.s. values, but also additional methods exist. ISO 2631-1 refers to the VDV method if shocks have a dominant effect (i.e. high crest factor). The VDV method is not convenient to use when results are to be compared to r.m.s. values, as the values are in different dimensions, with VDV increasing with the exposure time. The effect of higher emphasis on shocks is easier to compare using the r.m.q. method suggested by BS 6841 standard. The r.m.q. method gives the same emphasis to shocks as VDV, but is in same format as the r.m.s. method. As the crest factors in the field measurements showed values exceeding 9 (Chapter 5), the standard implies that higher emphasis on shocks might improve correlation to discomfort. There have been some studies that have compared differences of results in field using either the r.m.s. or r.m.q. methods (Wikstroem, et al 1991). However no conclusive evidence of either method being better was shown, thus there is a need to improve understanding the effects of shocks to discomfort.

The results from the field measurements in Chapter 5 showed that the rotational and floor axes were normally the least significant, because of the standard's weighting and multiplication factors. This suggests that basically the same overall vibration total value

(OVTV) can be achieved with less than twelve axes in most environments. Based on the results, the following hypotheses were considered:

- Only a few (or one) most dominating axes will determine the subjective feeling;
    - Other axes will have negligible effect and need not be measured and analysed;
- The seat rotational and floor translational axes, with the vibration magnitudes seen in the field measurements, have no practical effect on subjective feeling;
- OVTV based on the seat translational axes (including 1.4 factors) will largely determine the discomfort level.

Based on the previous studies and literature the following hypotheses can be added:

- Frequency weighting improves the correlation between measured vibration and discomfort;
- Multiplying factors should be larger for the horizontal axes than other axes;
- Higher emphasis to shocks (i.e. r.m.q. and VDV) improves the correlation;
- Inclusion of axes additional to the seat translational will improve the correlation.

There is a need to better understand which axes and locations contribute to the discomfort judgment and thus correlate with it. Also it is possible to optimise the number of locations and axes needed to be measured to obtain practical accuracy. For efficiency and ecological validity it is important to validate the standardised method based on stimuli that is present in real environments, because that is where people are exposed to it.

7.2 Goals of the trial part II

The goals of part II of the laboratory study are to validate the standard method and to evaluate the roles of frequency weighting, multiplying factors and averaging methods for predicting discomfort. If the standard is correct on emphasising the axes, then the evaluation process can be significantly simplified, as the rotational and floor axes are not needed. The analyses aim to answer the following questions:

- Does the correlation between vibration and discomfort improve when additional axes are included?

- Are there practical differences in correlation using different combinations of axes?
- Are the rotational axes as insignificant as the standard method implies based on the field measurements?
- Does the frequency weighting and the multiplying factors improve the correlation?
- Will more emphasis on shocks (i.e. the r.m.q. method) provide any better correlation than the default method (i.e. the r.m.s. method)?

7.3 Methods

The details of the laboratory trial, stimuli and subjects are presented in Chapter 6.

7.3.1 Vibration magnitudes

Vibration magnitudes were calculated for the frequency weighted and unweighted acceleration data with and without the multiplying factors and using the r.m.s. and r.m.q. averaging methods. Thus in total six sets of results for all axes, PVTVs and OVTVs were produced to compare the effects of weighting and averaging methods (see Table 7 in Chapter 3).

7.3.2 Selecting combinations of axes for calculating overall vibration total values

The standard allows several possible combinations of axes to be used in the analyses. Only three translational axes from the seat are required to be measured, but in a minimum case only one axis is enough to conduct the evaluation (if other axes are less than 25% of the dominant axis). Based on the guidance in ISO 2631-1 the following scenarios to produce OVTV are allowable for evaluating discomfort of whole-body vibration (for seated persons):

- A dominant axis (which could be any of the twelve axes);
- A dominant PVTV (rest of the PVTVs are less than 25 % of the dominant PVTV);
- A combination of PVTVs of seat, backrest and floor (where PVTVs are larger than 25 % of the dominant PVTV);
- All twelve axes.

Because of the number of combinations which are possible, the following practically realisable scenarios were used to analyse correlation between discomfort and vibration (Table 35).

Table 35. Practically realisable scenarios for calculating an overall vibration total value based on the ISO 2631-1 standard when using the seat, backrest and floor translational axes.

Scenario number	Explanation
1	Overall vibration total value of seat translational axes (without 1.4 multiplying factors for horizontal axes)
2	Overall vibration total value of seat translational axes (with 1.4 multiplying factors for horizontal axes)
3	Overall vibration total value based on point vibration total values of seat translational axes (without 1.4 multiplying factors) and backrest fore-and-aft axis (with 0.8 multiplying factor)
4	Overall vibration total value based on point vibration total values of seat translational axes (without 1.4 multiplying factors) and backrest translational axes (with multiplying factors)
5	Overall vibration total value based on point vibration total values of seat translational and rotational axes (without 1.4 multiplying factor for seat horizontal axes, but with multiplying factors for rotational axes)
6	Overall vibration total value based on point vibration total values of seat translational and rotational axes (with 1.4 multiplying factor for seat horizontal axes and with multiplying factors for rotational axes)
7	Overall vibration total value based on point vibration total values of seat translational and rotational axes and backrest translational axes (without 1.4 multiplying factor for seat horizontal axes and with all multiplying factors for other axes)

The scenarios were chosen for practical purposes whilst including most possible interpretations of ISO 2631-1. The floor axes were not used in any scenarios as the laboratory trial design did not include the effects of the floor vibration in order to limit the number of variables.

It would be feasible to greatly simplify the vibration measurement, if less than twelve axes are needed in the analyses without losing the accuracy. Normally the whole-body vibration measurement equipment include only the standard 3-axis seat pad sensor. Thus Scenarios 1 or 2 would be the most preferable.

Some commercial whole-body vibration measurement equipment include also a fourth sensor channel, and so Scenario 3 would be possible. However, the standard and field results imply that, in addition to seat translational axes, next importance is to measure all backrest axes, thus Scenario 4 is important to consider.

Because the effect of the backrest axes to discomfort can be simulated using the 1.4 multiplying factors, it could be possible to measure the translational and rotational axes from the seat and use the factors instead of measuring the backrest. Comparing Scenarios 1 to 2, and Scenarios 5 to 6, can be used to predict if the backrest axes need to be measured or if it can be replaced by the multiplication factors.

Analyses without rotational axes are the most attractive option, as they are hardest to measure in practice (and are potentially the most erroneous). This can be evaluated comparing the correlation of the scenarios with and without the rotational axes.

The effect of all possible axes can be evaluated based on Scenario 7.

7.3.3 Judgment method

The discomfort of subjects was acquired using the continuous judgment, cross-modal matching method. Arithmetic mean of last 10 seconds of judgment of each stimulus was calculated based on the analysis in Chapter 6.

7.3.4 Correlation analyses

The goal of the analyses was to find correlation between discomfort judgment and calculated vibration magnitudes of the chosen scenarios and different setups for calculating vibration magnitudes. Thus statistical analysis of coefficient of correlation was required. In this case Spearman method was used (r^2). Additionally Kendall's tau was calculated to validate the correlation results. Wilcoxon signed-rank test was used to evaluate any statistical differences amongst the results.

7.4 Results

The correlation values using Kendall's tau produced systematically similar results than Spearman rho, thus only Spearman values are shown.

7.4.1 Correlation between vibration magnitudes and judgments

Twenty-two test subjects evaluated 30 different stimuli three times in random order (the procedure explained in detail in Chapter 6). The data set was compared to the seven scenarios to determine the correlation for vibration and discomfort. Mean judgment values of the vibration generally increased with OVTVs of each stimulus in a nominally linear fashion (Figure 63). The correlation tended to improve when more axes were included in the analysis, the best occurring for the full 9-axis analysis (Scenario 7, r^2 0.850). However, it was also evident that the correlation (r^2) was almost identical for Scenarios 2 (0.823), 4 (0.836) and 6 (0.844). Scenario 1 had the worst correlation (r^2) of 0.623. The correlation (r^2) of Scenario 3 (0.799) and Scenario 5 (0.743) were better than for Scenario 1, but were clearly worse than the best scenario. The correlation between discomfort and vibration was positive and linear.

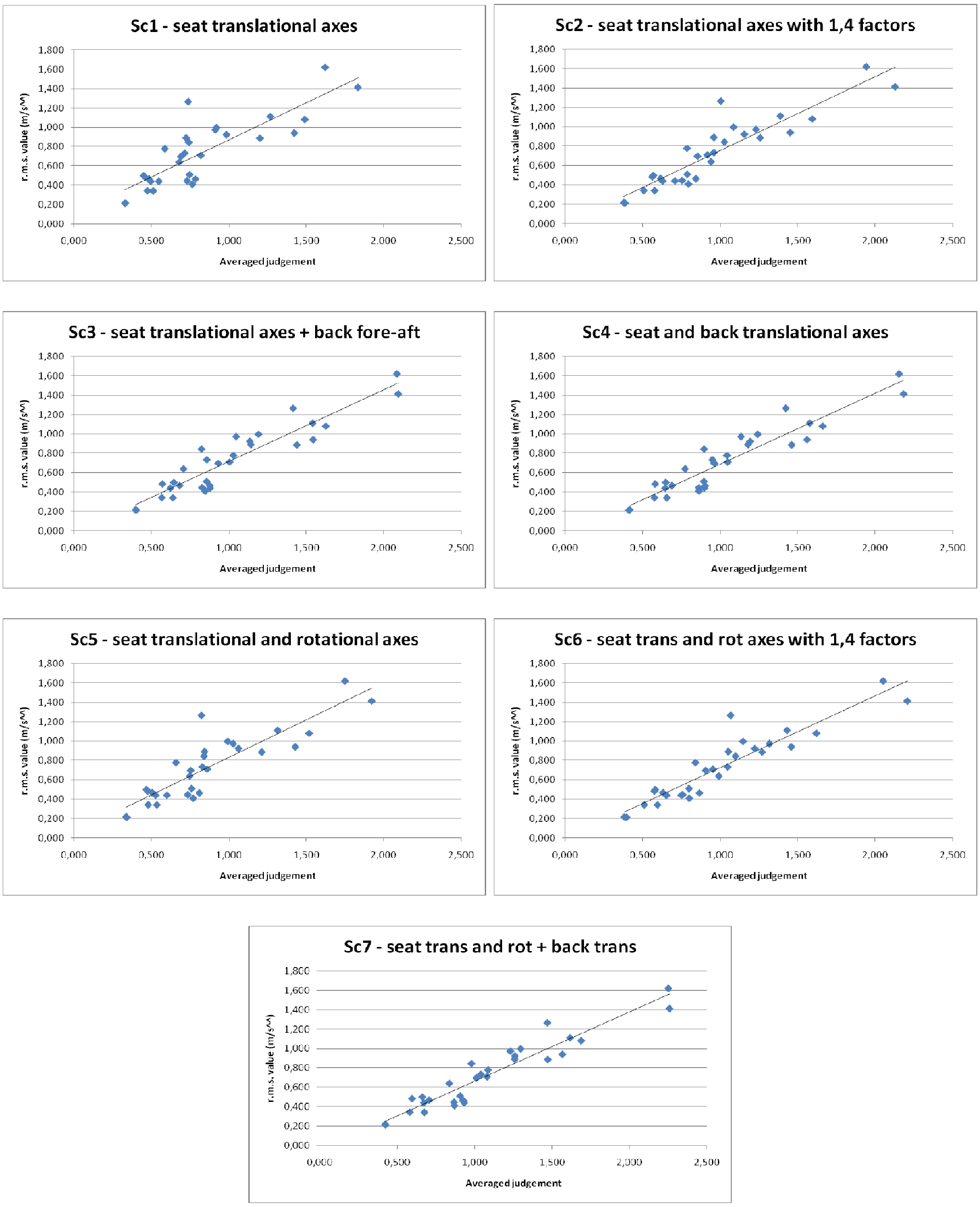

Figure 63. Correlation between mean judgements of all subjects and frequency weighted vibration magnitudes using the r.m.s. method and respective multiplying factors for chosen scenarios.

The correlation value changed significantly for each test subject (Table 36). In half of the cases (11/22) OVTV calculated using Scenario 6 provided the best correlation. Scenario 7 provided best correlation in 10 cases and Scenario 3 in one case. The best average correlation was for Scenario 7, but there was no statistical difference compared to Scenario 6 using Wilcoxon signed-rank test (p=0.617). Also Scenario 2 and 7 showed little statistical difference between correlations (p=0.0735). However, a clear statistical difference was found between Scenarios 1 and 2 ($p<0.001$); thus using the 1.4 multiplying factors for seat horizontal axes improved the correlation. Differences between Scenarios 1 and 7 ($p<0.001$) showed that additional axes improved correlation.

Table 36. The correlation (r^2) between discomfort judgments of individual subjects and frequency weighted vibration magnitudes using the r.m.s. method with respective multiplying factors for each scenario (the best scenario for each subject is embolden and underlined).

	Scenarios						
Subject	**1 Seat trans**	**2 Seat trans+1.4 factors**	**3 Seat trans+back x**	**4 Seat +back trans**	**5 Seat trans+rot**	**6 Seat trans+rot+1.4 factors**	**7 Seat trans+rot, back trans**
1	0.304	0.408	0.335	0.373	0.358	**<u>0.420</u>**	0.383
2	0.499	0.606	0.536	0.567	0.570	**<u>0.611</u>**	0.584
3	0.473	0.611	0.520	0.555	0.551	**<u>0.612</u>**	0.555
4	0.417	0.569	0.610	0.624	0.530	0.587	**<u>0.635</u>**
5	0.507	0.682	0.632	0.671	0.614	**<u>0.694</u>**	0.692
6	0.437	0.575	0.486	0.532	0.506	**<u>0.585</u>**	0.550
7	0.343	0.444	0.431	0.465	0.415	0.454	**<u>0.468</u>**
8	0.500	0.697	0.642	0.676	0.615	**<u>0.710</u>**	0.699
9	0.269	0.392	0.301	0.329	0.330	**<u>0.396</u>**	0.342
10	0.374	0.440	**<u>0.518</u>**	0.515	0.405	0.456	0.516
11	0.402	0.503	0.522	0.540	0.468	0.515	**<u>0.552</u>**
12	0.338	0.532	0.555	0.573	0.452	0.554	**<u>0.586</u>**
13	0.419	0.627	0.560	0.589	0.536	**<u>0.645</u>**	0.604
14	0.552	0.676	0.697	0.730	0.633	0.686	**<u>0.731</u>**
15	0.482	0.591	0.612	0.629	0.534	0.611	**<u>0.642</u>**
16	0.436	0.610	0.539	0.579	0.553	**0.635**	0.602
17	0.483	0.632	0.614	0.640	0.597	**0.653**	0.644
18	0.457	0.564	0.559	0.580	0.548	0.569	**<u>0.597</u>**
19	0.473	0.648	0.577	0.612	0.586	**<u>0.664</u>**	0.626
20	0.345	0.470	0.464	0.485	0.415	0.480	**<u>0.496</u>**
21	0.431	0.521	0.606	0.610	0.500	0.541	**<u>0.614</u>**
22	0.311	0.422	0.449	0.464	0.378	0.428	**<u>0.485</u>**
Average	**0.421**	**0.555**	**0.535**	**0.561**	**0.504**	**0.568**	**0.573**

The results show that using a single location will not improve correlation compared to multiple locations (Table 37). The best correlation was for the backrest, but also the dominant location for each stimuli showed practically similar correlation (p=0.842). The seat translational axes showed clearly worse correlation compared to the backrest axes (p=0.0001). Also the seat rotational axes showed statistically lower correlation than the backrest axes (p=0.007).

Table 37. The correlation (r^2) between discomfort judgments and frequency weighted point vibration total values with respective multiplying factors and the dominant (i.e. largest) point vibration total value for each test subject (best correlations are embolden and underlined).

	Point vibration total values (m/s^2)			
Subject	**Dom**	**Seat Trans**	**Seat Rot**	**Back Trans**
1	0.340	0.304	**0.370**	0.356
2	**0.548**	0.499	0.466	0.493
3	**0.527**	0.473	0.429	0.410
4	0.557	0.417	0.500	**0.614**
5	**0.631**	0.507	0.477	0.581
6	0.478	0.437	0.458	**0.485**
7	0.398	0.343	**0.494**	0.476
8	0.601	0.500	0.585	**0.653**
9	0.333	0.269	**0.354**	0.304
10	**0.487**	0.374	0.271	0.486
11	**0.508**	0.402	0.362	0.489
12	0.497	0.338	0.489	**0.603**
13	**0.564**	0.419	0.474	0.485
14	**0.627**	0.552	0.462	0.626
15	0.595	0.482	0.467	**0.608**
16	0.535	0.436	**0.607**	0.562
17	0.588	0.483	**0.635**	0.592
18	**0.546**	0.457	0.382	0.498
19	0.542	0.473	**0.553**	0.519
20	**0.445**	0.345	0.354	0.422
21	**0.570**	0.431	0.362	0.532
22	0.400	0.311	0.403	**0.536**
Mean	**0.514**	**0.421**	**0.453**	**0.515**

7.4.2 Effect of weighting and averaging methods

Applying the frequency weightings improved the correlation for all scenarios, except for Scenario 1 (Table 38). The scenario of the best correlation changed to 4 without the frequency weighting, but the best overall correlation remained Scenario 7 with the frequency weighting. The results from Scenario 1 and 2 show that weighting improved correlation when horizontal axes have more effect, thus suggesting that the vertical weighting is less effective than the horizontal weighting.

Scenarios from 3 to 7 included either the backrest or the rotational axes, thus their results were affected by the multiplying factors (Table 38). The results show that the correlation improved in all cases where multiplying factors were not used. Scenario 7 had the best correlation in both cases (with and without the factors). Effect of 1.4 multiplying factor was evaluated by comparing the correlation between Scenarios 1 and 2 to Scenario 4, which included the backrest axes. The results show that in each case where 1.4 multiplying factors were used the correlation was better than using the backrest axes.

The results show that none of the scenarios had better correlation with the r.m.q. method. Although the differences were small, they were systematic.

Table 38. Comparison of correlations (r^2) for using the r.m.s. and r.m.q. averaging methods for the frequency weighting with the multiplying factors, the frequency weighting without the multiplying factors and without the frequency weighting and the multiplying factors.

		OVTV Scenarios						
		1 Seat trans	**2 Seat trans+1.4 factors**	**3 Seat trans+ back x**	**4 Seat +back trans**	**5 Seat trans+rot**	**6 Seat trans+rot+ 1.4 factors**	**7 Seat trans+rot, back trans**
r.m.s. values	**Weighting w multp**	0.417	0.551	0.530	0.557	0.500	0.564	0.569
	Weighting. w/o multp	0.417	0.417	0.538	0.578	0.573	0.586	0.591
	W/o all	0.460	0.460	0.509	0.524	0.443	0.446	0.466
r.m.q. values	**Weighting w multp**	0.376	0.516	0.523	0.530	0.442	0.534	0.551
	Weighting. w/o multp	0.376	0.376	0.527	0.545	0.541	0.566	0.569
	W/o all	0.426	0.426	0.480	0.474	0.436	0.430	0.435

7.5 Discussion

7.5.1 Correlation between vibration and discomfort

The correlation calculated from the mean judgments of all test subjects was better than the mean correlation of each subject. This was an expected result, as averaging reduces the influence of outliers. A high correlation between the averaged discomfort values and vibration was found (r^2= 0.850; scenario 7). Based on the interpretation of the Spearman r^2 value, the result indicates that the vibration exposure alone contributed 85 % of the change in discomfort judgment(. The best correlation (r^2) for individual test subjects varied between 0.396 and 0.731. Thus there was a large variability between the subjects. However, for each subject the trend was similar: additional axes improved correlation. The correlation to vibration was positive and linear.

The results showed that the best correlation, using the standard's weighting procedure, was Scenario 7, which included the translational and rotational axes from the seat surface and the backrest axes. However, Scenarios 2 and 6, which used 1.4 factors to replace the backrest axes, had practically the same correlation as Scenario 7. Thus 1.4 factors can be used to replace the backrest axes in most cases with minimal reduction in predictive power for discomfort. Scenario 1 (seat translational axes), which would be convenient for the current commercial measurement equipment, showed the lowest correlation of all scenarios. It is clear that the additional axes improve correlation, or at least the 1.4 factors should be used, if translational seat axes are only measured. In many cases studies have used Scenario 1 for discomfort evaluation instead of scenario 2, which is the recommended way. For those data sets using Scenario 2 would be an easy option as it does not require additional data.

The field measurements implied that for most environments the rotational axes have only a small contribution to OVTV. This is because of small multiplying factors and the effect of the frequency weighting curves. The results in this study indicated that although the seat rotational axes did improve correlation, the effect was again relatively small (Scenario 4 compared to Scenario 7).

7.5.2 Effect of frequency weighting

The weighting curves improved correlation in practically all cases, but the effect was not significant. Vibration characteristics from a seat of a large work machine include mainly low frequencies, because of low dynamic damping factors of tires, rubber bushings, and seat. Thus the frequency weighting curves of the standard do not significantly change the frequency content. Because the laboratory trial used stimuli from field measurements, the effect of frequency weighting was small. The weighting would have a larger effect when using either flat spectrums or sinusoidal vibrations.

7.5.3 Effect of multiplying factors

There was no evidence that the standard's multiplying factors for the rotational and backrest axes improved correlation. This was seen for all scenarios and PVTVs. In fact, the results showed that correlation was worse when using the multiplying factors. All PVTVs showed better correlation without multiplying factors. However, for the best scenario, the correlation only marginally changed with or without the multiplying factors, which implies that the multiplying factors improve correlation for some individual axes. It depends on the combination of axes if the factors are useful or not. There might be an alternative set of multiplying factors which would be more optimal and improve the correlation.

The stimuli of the laboratory trial can be used to analyse the effects of the multiplying factors for the seat horizontal axes. It was previously concluded that Scenario 2 was better than Scenario 1. The difference between the scenarios is the 1.4 multiplying factors for the seat horizontal axes (Scenario 2), thus any improvement in correlation is caused by the factors. A previous study (Maeda and Mansfield 2006b) also indicated that higher factors for horizontal axes will improve the correlation.

By analysing each stimuli type used in the trial, it can be indicated if the factors improved correlation for all types of stimuli or just for some. Figures 64 to 68 show how Scenarios 1 and 2 affect the correlation for each main stimuli. Scenario 2 was systematically better, but differences varied significantly. Stimuli types A, B and E were significantly better for scenario 2 than 1. Scenarios C and D showed almost similar correlations. Detailed analyses of the frequency spectra of the main stimuli (Figure 50 in Chapter 6) showed no clear reason for the differences in the main stimuli. The same conclusions were made also based on the vibration magnitudes (Table 32 in Chapter 6).

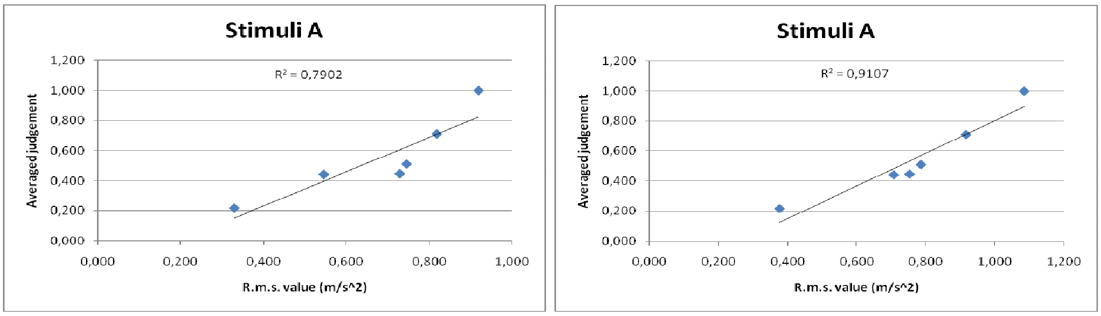

Figure 64. Differences in correlation for stimuli type A for scenarios 1 (left) and 2 (right) using averaged judgments from all subjects.

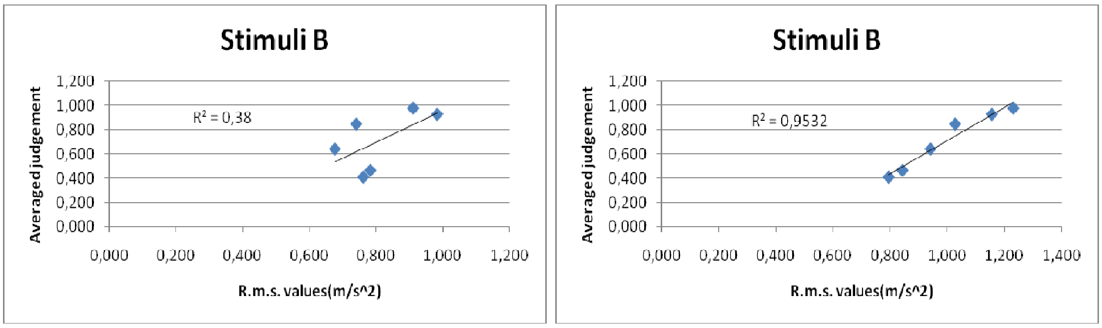

Figure 65. Differences in correlation for stimuli type B for scenarios 1 (left) and 2 (right) using averaged judgments from all subjects.

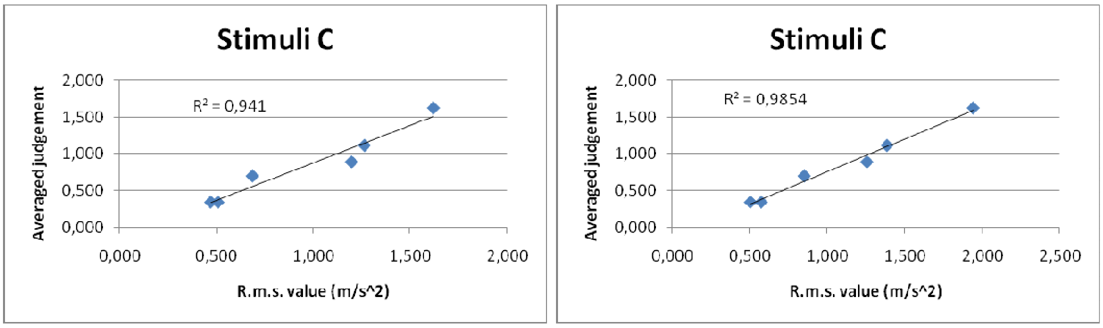

Figure 66. Differences in correlation for stimuli type C for scenarios 1 (left) and 2 (right) using averaged judgments from all subjects.

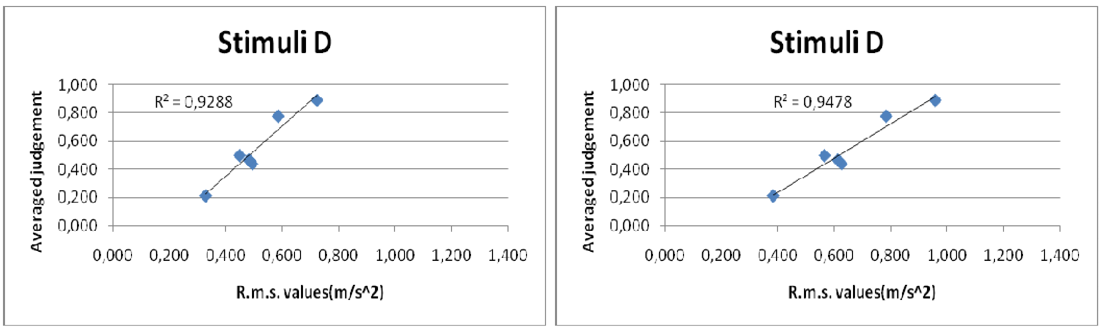

Figure 67. Differences in correlation for stimuli type D for scenarios 1 (left) and 2 (right) using averaged judgments from all subjects.

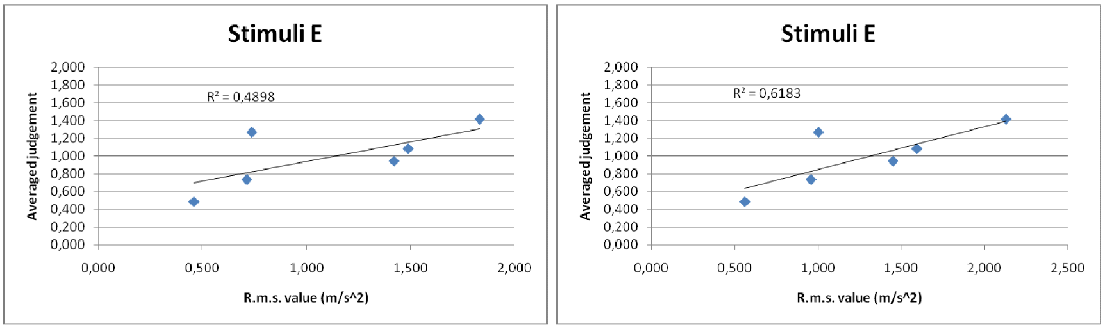

Figure 68. Differences in correlation for stimuli type E for scenarios 1 (left) and 2 (right) using averaged judgments from all subjects.

Figure 69 and Figure 70 show all stimuli types for Scenarios 1 and 2. This verifies the overall effect of 1.4 multiplying factors for improving the correlation. Based on the results it was evident that the fore-and-aft and lateral axes should be more emphasised compared to the vertical axis.

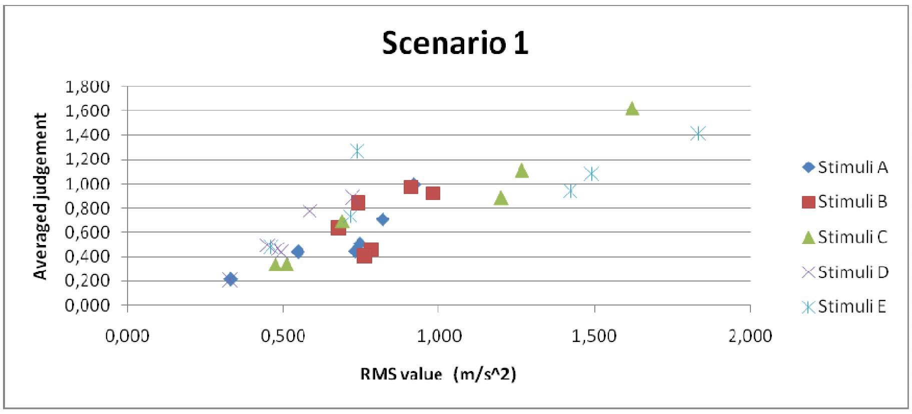

Figure 69. Correlation of averaged judgments and stimuli types using scenario 1 (seat translational axes with 1.0 multiplying factors for all axes).

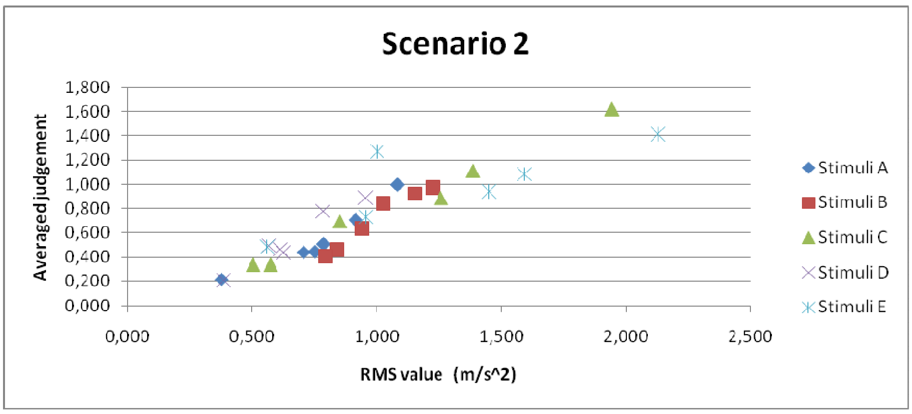

Figure 70. Correlation of averaged judgments and stimuli types using scenario 2 (seat horizontal axes with 1.4 multiplying factors).

7.5.4 Effect of emphasising shocks

The correlation did not improve when shocks were emphasised. This was analysed comparing correlations between the r.m.s. and r.m.q. methods. BS 6841 standard suggests using the r.m.q. method instead of the r.m.s. method in situations where shocks are expected to influence the results. The r.m.q. method showed a systematically poorer correlation than r.m.s. for all stimuli, thus there was no evidence that the use of vibration dose value (VDV) would improve correlation for the types of stimuli used in the trial. However, it should be noted that the stimuli used in this study were not designed to expose subjects to large shocks and so results from the tests in more severe environments might show the opposite trend. However, it is interesting to note that the r.m.q. method has been found worse also when shocks are present (Wikstroem, et al 1991), however, overall no clear differences have been found between the methods in most environments (Mansfield, et al 2000).

7.5.5 Optimal usage of the standard method

Based on the results, it is possible to improve the ISO 2631-1 method. The multiplying factors degraded correlation for most axes and scenarios. The results hinted that different factors for the additional axes will improve correlation. Also the 1.4 multiplying factor for the seat horizontal axes implied that the factors for horizontal axes should be higher compared to the vertical axes.

Individual PVTVs correlated inferior to OVTVs of any scenario. The results showed that dominant PVTV is not enough to evaluate discomfort. Using a single axis (even if it is dominant) is also problematic. In some cases, there might be no vibration on the axis. However, if one suggests that, for example, only a vertical axis will correlate with discomfort, then it should do it in all cases, not just in cases where the axis is clearly dominant. In any case, using the dominant single axis or PVTV for discomfort evaluation is not a good solution.

The optimal setup was found to be measuring the seat translational axes and evaluating them using the frequency weighted r.m.s. averaging with 1.4 multiplying factors for the horizontal axes. The correlation was practically the same as when including all axes, but the measurement configuration is much simpler.

7.5.6 Comparison to previous studies

Compared to other studies found in the literature review (Chapter 2), similar and new results were found. In this case the r.m.s. method was better than the r.m.q. method, which has been also concluded from a field study (Wikstroem, et al 1991). Effect of frequency weighting was concluded to improve correlation, but only slightly. This was also concluded by Mansfield et al. (2000). Els (2005) concluded that there was no difference between frequency weighted or unweighted r.m.s. values to the discomfort. The results showed similar results to Parsons and Griffin (1983), that including more axes will improve correlation.

7.5.7 Scope and limitations of the results

The vibration amplitudes from the backrest depend on the location of the sensor, thus the correlation might be different if it was placed on a different location. However, based on the standard guidance it is hard to determine the best location as backrests have different height and there is no specific information on the position of the sensor. Thus the argument of using the 1.4 multiplying factors to replace the backrest axes is valid and potentially more repeatable, as the results give almost similar responses.

The study was limited to using subjects in a seated posture and leaning against the backrest using a European small-car seat, which had previously been run-in. For this type of seat, the vibration at the seat cushion and backrest has been transmitted through the seat mounting points and therefore would be expected to correlate. The results might not accurately predict responses in a work machine seat, which has a different design and results in occupants adopting a different posture with different backrest contact. However, the stimuli from mobile work machines were used in the study, along with those from other road and off-road vehicles.

Most studies, which have investigated the evaluation method of ISO 2631-1, have used sinusoidal or random stimuli (see Chapter 2). This study used stimuli which were adapted from those measured in the field (Chapter 5) and thus were more representative of real exposure situations. As there are no similar studies, it is not possible to evaluate how the results compare regarding other types of field-like stimuli. Although the amplitude ranges of the stimuli were limited, they covered a wide variety of vibration exposure characteristics that commuting people are exposed in every day work life, such as cars, buses and trains.

7.5.8 *Further work*

A limited number of stimuli and subjects were used, thus further work should be conducted in the laboratory and field to verify the results of this trial. It is recommended to use field-like stimuli of other environments for different durations and conduct similar types of analyses for correlation. Additionally it is suggested that a different method (e.g. the Magnitude Estimation method) is used, instead of the continuous judgment method.

7.6 Conclusions

The results showed that a significant correlation between vibration exposures and discomfort can be achieved using the ISO 2631-1 method in the laboratory. The ambiguous guidance of the standard allows wide variety of possibilities to combine axes and locations, but greater complexity in analysis does not necessarily guarantee a better correlation between the measured vibration magnitude and ratings of discomfort.

For validating the standard procedure and finding the best setup, the following conclusions were made:

- The correlation between vibration exposure and discomfort was best when all possible axes were included; however:
    - small statistical differences were found when using just seat translational axes with 1.4 multiplying factors instead of the full 12-axis method;
    - rotational axes had marginal effect;
- The use of frequency weighting only slightly improved the correlation, which is assumed to be caused by the low frequency content of the stimuli;
- The multiplying factors of the backrest and rotational axes degraded correlation;
- The r.m.s. method provided slightly, but systematically, better correlation than the r.m.q. method;
- No explanation was found why the 1.4 multiplying factors seemed to be better suited for some stimuli characteristics than others;
    - However, the factors still improved correlation for all stimuli types.

In the light of the results and the complexity of the current standard, it can be concluded that there is a need and possibility to improve and simplify the current method, or to develop a completely new method. The primary goal of the development is to improve the current standardised method by optimising the measurement process (i.e. minimising the number of measured axes) and the analysis procedure. The multiplying factors are the best approach to improve the correlation.

8 Chapter 8 - Laboratory trial part III: improving the ISO 2631-1 method

8.1 Introduction

The results from Chapter 7 showed that the correlation between the r.m.s. values and discomfort judgment changed depending on how the weighting and multiplying factors were used and which axes were included. The results showed that replacing the backrest axes by multiplying the seat horizontal axes with 1.4 factors gave practically the same correlation as including the backrest axes. Also it was evident that the standard’s multiplying factors for the backrest and rotational axes decreased the correlation, even though their purpose is to improve it. Although the rotational axes improved correlation overall (even when using the multiplying factors), the effect was marginal.

The conclusions from Chapter 7 suggested that by optimising the multiplying factors the correlation between vibration exposure metrics and discomfort can be improved by the simplest and most effective way. However, because of a large number of possible combinations of factors for all twelve axes, a reduction of factor ranges need to be done before any calculations. This can be done based on the results from the previous chapters which showed that:

- Using 1.4 multiplying factors (instead of 1.0) for the seat fore-and-aft and lateral axes indicated improvement in correlation;
- The multiplying factor for the backrest fore-and-aft axis improved correlation;
- The multiplying factors for the seat rotational axes and the backrest horizontal axes degraded correlation;
- The floor translational and seat rotational axes had marginal contribution to the overall vibration total value (OVTV) and discomfort;
- Most significant axes were the seat translational axes and the backrest fore-and-aft axis.

It seems probable that by emphasising the seat horizontal axes, the correlation would improve, because the 1.4 factor had a positive impact. This suggests that trying higher factors for the seat horizontal axes would be a good starting point to improve correlation. Another study has shown also problems relating to the multiplying factors

(Maeda and Mansfield 2006b). The study indicated that the horizontal axes should be more emphasised compared to the vertical axis. However, the stimuli were artificial (i.e. frequency content did not exhibit characteristics of a work machine), thus a study to confirm the findings using field-like stimuli should be conducted.

8.2 Goals of the trial part III

Based on the practical possibilities and the results from Chapter 7 several parts of the standard method were considered to be adequate and not to be a subject of change at this time:

- Averaging vibration values using the r.m.s. method;
- The location of the measurement points and the axes;
- The root-sum-of-squares (r.s.s.) for combining the r.m.s. values of each axis and location;
- The frequency weighting curves.

The goal is to find best possible combination of multiplying factors for each of the measured nine axes so that the results correlate best with the discomfort judgment. The results should show what relative emphasis of the axes will give the best possible correlation. As the optimisation of the multiplying factors seems to be the most effective way to increase correlation, two different methods should be used to find and validate best multiplying factors for each axis: 1) brute force and 2) multiple linear regression model.

8.3 Methods

The trial procedure, subjects and judgment method are explained in detail in Chapter 6. The calculation of vibration magnitudes, correlation methods and standard scenarios are explained in detail in Chapter 7.

8.3.1 Finding optimal combination of multiplying factors

8.3.1.1 Brute force

Brute force search is a trivial, but very general problem-solving technique. The algorithm tests all possible combinations without any optimisation. The brute force algorithm is simple to implement and will always find the answer if it exists. If the combinations (i.e. calculation time) can be limited to a practical level, then the method is the best option. The problems relating to other, more intelligent, methods are that the implementation will take longer and more errors can occur in the analyses. An example of an intelligent method is the Nelder-Mead method (also known as downhill simplex method), which uses geometric shapes to search the optimum value without going through all possible combinations. However the method requires pre-knowledge of the problem and theory to be implemented and does not guarantee a result. A further problem with the Nelder-Mead method is that optimisation will only find a single best-fit for each set of initial conditions and therefore multiple searches with many sets of initial conditions are required, with no guarantee of finding the best optimisation for complex multi-factorial systems.

To use the brute force search method the first task is to optimise the number of possible combinations. Using all nine measured axes and a range of multiplying factors from 0.0 to 3.0 (best guess based on the previous results) at 0.1 resolution gives 26439622160000 possible combinations (31^9) to test. If an average computer can calculate and test 1000 combinations in a second, then it will take 306014 days to finish, which is not acceptable.

Because the factors are relative to each other, the factor of one of the axes does not need to change, thus limiting the combinations to 31^8, which can be calculated in 9871 days. Also by reducing the range and resolution of the factors, the combinations can be significantly reduced. At the beginning it is not necessary to use 0.1 step resolution, because the first goal is to find approximate relations between the factors. If 0.2 step resolution is used, then the calculation time is reduced to only 30 days. So using 4-5 normal PC-computers the analysis can be conducted in a week.

Table 39 shows the range and steps of multiplying factors tried for each axis. The seat vertical was considered the axis to which rest of the axes were compared to, thus the results show relative emphasis to the vertical axis. As the seat translational axes were identified as the most important axes, the resolution of the step was 0.1 for them. For the rest the step size was 0.2. So the final number of combinations used was 1.70×10^9 for the initial brute force optimisation and it was shown that by using a Python programming language running on a normal PC that 1000 calculations per second was possible. The task was divided to four Pentium PC’s, thus reducing the calculation time to less than 5 days.

Table 39. The range and steps of multiplying factors for brute force search.

Axis	Range	Step
Seat fore-and-aft	[0.0...3.0]	0.1
Seat lateral	[0.0...3.0]	0.1
Seat vertical	[1.0]	-
Seat roll	[0.0...2.0]	0.2
Seat pitch	[0.0...2.0]	0.2
Seat yaw	[0.0...2.0]	0.2
Backrest fore-and-aft	[0.0...2.0]	0.2
Backrest lateral	[0.0...2.0]	0.2
Backrest vertical	[0.0...2.0]	0.2

8.3.1.2 Multiple linear regression model

Another method to find covariance between vibration values and judgments is to calculate a regression model. In this case we can use a multiple linear regression model to calculate regression between all nine axes (i.e. independent variables) and judgment value (dependent variable). The general purpose of the multiple regression is to learn more about the relationship between several independent variables and a dependent variable.

The selection of the independent variables and the dependent variable has following general rules:

- The correlation between each independent variable to the dependent variable has to be linear;
- The independent variables should not correlate with each other;
- All variables should have been measured in continuous scale (such as interval or ratio scale);
- The number of observations should be at least five times higher than the number of independent variables (at least ten times is recommended).

In this case the dependent variable was the averaged judgment value of each stimulus and independent variables were the frequency weighted r.m.s. values of the measured axes. However, because of the measurement setup, some axes significantly correlated (e.g. the seat and backrest fore-and-aft). Only axes that did not correlate significantly could be used in the regression model. A correlation test was made to the axes.

The normal approach using the linear regression modelling is to assume linear summing of independent variables:

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + ... + \beta_n X_{in} \tag{25}$$

Where Y_i is the dependent variable, β_n the model coefficients and X_n the independent variables.

Even though the linear regression model is based on the linear assumption the independent variables do not need to conform to this (as long as the dependent Y_i is linear in the coefficients β_n). As the standard weights the r.m.s. values of each axis using the second power summing, then this could be also done to the independent variables of the regression model:

$$Y_i = \beta_0 + \beta_1 X_{i1}^2 + \beta_2 X_{i2}^2 + ... + \beta_n X_{in}^2 \quad (26)$$

Both approaches are valid and will be used to determine the multiplying factors.

8.3.2 Visual evaluation of results

Visual evaluation of the effect of changing multiplying factors was made for the seat translational axes using a contour map, where the multiplying factor for one axis remains fixed while the factors for the other axes increase. The contour map will show the elevation of correlation using colour map in 2D.

8.3.3 Validation of results

Validation of the found multiplying factors was done by dividing the subjects into two groups randomly. The correlations for both groups were calculated and compared based on the results. The validation was also done for data from other publications to verify if the results can be used to conclude the effect more generally.

8.4 Results

All analyses were made also using Kendall's tau correlation and practically the same results were obtained. Both methods showed systematically the same conclusions, thus the results here are only presented using the Spearman method.

8.4.1 Best combination of multiplying factors

8.4.1.1 Brute force

The brute force optimisation of the multiplication factors showed that it was possible to improve the correlation between the weighted vibration and the subjective responses (Table 40). The results show that the best correlation found was better than using any standard scenarios (Spearman r^2 0.850). The best correlation was found using only the seat translational axes with emphasising the fore-and-aft and lateral axis compared to vertical. The best top ten correlations were achieved without the backrest or rotational axes (the factors were zero). The same correlation was possible to achieve with different combinations of multiplying factors. This suggests clustering of the best values.

Table 40. The top ten combinations of multiplying factors for all measured nine axes.

Spearman		**Seat**						**Back**		
r^2	**P**	**x**	**y**	**z**	**roll**	**pitch**	**yaw**	**x**	**y**	**z**
0.949920	< 0.001	2.7	1.8	1.0	0.0	0.0	0.0	0.0	0.0	0.0
0.946454	< 0.001	2.7	1.7	1.0	0.0	0.0	0.0	0.0	0.0	0.0
0.944723	< 0.001	2.6	1.6	1.0	0.0	0.0	0.0	0.0	0.0	0.0
0.944723	< 0.001	2.6	1.9	1.0	0.0	0.0	0.0	0.0	0.0	0.0
0.944723	< 0.001	2.7	1.9	1.0	0.0	0.0	0.0	0.0	0.0	0.0
0.942994	< 0.001	2.5	1.7	1.0	0.0	0.0	0.0	0.0	0.0	0.0
0.942994	< 0.001	2.6	1.7	1.0	0.0	0.0	0.0	0.0	0.0	0.0
0.942994	< 0.001	2.6	1.8	1.0	0.0	0.0	0.0	0.0	0.0	0.0
0.942994	< 0.001	2.8	1.7	1.0	0.0	0.0	0.0	0.0	0.0	0.0
0.942130	< 0.001	2.4	1.6	1.0	0.0	0.0	0.0	0.0	0.0	0.0

A more detailed brute force search using step resolution 0.01 produced somewhat better correlation (r^2 from 0.949920 to 0.96297) and showed a small contribution of the additional axes. However, no significant differences were found and since in practice the second search is too precise and the seat translational axes alone produced a good correlation, the results from the smaller step resolution were not considered in the analysis.

Based on the results an optimised model was created, providing the best set of multiplying factors for the vibration stimuli used in the experiment:

$$a_v = \left(2.7^2 a_{wx}^2 + 1.8^2 a_{wy}^2 + 1.0^2 a_{wz}^2\right)^{\frac{1}{2}} \qquad (3)$$

where a_v is discomfort value, a_{wx} is the frequency weighted r.m.s. value for the seat fore-and-aft axis, a_{wy} is the frequency weighted r.m.s. value for the seat lateral axis, a_{wz} is the frequency weighted r.m.s. value for the seat vertical axis.

8.4.1.2 Linear regression models: selecting independent and dependent variables

The results showed that there was a high correlation between axes of same direction (Table 41). For example the seat fore-and-aft axis was highly correlated with the seat pitch and backrest fore-and-aft axes. The correlation was significant ($p < 0.005$). However, the correlation between the different directions was not significant. The rotational axes were significantly correlated with the respective translational axes (e.g. the seat lateral and roll), thus they could not be used. Also the backrest axes were directly correlated with the respective seat axes. Based on the results only either the seat or backrest translational axes could be used in the regression model. Based on the practicality, the seat translational axes were chosen.

Table 41. The correlations (Pearson r) and p-values for all independent variables.

				Pearson (r)					
	Seat x	**Seat y**	**Seat z**	**Seat roll**	**Seat pitch**	**Seat yaw**	**Back x**	**Back y**	**Back z**
Seat x	1.000	.370	.281	.466	.971	.608	.933	.450	.316
Seat y	.370	1.000	.258	.956	.423	.780	.367	.981	.078
Seat z	.281	.258	1.000	.262	.294	.476	.451	.296	.801
Seat roll	.466	.956	.262	1.000	.508	.844	.459	.978	.163
Seat pitch	.971	.423	.294	.508	1.000	.667	.965	.483	.321
Seat yaw	.608	.780	.476	.844	.667	1.000	.682	.820	.364
Back x	.933	.367	.451	.459	.965	.682	1.000	.430	.451
Back y	.450	.981	.296	.978	.483	.820	.430	1.000	.129
Back z	.316	.078	.801	.163	.321	.364	.451	.129	1.000
				Sig 1-tailed (p)					
Seat x	.000	.022	.066	.005	.000	.000	.000	.006	.045
Seat y	.022	.000	.084	.000	.010	.000	.023	.000	.341
Seat z	.066	.084	.000	.081	.057	.004	.006	.056	.000
Seat roll	.005	.000	.081	.000	.002	.000	.005	.000	.195
Seat pitch	.000	.010	.057	.002	.000	.000	.000	.003	.042
Seat yaw	.000	.000	.004	.000	.000	.000	.000	.000	.024
Back x	.000	.023	.006	.005	.000	.000	.000	.009	.006
Back y	.006	.000	.056	.000	.003	.000	.009	.000	.248
Back z	.007	.045	.341	.000	.195	.042	.024	.006	.000

The dependent variable is the averaged judgments of all subjects for each stimulus (Table 42). The independent variables are the seat translational axes with frequency weighting (without the multiplying factors).

Table 42. The selected dependent and independent variables used for calculating the regression model. The frequency weighted r.m.s. values (without multiplying factors) for seat translational axes are used as independent variables and averaged judgments of subjects for each stimuli are used as dependent values.

		Independent		Dependent
Stimulus	**Seat x**	**Seat y**	**Seat z**	**Judgment**
1	0.308	0.284	0.702	0.709
2	0.192	0.162	0.701	0.509
3	0.154	0.107	0.704	0.445
4	0.429	0.401	0.706	0.998
5	0.404	0.215	0.297	0.441
6	0.149	0.108	0.273	0.216
7	0.250	0.803	0.349	0.974
8	0.163	0.705	0.158	0.845
9	0.082	0.659	0.133	0.639
10	0.270	0.554	0.765	0.924
11	0.153	0.272	0.718	0.464
12	0.103	0.199	0.728	0.409
13	0.741	0.803	1.197	1.622
14	0.400	0.417	1.126	1.113
15	0.302	0.238	1.135	0.887
16	0.335	0.389	0.458	0.697
17	0.171	0.208	0.432	0.341
18	0.123	0.130	0.437	0.342
19	0.472	0.435	0.331	0.891
20	0.225	0.323	0.297	0.440
21	0.111	0.171	0.257	0.212
22	0.473	0.246	0.240	0.778
23	0.351	0.163	0.287	0.467
24	0.341	0.087	0.277	0.499
25	0.620	0.915	1.461	1.415
26	0.349	0.461	1.371	1.082
27	0.211	0.210	1.389	0.941
28	0.296	0.147	0.317	0.483
29	0.660	0.216	0.243	1.267
30	0.352	0.550	0.286	0.733

8.4.1.3 Regression model 1

The results show that each independent variable had positive correlation to the judgment (Table 43). The fore-and-aft axis had the strongest effect to the judgment, the lateral the second and the vertical the lowest influence. Collinearity statistics show good tolerance, so the correlation between independent variables did not affect the results. P-value was below 0.05, so all results were significant.

Table 43. Multiple linear regression model parameters for model 1.

	Unstandardised Coefficients			
	B	**Std. Error**	**t**	**Sig.**
Constant	-.005	0.056	-.095	0.925
Seat x	1.118	0.152	7.378	<0.001
Seat y	0.640	0.108	5.907	<0.001
Seat z	0.275	0.061	4.510	<0.001

Table 44 shows the model summary. The correlation was calculated using Pearson's method.

Table 44. Summary for regression model 1 (Pearson).

r	r^2	Adjusted r^2	Std. Error of the Estimate
0.942	0.888	0.875	0.124

The unstandardised coefficients (B) were used to form the regression model:

$$a_v = -0.005 + 1.118 a_{wx} + 0.640 a_{wy} + 0.275 a_{wz} \tag{27}$$

Where a_v is the discomfort value, a_{wx} is the frequency weighted r.m.s. value for the seat fore-and-aft axis, a_{wy} is the frequency weighted r.m.s. value for the seat lateral axis, a_{wz} is the frequency weighted r.m.s. value for the seat vertical axis.

As the coefficients are relative to each other, they can be scaled so that the seat vertical coefficient is 1.0 (Table 45).

Table 45. Parameter transformation to comply with the standard multiplying factors, where vertical axis has 1.0 factor.

Axis	Original	Scaled
Seat fore-and-aft (x)	0.275	4.1
Seat lateral (y)	0.640	2.3
Seat vertical (z)	1.118	1.0

Now the regression model can be described as:

$$a_v = -0.005 + 4.1a_{wx} + 2.3a_{wy} + 1.0a_{wz} \quad (28)$$

8.4.1.4 Regression model 2

The results show that each independent variable had positive correlation to the judgment (Table 46). The fore-and-aft axis had the strongest effect to the judgment, the lateral the second and the vertical the lowest influence. Collinearity statistics show good tolerance, so the correlation between independent variables was not affecting the results. P-value was below 0.05, so all results were significant.

Table 46. Multiple linear regression model parameters for model 2.

	Unstandardised Coefficients			
	B	**Std. Error**	**t**	**Sig.**
Constant	0.369	0.042	8.89	<0.0001
Seat x	1.426	0.242	5.89	<0.0001
Seat y	0.519	0.144	3.59	<0.0001
Seat z	0.184	0.048	3.79	<0.0001

Table 47 shows the model summary. The correlation was calculated using Pearson's method.

Table 47. Model summary.

r	***r*²**	**Adjusted *r* Square**	**Std. Error of the Estimate**
0.917	.840	.820	0.1507

The unstandardised coefficients (B) were used to form the regression model:

$$a_v = 0.369 + 1.426a_{wx}^2 + 0.519a_{wy}^2 + 0.184a_{wz}^2 \quad (29)$$

Where a_v is the discomfort value, a_{wx} is the frequency weighted r.m.s. value for the seat fore-and-aft axis, a_{wy} is the frequency weighted r.m.s. value for the seat lateral axis, a_{wz} is the frequency weighted r.m.s. value for the seat vertical axis.

As the coefficients are relative to each other, they can be scaled so that the seat vertical coefficient is 1.0 (table 48).

Table 48. Parameter transformation to comply with the standard multiplying factors, where vertical axis has 1.0 factor.

Axis	Original	Scaled
Seat fore-and-aft (x)	1.426	7.75
Seat lateral (y)	0.519	2.82
Seat vertical (z)	0.184	1.00

Now the regression model can be described as:

$$a_v = 0.369 + 7.75a_{wx}^2 + 2.82a_{wy}^2 + 1.0a_{wz}^2 \quad (30)$$

The equation can be formulated to match the format of the brute force equation:

$$a_v = 0.369 + (2.78)^2 a_{wx}^2 + (1.68)^2 a_{wy}^2 + (1.0)^2 a_{wz}^2 \quad (31)$$

Now the factors using regression model 2 are closely matched with the brute force equation (model has no square root for the summed value, but it does not affect the correlation as a ranking method is used).

8.4.2 Visual evaluation of clustering of multiplying factors

The results showed significant clustering of the seat horizontal multiplying factors using the brute force method. This can be visualised using contour mapping (Figure 71). The figure shows that the correlation (higher elevation) improved when the seat fore-and-aft multiplying factor was between 2.0 and 3.1 and the seat lateral factor between 1.3 and 2.1. The figure also shows clear clustering of the best combinations and that the standard multiplying factors (1.4) for the seat horizontal axes did improve correlation, but not as much as higher factors.

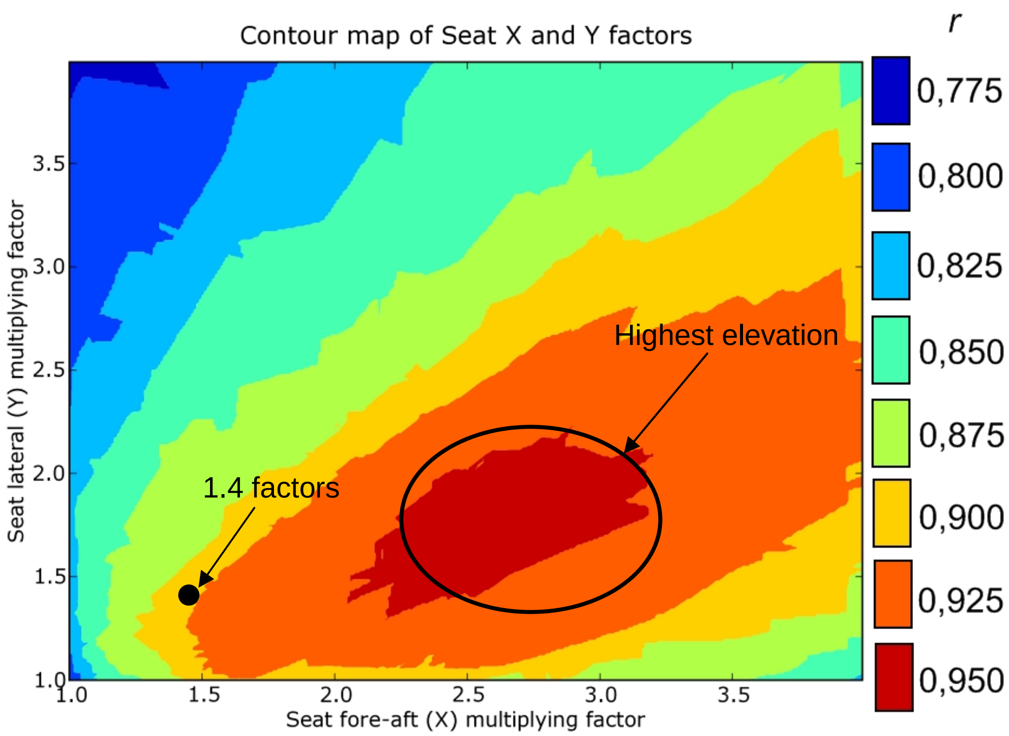

Figure 71. Contour map of the seat translational axes multiplying factors where the vertical axis is 1.0. The elevation (i.e. the correlation r) is increased for warmer colours.

The results show that the 1.4 factors did improve the correlation if compared to having no factors, but increasing the factors improved the correlation even more (Figure 72). Especially increasing the fore-and-aft factor the correlation improves significantly.

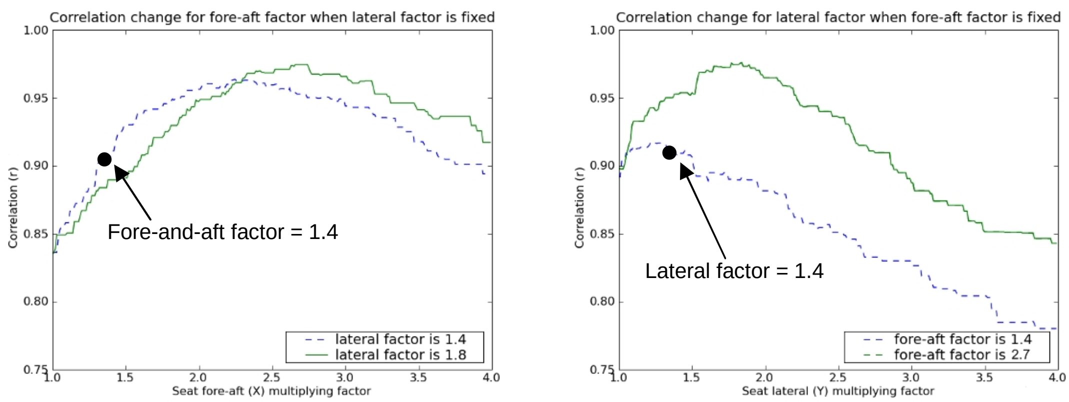

Figure 72. Left figure shows the contour map sliced from the seat lateral factor at 1.4 and 1.8. Right figure shows curves sliced from the seat fore-and-aft factor at 1.4 and 2.7.

A more detailed contour map was created based on the previous contour map (Figure 73). The figure shows that the correlation was best (highest elevation) when the fore-and-aft multiplying factor was between 2.6 and 2.9 and the lateral between 1.7 and 2.0. Again clear clustering of the best values was evident.

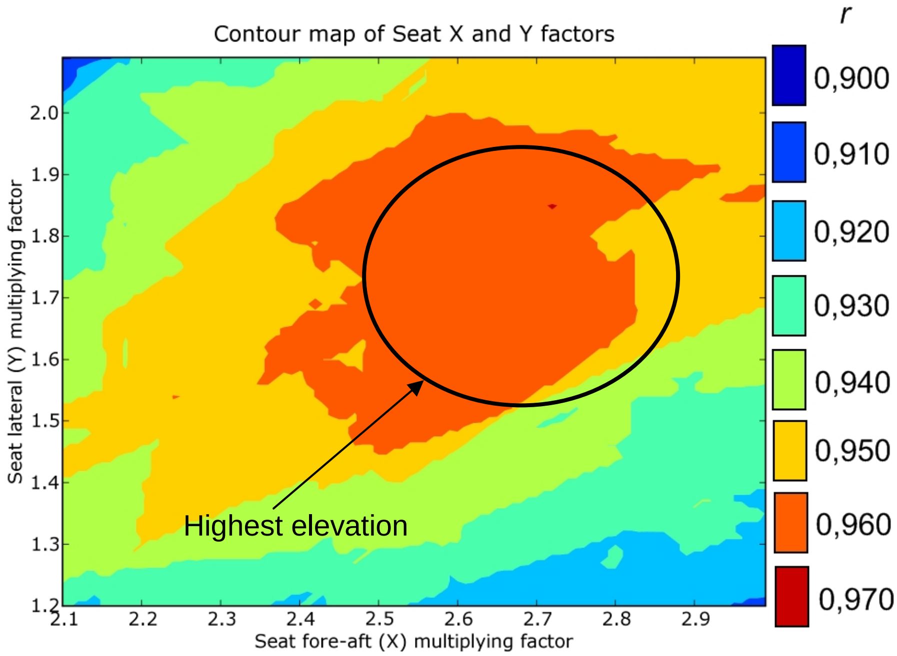

Figure 73. Contour map of the seat translational axes' multiplying factors where the vertical axis is 1.0.

Figure 74 shows the even more detailed contour map, where the highest elevation shows that the correlation was best at fairly narrow set of multiplying factors where the seat fore-and-aft multiplying factor was 2.6-2.8 and the lateral multiplying factor 1.7-1.85. The results also explain why smaller step size produced better correlation, as the highest peaks were between 0.1 decimal values.

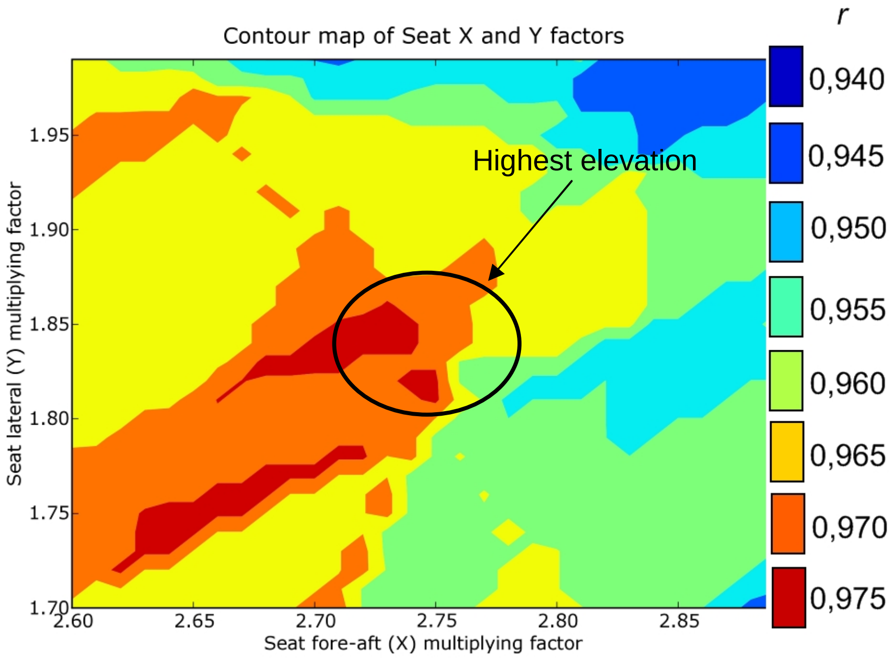

Figure 74. Contour map of seat translational axes' multiplying factors where vertical axis is 1.0.

8.4.3 Improvement in correlation for new multiplying factors

The new models based on brute force method and linear regression models were used to create Scenarios 8 (brute force), 9 (regression model 1) and 10 (regression model 2). Spearman correlation was calculated for all subjects and compared to the best correlation found using the standard scenarios (Table 49).

The multiplying factors found using the brute force method (seat fore-and-aft 2.7, lateral 1.8 and vertical 1.0) produced better correlation for 19 out of 22 subjects compared to the best standard scenario. It also improved the average correlation for all subjects to vibration, and the correlations of the "worst" and the "best" subject. There was a clear improvement from the best standard scenario using Wilcoxon signed-rank test ($p<0.001$).

The regression model 1 (Scenario 9) improved correlation for 11 out of 22 subjects. The improvement was not statistically significant for the best standard scenario ($p=0.610$). However, using regression model 2 (Scenario 10) the correlation was improved for 17 out of 22 subjects and was statistically significant ($p<0.005$).

Comparison of the new scenarios showed that the multiplying factors for Scenario 8 produced the best results, although there was no statistical difference to Scenario 10 ($p=0.078$).

Table 49. Comparison between correlations of the best standard scenario and scenarios with optimised multiplying factors for the seat translational axes (Scenario 8: seat fore-and-aft 2.7, lateral 1.8 and vertical 1.0, Scenario 9: seat fore-and-aft 4.1, lateral 2.3 and vertical 1.0, Scenario 10: seat fore-and-aft 2.78, lateral 1.68 and vertical 1.0). Scenarios 8 and 10 use root-sum-of-squares method for combining the axes, while Scenario 9 uses direct summing.

	Best standard scenarios		**Scenario 8**	**Scenario 9**	**Scenario 10**
Test subject	r^2	**Scenario**	r^2	r^2	r^2
1	0.420	Sc 6	0.471	0.446	0.469
2	0.611	Sc 6	0.610	0.568	0.598
3	0.612	Sc 6	0.615	0.574	0.602
4	0.635	Sc 7	0.650	0.646	0.663
5	0.694	Sc 6	0.752	0.722	0.735
6	0.585	Sc 6	0.560	0.530	0.561
7	0.468	Sc 7	0.484	0.504	0.484
8	0.710	Sc 6	0.803	0.752	0.804
9	0.396	Sc 6	0.409	0.368	0.394
10	0.518	Sc 3	0.531	0.480	0.544
11	0.552	Sc 7	0.584	0.564	0.579
12	0.586	Sc 7	0.710	0.702	0.706
13	0.645	Sc 6	0.714	0.636	0.706
14	0.731	Sc 7	0.751	0.730	0.748
15	0.642	Sc 7	0.674	0.641	0.678
16	0.635	Sc 6	0.680	0.688	0.676
17	0.653	Sc 6	0.716	0.722	0.713
18	0.597	Sc 7	0.567	0.551	0.557
19	0.664	Sc 6	0.707	0.686	0.693
20	0.496	Sc 7	0.548	0.513	0.545
21	0.614	Sc 7	0.621	0.609	0.617
22	0.485	Sc 7	0.493	0.484	0.512

8.4.4 Validating results

8.4.4.1 Correlation for two random groups

The validation was done by dividing the trial participants into two groups in random and testing whether the results using the new multiplying factors (Scenario 8) will indicate the same conclusions as for the whole group (Table 50).

Table 50. Participants divided into two groups.

Participant number	
Group 1	**Group 2**
2	4
13	12
17	7
20	1
18	16
3	6
22	14
10	11
8	21
19	15
5	9

For the both random groups the multiplying factors found using the brute force method were used as an additional Scenario 8 and compared against the best standard scenarios (6 and 7) (Table 51). The results show that the new factors were better than any standard scenario for the both groups and all together. Group 1 had systematically higher correlation for all scenarios than group 2.

Table 51. Comparison between the best standard scenarios (6 and 7) and best new scenario (8) for groups 1, 2 and all. Scenario 6 includes seat translational (with 1.4 multiplying factors for fore-and-aft and lateral axes) and rotational axes (with respective multiplying factors), Scenario 7 includes seat translational and rotational axes and backrest translational axes with respective multiplying factors, and Scenario 8 includes seat translational axes with 2.7, 1.8 and 1.0 multiplying factors (x, y and z).

	Correlation (Spearman r^2)		
Scenario	**Group 1**	**Group 2**	**All**
Sc 6	0.873	0.820	0.844
Sc 7	0.891	0.810	0.850
Sc 8	0.971	0.902	0.950

8.4.4.2 Multiplying factors from other studies

Only one paper was found which suggested new multiplying factors for seat horizontal axes (Maeda and Mansfield 2006b). Maeda and Mansfield proposed a 2.47 factor for the both horizontal axes, which would match the discomfort of the vertical axis. The results suggested that similar response was noticed for all axes, but because of different weighting curves for the horizontal axes higher factors were needed to compensate the difference.

8.4.4.3 Using new factors for data from other studies

The new set of multiplying factors (Scenario 8) for the seat translational axes were tested using data from a previous trial from other researchers. Mansfield and Maeda (2006) used stimuli which had equal energy from 1 to 20 Hz. The stimuli were made up by having single-axis, dual-axis or tri-axial vibration. Three amplitude levels (unweighted r.m.s.) 0.2 m/s^2, 0.4 m/s^2 and 0.8 m/s^2 were used for generating 17 different stimuli. Each test subject was exposed to three repeats of the stimuli. The subjects estimated the magnitude of each stimulus using Stevens' method (i.e. the ME method).

For comparison with the results in this study the unweighted values were converted to weighted ones using 0.39 multiplier for the horizontal axes and 0.86 for the vertical axis as described in the study (Table 52). Additionally the values were combined using standard Scenario 2, where 1.4 multiplying factors were used for the seat horizontal axes and Scenario 8, which include the new factors (fore-aft 2.7, lateral 1.8 and vertical 1.0).

Table 52. Summary of the weighted vibration magnitudes used by Mansfield and Maeda (2006) (adapted from the source).

	Vibration magnitude (m/s^2 r.m.s.)					
Stimulus	**x-axis**	**y-axis**	**z-axis**	**r.s.s. scenario 1**	**r.s.s. scenario 2**	**r.s.s. scenario 8**
1	0.078	-	-	0.078	0.109	0.211
2	-	0.078	-	0.078	0.109	0.140
3	-	-	0.172	0.172	0.172	0.172
4	0.156	-	-	0.156	0.218	0.421
5	-	0.156	-	0.156	0.218	0.281
6	-	-	0.344	0.344	0.344	0.344
7	0.312	-	-	0.312	0.437	0.842
8	-	0.312	-	0.312	0.437	0.562
9	-	-	0.688	0.688	0.688	0.688
10	-	-	0.860	0.860	0.860	0.860
11	-	-	1.032	1.032	1.032	1.032
12	0.156	0.156	-	0.221	0.309	0.506
13	0.156	-	0.344	0.378	0.407	0.544
14	-	0.156	0.344	0.378	0.407	0.444
15	0.078	0.078	0.172	0.204	0.231	0.306
16	0.156	0.156	0.344	0.409	0.462	0.612
17	0.312	0.312	0.688	0.817	0.925	1.224

Figure 75 shows correlation for all 15 subjects using scenarios 1, 2 and 8. In all cases applying the multiplying factors (scenario 2 or 8) was better than not having any factors (Wilcoxon $p<0.05$). For 9 out of 15 subjects scenario 8 was the best, but no statistical differences were found to Scenario 2 ($p=0.250$).

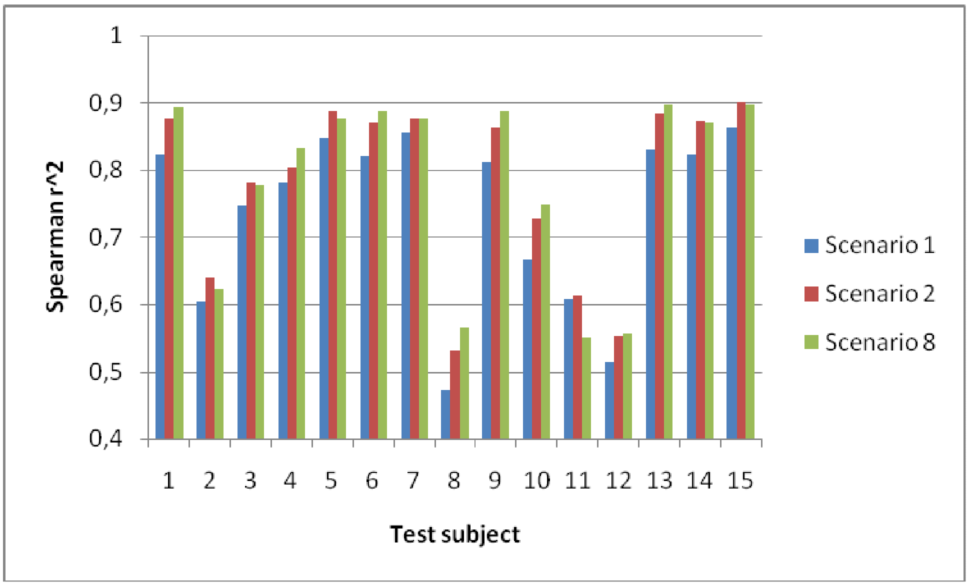

Figure 75. Spearman correlation (r^2) for each test subject for scenarios 1, 2 and 8.

8.5 Discussion

The results from the previous publications have indicated that the standard's method itself might not be valid. There have been doubts expressed at least with the frequency weighting (Maeda, et al 2008), the multiplying factors (Maeda and Mansfield 2006b) and the discomfort scaling (Maeda 2005). Griffin (1998) has criticised the current standard of using the r.m.s. method instead of the r.m.q. or VDV methods. However, no alternative methods have been proposed to replace the current standard regarding discomfort.

Based on the analyses of the standard method in Chapter 7, it was evident that the most effective way to improve the method is to optimise the multiplying factors. This was also suggested by another publication (Maeda and Mansfield 2006b). The analyses indicated that the seat horizontal axes should be given more emphasis and that higher emphasis of the seat translational axes would minimise the need to use the additional axes.

Although some publications have criticised the current standard, there have been no suggestions on an improved model for predicting discomfort. The evidence in Chapter 7 showed that the frequency weighting did not have a significant role. This can be because in practice several dynamic components act as natural low pass filter, thus the stimuli only contains low frequencies. This might be one reason why laboratory studies do not directly correlate to real environments.

Also other methods such as r.m.q. and VDV, which have been suggested to replace the r.m.s. method when evaluating health effects, have not been shown to work better for discomfort. Even though British Standard BS 6841 suggests using the r.m.q. method for discomfort if crest factor of six is exceeded, it does not give any guideline or values how to interpret the results.

8.5.1 Improvement in correlation using the new multiplying factors

The brute force calculations indicated that the seat translational axes alone can be used to evaluate discomfort. This was expected as the backrest and rotational axes had high correlation to the seat translational axes. Based on the calculations the seat fore-and-aft axis should be emphasised 2.7 times, the lateral axis 1.8 times compared to the vertical axis.

Even though the more detailed brute force search showed better results, the 0.01 step size is considered an excessive level of precision, considering the limited size of the data set used to determine the factors. The same practical accuracy was possible using only the seat translational axes, thus the rest of the analyses was done using the best factors derived from the first search. However the results showed that the seat rotational and backrest axes do improve correlation with the proper factors, but the biggest improvement of correlation is possible by optimising the multiplying factors for the seat horizontal axes. The calculation time also dramatically shortens when using lower step resolution.

The results showed that by increasing the multiplying factors of seat fore-and-aft and lateral axes, the correlation improved systematically. The results showed similar implications than Maeda and Mansfield (2006), which showed higher multiplying factors (2.47) for seat horizontal axes than 1.4. The study concluded that frequency weightings for seat horizontal axes underestimated the effect of vibration.

8.5.2 Confidence in the new multiplying factors

Both the brute force and linear regression model 2 showed similar results where the fore-and-aft axis should be emphasised at 2.7 times and lateral axis 1.8 times compared to the vertical axis when axes are summed using a second power method. The brute force results showed clear clustering of the factors, which was evident from the contour maps. This also explained why the same correlation was possible with different combinations of factors. The results were also obtained using Kendall's tau correlation and similar results were found, thus the statistical analyses have a high confidence level.

The validation of the results, by dividing the participants in random into two groups and calculating the results again, showed that the new factors gave systematically better correlation than the best standard scenario.

The results from another study were used to test the new factors. It was shown that the higher factors improved correlation, but in this case there was no statistical improvement compared to 1.4 multiplying factors (Scenario 2). The laboratory trial was conducted using Steven's magnitude estimation method and values were averaged using geometric mean. These differences might have influenced the results. However, the positive impact of higher multiplying factors was evident, and in average Scenario 8 was better than Scenario 2.

8.5.3 Comparison of results from different methods

Regression model 1 was based on linear summing, thus not directly comparable with the brute force model. However, a similar trend in emphasising the fore-and-aft and lateral axes was noted. Regression model 2 however had the second power summing, thus the results were a close match to the brute force equation. As the square root does not change the correlation using the Spearman method, the results indicated very similar multiplying factors.

The both regression models gave results with a good confidence level. Even though the regression model's correlation was lower for model 2, it was using Pearson's correlation, which does not give best evaluation for this type of data. If Spearman correlation was used, then model 1 had 0.894 (r^2) and model 2 had 0.941 (r^2). Thus clearly the second power emphasis improved correlation to the discomfort. Thus model 2 was better and as the factors were so close with the brute force results, only one set of multiplying factors (equation 31) was used for validating the results.

The regression model could not be used to include more than the seat translational axes, as the method does not work when the independent variables have high correlation. For the seat axes the regression model showed similar emphasis for the axes. The factors of model 1 were higher than the brute force results, but this was expected as the regression model equation sums the axes linearly without second power emphasis. The higher factors for the both fore-and-aft and lateral axes compensate this effect. Model 2 had practically the same multiplying factors than the brute force model.

8.5.4 Applicability of the standard method

The whole purpose of evaluating discomfort from whole-body vibration is to understand what characteristics in the vibration cause discomfort and how to minimise them. If the method does not predict discomfort reliably it will not be used. Other methods such as r.m.q. and VDV, which have been suggested as superior to the r.m.s. method when evaluating health effects, were not shown to work better for discomfort for the range of stimuli used in this study. It might be that different circumstances and environments will lead to different emphasis of the axes, thus no generalised model can be realised. In this case the model should allow changeable parameters for each type of environment (e.g. train, car, boat). However, this study design used commonly experienced vibration stimuli from road and off-road vehicles designed to capture the widest population of those exposed.

Because the number of included axes will directly affect the size of OVTV, it is not logical that axes can be neglected without compensation. Thus multiplying factors for each combination of PVTVs should be introduced to allow comparison of results using different number of axes. However, based on the results it can be speculated if absolute discomfort level can be even predicted, as it will always depend on also other factors than the vibration. It is more likely and practical that the method can be used to predict relative discomfort between different vibration exposures. And it is likely that causality between vibration and discomfort is not direct, thus only relative changes of rather limited differences can be evaluated.

8.5.5 Scope and limitations of the new model

To avoid problems and misuse relating to the standard method, it is important to limit the new method for a specific scope, instead of developing an "all purpose" model. This improves the practical usability of the model. Based on the recommendations and experience of the previous work the model should have the following constrains:

- The model only predicts relative change in discomfort relating to change in the frequency weighted vibration amplitude for a seated person (with backrest);
    - As other physical and physiological factors (i.e. noise and tiredness) change absolute discomfort level, the method can only predict the relative change related to the vibration if the other factors remain the same.
- Following axes are needed to be measured (minimum requirement);

    - A seat fore-and-aft, lateral and vertical axis;

- The vibration should not include high shocks (i.e. crest factor above 9.0);

It might be that different circumstances and environments will lead to different emphasis of the axes, thus no generalised model can be realised. In this case the model should allow changeable parameters for each environment. The best approach is to use brute force, contour mapping and linear regression modelling to optimise the factors.

8.6 Conclusions

It was previously concluded that the best approach to improve the current standardised model would be to optimise the multiplying factors. The results here showed that:

- Higher multiplying factors for the seat horizontal axes improved the correlation between vibration magnitude and discomfort;
- The seat translational axes alone could be used, if the multiplying factors were optimised;
- The brute force and linear regression method showed similar results;
- Several combinations of the multiplying factors are possible as clustering of the factors were noted;
- Most likely a good prediction is possible if relative change in discomfort is evaluated instead of the absolute discomfort.

All analyses confirmed that the new multiplying factors gave better results than any standard scenario. Based on the results of previous chapter a clear indication of improvement has been found. The results should be validated in a field environment using the similar method than in the laboratory trial.

9 Chapter 9 - Field trial: validating the ISO 2631-1 method and results from the laboratory trial

9.1 Introduction

It can be assumed that the ISO 2631-1 standard has been created for practical use. Even though the method and procedure is based on laboratory studies, it should also work in the field. However, it has not been widely adopted for predicting discomfort from vibration. It is of importance to understand how well the method predicts discomfort in field environments, where there are much larger possibilities for errors. Also it is necessary to understand how to simplify the guidance to improve the accuracy of the results and comparison to other measurements (the confusing guidance has been discussed in Chapter 2).

It was previously noted in Chapter 2 that only a few 12-axis measurements have been reported and only a few field trials have been made where discomfort to vibration has been evaluated. Only one study was found where 12-axis vibration and subjective judgments were simultaneously measured (Parsons and Griffin 1983). The study was conducted using several cars on different road types. Subjects judged each leg lasting 20 seconds by marking a point in a line. The study was conducted on a closed test track and each subject was tested separately. The method described in the study was similar to that in the standard, but did not include multiplying factors and frequency weightings were based on 8 subjects, thus not the same as in the standard. The results from the study suggested that the r.m.s. method using root-sum-of-squares (r.s.s.) summing is the best for car-type environments. The study weighted the axes based only on the frequency weightings, thus no multiplying factors were used like in the standards.

The results in previous Chapters 7 and 8 showed that it was possible to achieve good correlation between the vibration exposure and subject's judgment. Even though the best standard scenario (all nine measured axes) already showed high correlation for all subjects (r^2 of 0.850), it was further improved (up to r^2 of 0.950) and simplified by introducing higher multiplying factors for seat horizontal axes (2.7 for the fore-and-aft, 1.8 for the lateral and 1.0 for the vertical axis). Using the aforementioned factors, only the seat axes were necessary for achieving the best correlation. This was because of high correlation between the seat and backrest translational axes due to the seat structure and minimal effect of the seat rotational and floor translational axes to the discomfort.

Based on the field measurements in Chapter 5, it was concluded that the seat rotational and floor translational axes will have a marginal effect on the overall vibration total value (OVTV) if standard weighting is used. Additionally, because of high correlation between seat and backrest axes, it can be assumed that using the seat translational axes will give as good results as using both the locations. This allows simpler and more comparable results as a sensor location can vary significantly between measurers and machines.

Field measurements will introduce several new factors and possibilities for errors, which can be confined in a laboratory: stimuli cannot be completely controlled, noise and other factors are present and will influence the judgment, repeatability depends on the chosen tracks, which might change quickly, and so on. It might be that the vibration is not the dominant factor for the discomfort in the chosen environment, thus results might show low or inconsistent correlation to the vibration. There is not enough information on multi-factorial effects on discomfort and how they relate. It might be that separately evaluating each factor might give wrong indication of the discomfort in real environments where all factors are present simultaneously.

9.2 Goals of the field trial

The purpose of the field trial is to validate if the standard method can be used in the field for predicting discomfort from whole-body vibration using a similar approach to that in the laboratory trial (Chapter 8). Answers to the following questions were regarded as most important:

- Does the standard method adequately predict discomfort in the field?
    - Adequately is defined as Spearman $r^2 > 0.5$;
- Do the optimised multiplying factors found in the laboratory trial improve correlation compared to the standard multiplying factors?
- What multiplying factors best describe the discomfort for whole-body vibration in the field?
    - Are the best found multiplying factors systematic within subjects and groups?

9.3 Methods

9.3.1 Measurements

9.3.1.1 Field environment

The trial was conducted in Finland using normal road conditions around the Oulu county area. The route consisted of asphalt, gravel, cobblestone and off-road surfaces driven at various speeds (Table 53). The speed and location were recorded using a GPS device. The legs were driven either in order from 1 to 11 or in reverse order from 11 to 1. The speed was maintained as accurately as possible whilst maintaining safety on the public roads. The driver did not participate actively in data collection or subjective rating, although vibration at their seat was measured.

Table 53. Legs used in the field trial.

Leg	Surface	Speed (km/h)	Description
1	Asphalt	50	Three speed humps
2	Asphalt	45	Even city road
3	Cobblestonestone road	20	City centrum; pot holes
4	Cobblestonestone road	30	City centrum; pot holes
5	Asphalt	55	Even city road
6	Gravel	15	Rough gravel road with pot holes
7	Gravel	50	Gravel road with some pot holes
8	Off road	10	Uneven; pot holes
9	Asphalt	30	Speed humps
10	Gravel	20	Road construction site with loose gravel
11	Asphalt	110	Highway

Figure 76 shows the asphalt road type (legs 1, 2, 5, 9 and 11). Figure 77 shows the cobblestone road surface (legs 3 and 4). Figure 78 shows off-road surface (leg 8). Figure 79 shows gravel road (legs 6 and 7) and Figure 80 the construction gravel road (leg 10). All road surfaces represented typical environments found in Finland. For example a cobblestone road is typical in city centers in Finland and there are hundreds of thousands of kilometres of gravel roads in the country side.

Figure 76. Asphalt surfaces used in the trial.

Figure 77. Cobblestone road surfaces used in the trial.

Figure 78. Off-road surface used in the trial.

Figure 79. Gravel road surfaces used in the trial.

Figure 80. Construction gravel road surface used in the trial.

9.3.1.2 Test subjects

Three test groups of seven subjects were used (Table 54). Groups 1 and 2 were driven on the same day in October 2008, while group 3 was driven in June 2009. The route was driven in same order for groups 1 and 3, while for group 2 the route was driven in reversed order. Group 3 had four subjects from groups 1 and 2, and two new subjects. The subjects were chosen and divided into the groups randomly. The average height was 180 cm and weight 79 Kg, average age was 28 years. Most subjects were men. Each test subject signed a consent form and was given information about the trial.

Table 54. The characteristics of the test subjects. Group 3 had subjects from groups 1 and 2 (same Subject id). Each seat had a fixed Seat id number.

Group	Seat id	Subject id	Height (cm)	Weight (kg)	Gender
1	1	1	184	85	Male
1	2	2	182	90	Male
1	3	3	188	88	Male
1	4	4	190	100	Male
1	5	5	170	70	Male
1	6	6	191	85	Male
1	7	7	192	75	Male
2	1	9	190	78	Male
2	2	10	176	58	Female
2	3	11	170	63	Male
2	4	12	183	80	Male
2	5	13	184	95	Male
2	6	14	180	92	Male
2	7	15	178	72	Male
3	1	16	181	77	Male
3	2	17	155	60	Female
3	3	11	170	63	Male
3	4	5	170	70	Male
3	5	13	184	95	Male
3	6	14	180	92	Male

9.3.1.3 Measurement setup

Based on the goals of the trial, it was necessary to evaluate a number of subjects simultaneously on different road surfaces. A car with several seats (i.e. minibus) was considered a best option for conducting the measurements, thus a Volkswagen Transporter was used (Figure 81). The vehicle had seven seats at the back and two seats at the front. The back seats were used in the test. The test subjects sat on the seats with a remote dial pad to indicate discomfort. The vibration was recorded simultaneously with the discomfort judgment using the measurement device.

Figure 81. The test vehicle used in the field trial. Seven subjects was tested simultaneously.

Figure 82 shows the seating and measurement arrangement. The full 12-axis measurements were conducted as a reference from the driver's seat. From the subjects the seat and backrest translational axes were measured along with the discomfort judgment. Because the measurement device itself doubled as a backrest sensor, the device could not be installed between the subject and the cushion. The device was installed on the outer side of the backrest using an adhesive tape (Figure 83). Before the trial it was confirmed that the backrest sensor location gave practically the same vibration levels as the correct location (i.e. sensor between a backrest and a human) after frequency weighting.

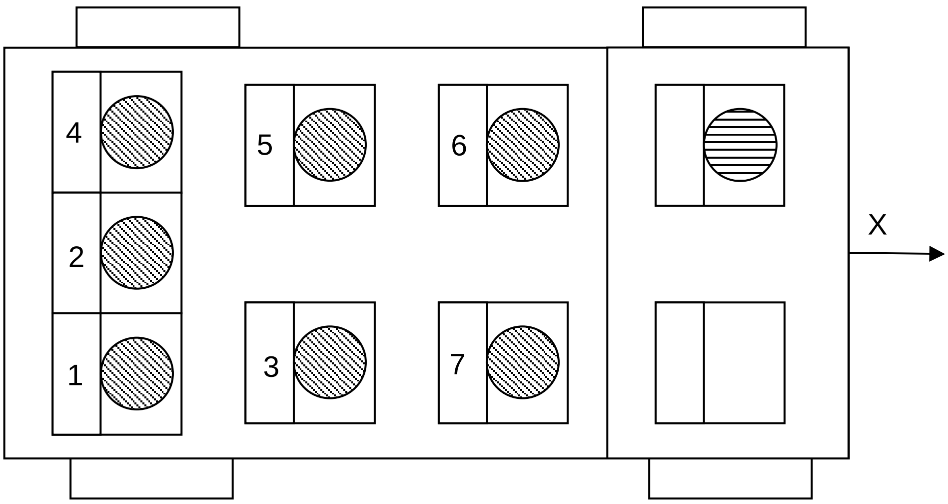

Figure 82. Seating and measurement arrangement including seat ID numbers (top view). Circles with diagonal patterns represent 6-axis measurement locations, a circle with a horizontal pattern represents the 12-axis measurement location (driver).

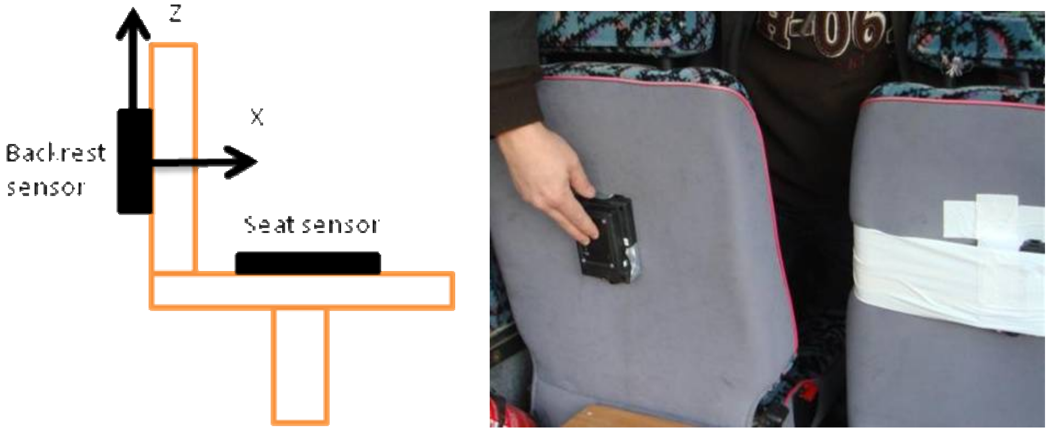

Figure 83. Sensor configuration for each subject (left) and location of the backrest sensor (right).

9.3.1.4 Equipment

The trial was conducted using a commercial measurement device (TITAN by Vibsolas Ltd) for gathering both the seat and backrest translational axes and the judgment data from the test subjects, and a measurement device (HERCULES by Vibsolas Ltd) to measure all twelve axes from the driver (Figure 84). TITAN saved acceleration data from the axes and discomfort judgment at 256 Hz sampling rate. HERCULES saved acceleration data from the twelve axes at 2000 Hz sampling frequency.

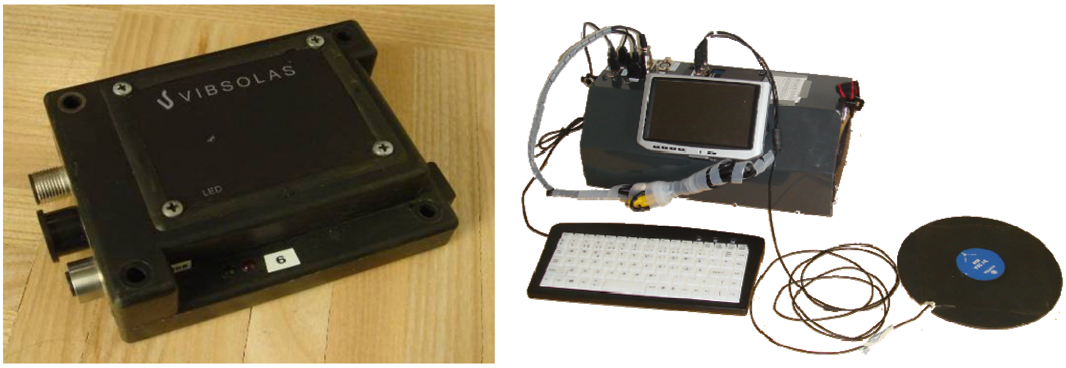

Figure 84. TITAN (left) and Hercules (right) measurement devices used in the field trial.

The continuous judgment method was previously chosen (Chapter 3) as the method for acquiring judgment data, as it is feasible to use both in a laboratory and in a field for long exposure durations. A development of the field version of the remote control dial was required, which could be used with the TITAN device (Figure 85). The dial pad had an indicator for the full range. The extremes of the knob where labelled as "no discomfort" and "high discomfort".

Figure 85. The developed remote dial pad given for each subject to judge discomfort. A tape around the dial indicated scaling from "no discomfort" to "high discomfort".

9.3.1.5 Trial procedure

Each group of seven subjects were driven through Oulu county area where there were eleven legs each lasting between 90 and 120 seconds (Figure 86). The subjects evaluated discomfort for each leg of the route separately. The subjects were instructed to evaluate the discomfort continuously based on their most current feeling (i.e. instantaneous judgment).

Figure 86. Oulu county area from up above and the whole test route (yellow line) used in the trial.

Each leg was driven once. A measurement supervisor indicated the start and end of each leg verbally. Between legs the subjects were instructed to relax and not talk to each other. There was no communication between the subjects for the entire route. The subjects did not see each other's judgments. The windows were shaded with blinds to decrease distraction. Also the test subjects did not see the driving direction as an additional blind was installed between the driver and cabin. Figure 87 shows a test subject conducting a judgment. Before the trial each test group was given a briefing of the trial procedure in a meeting room. They signed a consent form and completed a health screen questionnaire.

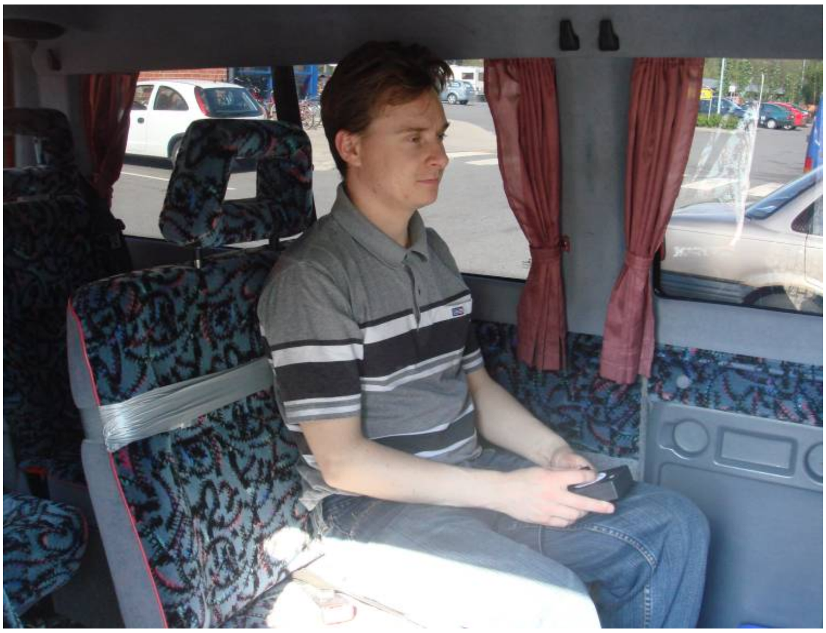

Figure 87. A test subject conducting a judgment during the measurements.

9.3.2 Analyses

Analyses of the data were conducted using similar principles as in the laboratory trial (Chapter 6). Because no references were found using similar approaches for acquiring judgment data and using longer exposure durations, it was necessary to analyse the data from different perspectives.

9.3.2.1 Vibration magnitudes and frequency characteristics of the legs

To verify the stimuli types it was necessary to conduct analyses of the vibration characteristics. Vibration magnitudes were calculated and evaluated based on the standard method of the frequency weighted r.m.s. values without multiplying factors for each axis. Also crest factors were calculated to verify the validity of results using the r.m.s. method.

Frequency characteristics of the legs were analysed based on the power spectral density figures. The frequency weighting curves were applied, as it was decided to apply the standard weighting curves for the measured vibration for all analyses.

9.3.2.2 Effect of additional axes to overall vibration total value

Based on the assumption that the seat translational axes will effectively give the same results using optimised multiplying factors, as using all twelve axes with respective multiplying factors, it was necessary to validate how large a contribution the additional axes have in this trial. Based on the previous results it was assumed that the seat rotational and the floor translational axes have a relatively small contribution (less than 10 %). This was validated using 12-axis measurements from the driver in a similar manner as in Chapter 5 using equations 21 and 22.

Even though the backrest translational axes have been noted to make a large contribution to OVTV, they tend to have high correlation with the seat translational axes (Spearman $r^2 > 0.90$), thus the seat axes alone should give similar results with proper multiplying factors. This was the result of the laboratory trial (Chapter 8). This was validated in the field trial by calculating correlations for each axis from the seat and backrest.

9.3.2.3 Analysis of judgment style

It was already noted in the laboratory trial (Chapter 6) that subjects had different styles of judging: some considered their discomfort as cumulative from beginning of a stimulus, while others judged instantaneous discomfort. In the laboratory trial there was no effect of the judgment styles to the overall judgment value, as stimuli were short (15 seconds) and an averaged value of the last 10 seconds of each stimulus was calculated. However, in the field trial stimuli were longer (up to 2 minutes) and several judgment and vibration data pairs were calculated, thus the judgment style will be of more importance. A visual analysis of different judgment styles was considered necessary between the subjects and for the different legs. Based on the visual inspection of the judgment styles, outliers were removed from the analysis.

9.3.2.4 Selecting best averaging window size and delay

The data were sampled at 256 Hz rate, thus the raw data needed to be averaged before comparison of judgment data to vibration amplitudes was done. Previous research using the continuous judgment method concluded an optimal averaging window of 2.5 seconds with 1 second delay between vibration and judgment data (Kuwano and Namba 1985). This conforms to the findings regarding the psychological present, which a subject can consider as “one moment” without relying on a long term memory. The optimal averaging size changes amongst subjects, thus different window sizes should be considered to find a good compromise.

A pilot study noted a 2 second delay for reaction to a vibration stimulus (Bhalchandra 2008). This was confirmed in the laboratory trial (Chapter 6). This suggests trimming each leg from the start. The references from noise studies and experience from the laboratory trial can be considered as a basis for testing different combinations of parameters for finding the optimal setup for analysing the correlation from the field measurements.

Instead of using consecutive averaging windows, overlapping windows were considered for improving the correlation. There are no references for using overlapping windows with the continuous judgment method, thus the overlap was considered to be half of the chosen averaging window size (Figure 88). The assumption was that the overlapping improves the correlation and decreases the effects of different judgment styles.

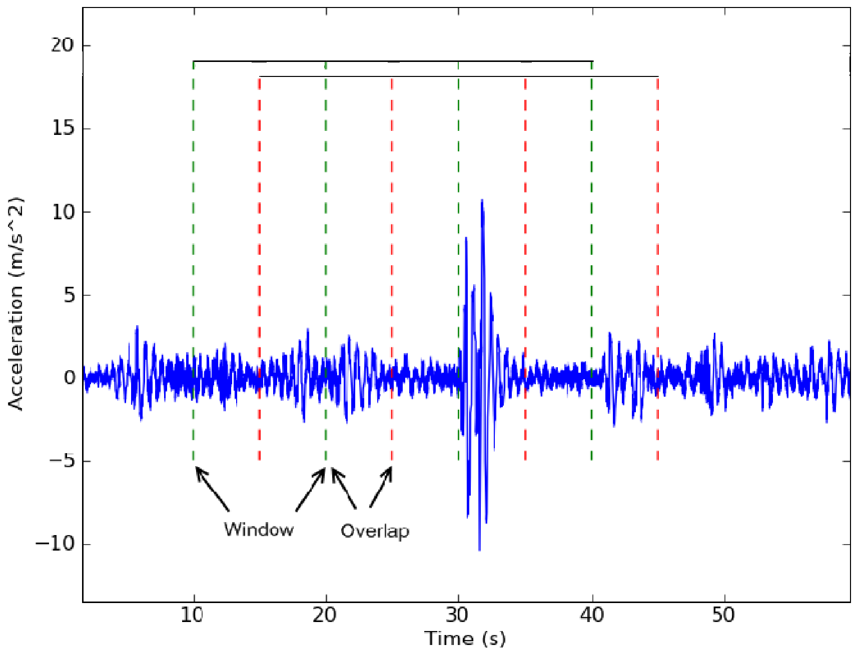

Figure 88. Illustration of overlapped values calculated from the vibration data.

Several setups were created for finding the best combination of parameters (Table 55). The standard Scenario 2 (seat translational axes with 1.4 multiplying factors for the seat fore-and-aft and lateral axes) was selected as it conforms best to the standard and is the simplest form of the method. The parameters included testing different reaction delays, averaging and overlapping window sizes. It was also considered necessary to trim the data from the beginning of each leg similarly as in the laboratory trial (see

Chapter 6). The reason is to minimise differences between the subjects, because of different delays at the start of each stimulus. A ten second trim was considered enough based on a visual inspection to be sure that all subjects had reached their initial discomfort level. Also a five second trim from the end of each leg was done to ensure synchronised endings.

Table 55. Setups for testing best parameters for comparing correlation between vibration and judgment values.

Setup	Delay (s)	Averaging size (s)	Overlap size (s)	Trim (start,end) (s)
1a	0	2.5	1.25	10,5
1b	2.5	2.5	1.25	10,5
2a	0	5.0	2.5	10,5
2b	2.5	5.0	2.5	10,5
3a	0	10	5.0	10,5
3b	2.5	10	5.0	10,5
4a	0	20	10	10,5
4b	2.5	20	10	10,5
5a	0	30	15	10,5
5b	2.5	30	15	10,5

As Spearman correlation was used, it was necessary to analyse how sample size affects the correlation and what is the minimum sample size and correlation to be accepted. This is the compromise of choosing the best setup from Table 55. Spearman correlation gives more confidence if the number of samples is increased (Figure 89). The figure can be used to determine the optimal number of sample sizes to minimise the effect of outliers, but to still have good confidence in the results. It can be concluded that at least a sample size of 22 should be considered as minimum. Similar to the other chapters, Kendall's tau was used to verify results of the Spearman correlation. Wilcoxon signed-rank test was used to evaluate statistical differences between the scenarios and the setups.

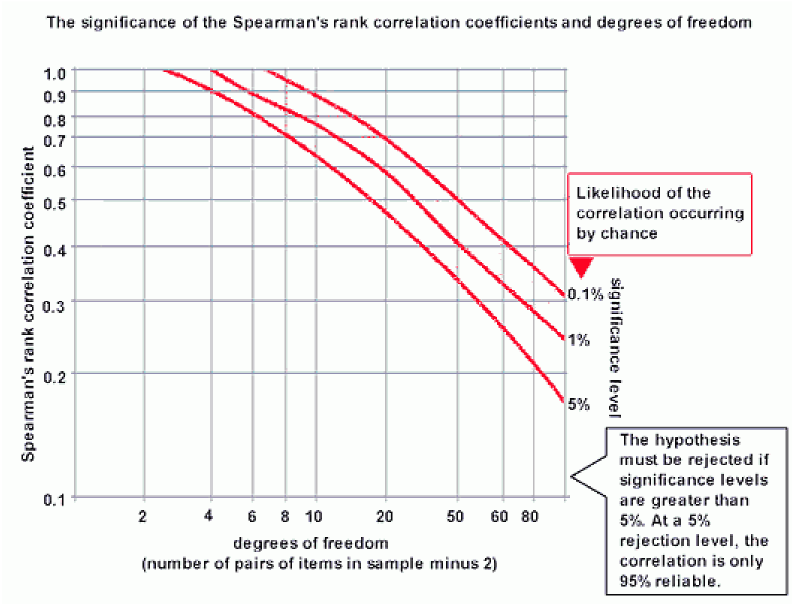

Figure 89. Spearman confidence table for determining the goodness of a correlation value compared to a sample size.

9.3.2.5 Normalising the judgments

To calculate correlation between the vibration and the discomfort judgment for each subject a normalisation was not needed as Spearman correlation is not affected by absolute values (i.e. ranking method).

For averaging judgment data for each group a normalisation was required, because the chosen method for judging vibration does not restrict a subject to evaluating discomfort on a fixed scale. Normalisation of each test subject was done for the whole route by considering the smallest judgment value as zero and highest as two, thus the judgment values of each subject was converted to between 0.0 and 2.0. The averaging of the judgment values for each group was done using an arithmetic mean.

9.3.2.6 Correlation between vibration magnitudes and discomfort

Correlation was calculated between the averaged judgment values and the frequency weighted r.m.s. values of the applicable standard scenarios (i.e. scenarios using the seat and backrest axes) (Table 56). Additionally the correlation was calculated for the best set of multiplying factors found in the laboratory trial (Chapter 8). The correlation analyses were made using Spearman r^2.

Table 56. Practically realisable scenarios based on the ISO 2631-1 standard when using the seat and backrest translational axes.

Scenario number	Explanation
1	Overall vibration total value of seat translational axes (without 1.4 multiplying factors for horizontal axes)
2	Overall vibration total value of seat translational axes (with 1.4 multiplying factors for horizontal axes)
3	Overall vibration total value based on point vibration total values of seat translational axes (without 1.4 multiplying factors) and backrest fore-and-aft axis (with 0.8 multiplying factor)
4	Overall vibration total value based on point vibration total values of seat translational axes (without 1.4 multiplying factors) and backrest translational axes (with multiplying factors)

9.3.2.7 Optimising new multiplying factors

Using a similar approach to the laboratory trial, a best set of multiplying factors was calculated for the data gathered in the field trial. This was accomplished using the brute force method as it was concluded to produce the best results for finding the factors. The multiplying factors were calculated for each subject and group. Only the seat translational axes were used for simplifying the analyses. It was expected that practically the same correlation can be achieved using the seat axes than the seat and backrest axes. The correlation analyses were made using Spearman r^2.

9.3.2.8 Clustering of multiplying factors

In the laboratory trial (Chapter 8) it was found that the brute force method produced several sets of multiplying factors which gave practically the same correlation. This suggested clustering of the factors. The contour maps were created, which confirmed the findings visually. A similar approach was used also for the field data.

9.4 Results

All correlation analyses showed systematic results for both Spearman rho and Kendall's tau methods, thus results presented here are based only on the Spearman r^2 values.

9.4.1 Vibration characteristics of the legs

9.4.1.1 Vibration magnitudes

Frequency weighted vibration magnitudes (r.m.s.) from the seat and backrest axes showed moderate levels of vibration typically found in a car (Parsons and Griffin 1983) (Table 57). The vibration magnitudes of most legs were less than 0.60 m/s^2 except in leg 8, which was off-road (dominant r.m.s. value was 0.75 m/s^2). Thus the results of the trial can be considered to represent passenger discomfort in a normal car and road types. The vertical axis was dominant for all legs, which is normal when using a car. Speed humps increased the vibration magnitudes significantly on asphalt surfaces. There was a variation in the vibration magnitudes amongst subjects due to the seat location, but the levels were consistent (i.e. high correlation).

Because of the seating arrangement the magnitudes were slightly different for each subject. However, high correlation (Spearman r^2 > 0.98) was found between the seating locations. The vertical axis was highest for all legs, which is common in this type of vehicle and selected road conditions. Also a standard deviation was highest for the vertical axis. The seat and backrest axes had also high correlation (Spearman r^2 > 0.90). Crest factors were below 9 for all cases.

Table 57. Frequency weighted r.m.s. values (m/s^2) without the multiplying factors, and standard deviations for all legs (without multiplying factors) averaged from subjects from group 1.

	Seat						Back					
	x		y		z		x		y		z	
Leg	**avg**	**s.d.**	**avg**	**s.d.**	**avg**	**s.d.**	**avg**	**s.d.**	**avg**	**s.d.**	**avg**	**s.d.**
1	0.298	±0.106	0.130	±0.025	0.533	±0.155	0.574	±0.141	0.158	±0.023	0.619	±0.130
2	0.104	±0.024	0.073	±0.010	0.197	±0.050	0.164	±0.037	0.095	±0.012	0.305	±0.042
3	0.250	±0.070	0.256	±0.052	0.503	±0.129	0.450	±0.117	0.300	±0.035	0.574	±0.094
4	0.261	±0.068	0.196	±0.044	0.541	±0.159	0.481	±0.118	0.265	±0.049	0.793	±0.117
5	0.086	±0.026	0.085	±0.011	0.228	±0.063	0.164	±0.048	0.116	±0.024	0.399	±0.050
6	0.295	±0.077	0.383	±0.070	0.513	±0.156	0.498	±0.159	0.432	±0.033	0.562	±0.130
7	0.146	±0.033	0.249	±0.036	0.588	±0.195	0.274	±0.056	0.365	±0.083	1.231	±0.167
8	0.349	±0.083	0.624	±0.109	0.748	±0.145	0.633	±0.146	0.702	±0.048	0.759	±0.124
9	0.288	±0.068	0.171	±0.023	0.470	±0.117	0.522	±0.116	0.199	±0.019	0.554	±0.100
10	0.234	±0.048	0.301	±0.053	0.564	±0.143	0.425	±0.105	0.372	±0.032	0.891	±0.108
11	0.171	±0.040	0.119	±0.017	0.407	±0.114	0.319	±0.092	0.173	±0.035	0.631	±0.095

9.4.1.2 Frequency characteristics

The legs used in the analysis can be divided in to five classes depending on the surface type: 1) asphalt road with speed humps, 2) cobblestone road, 3) gravel road, 4) off-road and 5) highway asphalt road. Each type was analysed using power spectral density functions (Figures 90 - 92). Frequency weighted vibration data from subject 5 from group 1 was used for the analyses, as the location was in the middle of the vehicle, thus best describes the overall vibration characteristics of the car.

The asphalt roads, with and without the speed humps, showed dominant frequencies in 1-2 Hz area (Figure 90). The highway asphalt showed resonance peaks over 10 Hz for all axes, which is most likely due to the road characteristics. The gravel and cobblestone roads showed similar characteristics for all axes: dominant frequencies were below 2 Hz, but the lateral axis showed peaks also at 13 Hz. This was consistent for both road types, and for the off-road as well. The frequency weighting curves attenuated differences between the different legs, as they emphasise lower frequencies.

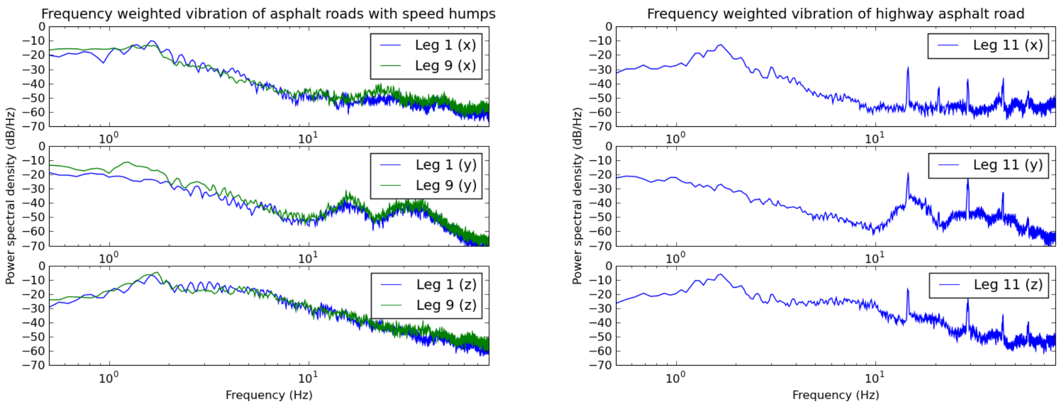

Figure 90. Frequency weighted power spectral density function of asphalt road with speed humps (legs 1 and 9) and highway asphalt (leg 11) for all translational axes from the seat (subject 5 and group 1).

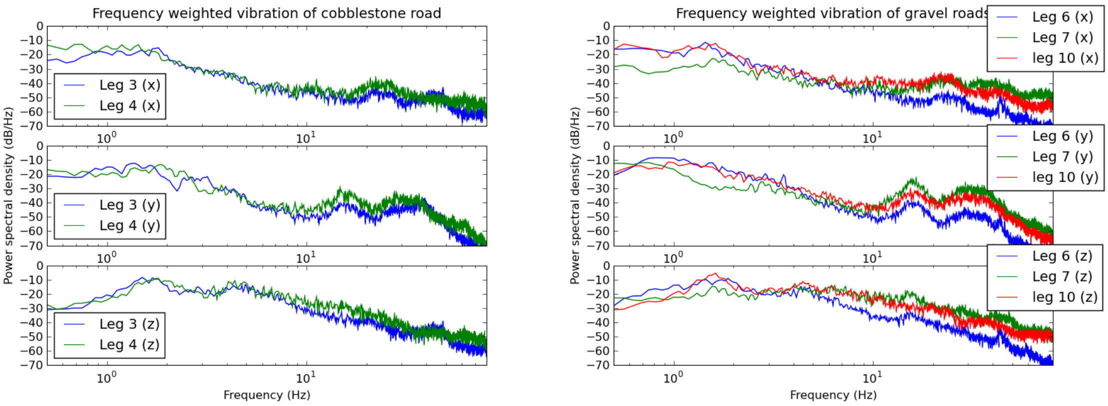

Figure 91. Frequency weighted power spectral density function of cobblestone road (legs 3 and 4) and gravel road (legs 6, 7 and 10) for all translational axes from the seat (subject 5 and group 1).

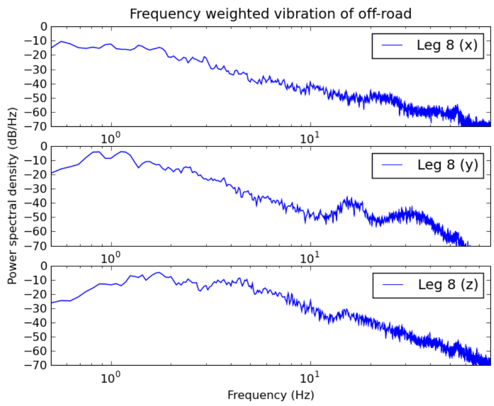

Figure 92. Frequency weighted power spectral density function of off-road (leg 8) for all translational axes from the seat (subject 5 and group 1).

9.4.1.3 Effect of seat rotational and floor translational axes to overall vibration total value

Twelve-axis measurements were made from the driver's seat. The driver did not participate in the judgment study, but served as a reference for measuring also the floor and seat rotational axes. Although these were not used in further analysis they confirmed that between 83 and 92% of OVTV occurred from the seat translational and the backrest translational data, a result in agreement with the observations in Chapter 6. Therefore, the floor translational and the seat rotational data was not considered in further analyses in this chapter, as they will have a marginal effect compared to the complexity they cause for the measurements.

9.4.1.4 Correlation between the seat and backrest translational axes

Because of the measurement equipment used in the trial, the backrest sensor had to be installed on the outer surface of the backrest. The sensor location was validated by comparing the frequency spectra and r.m.s. values between the backrest sensor on the driver (reference seat), which was installed correctly, and on the seat behind the driver (seat id 6), where the sensor was on the outer surface of the backrest. Even though it was already noted in Table 57 that the r.m.s. values varied amongst the seat locations, the frequency spectra showed that similar trend was seen on both sensor locations (Figure 93). This was validated for all legs and with and without frequency weighting. Some differences were found depending on the leg and direction, but the dominant frequencies had similar amplitudes.

Thus the backrest sensors of the subjects were used for analysis of the standard scenarios. However, because of high correlation between the backrest and seat axes, it was considered enough to use the seat translational axes for calculating the new multiplying factors. This simplified the calculation process.

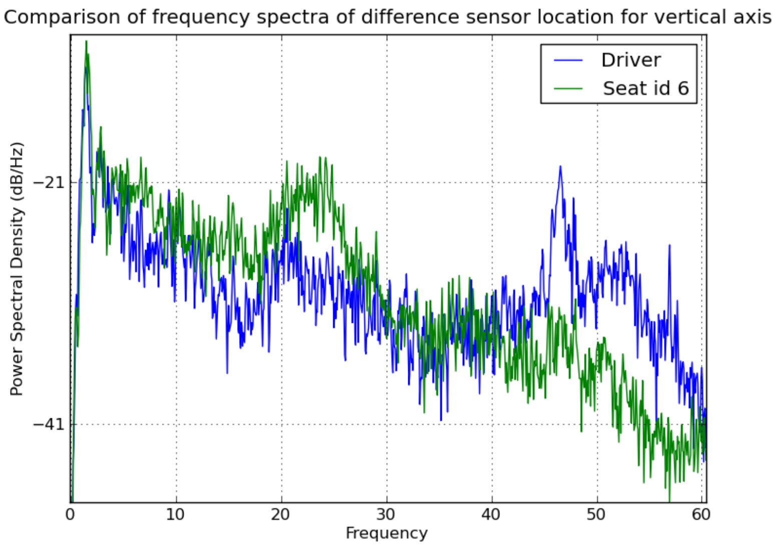

Figure 93. Frequency spectra (without weighting) for two different sensor locations for backrest vertical axis. Blue line is for the reference location where the sensor was installed between the subject and the cushion, and green line is where the sensor was installed outside the backrest, behind the subject.

9.4.2 Characteristics of judgment response

9.4.2.1 Delay between vibration and judgment

Each leg lasted between 90 and 120 seconds and the test subjects were instructed to estimate instantaneous discomfort using the remote dial. The dial was in "no discomfort" position at the beginning of each leg, thus a delay was noted before the subjects started to react to the vibration stimulus (Figure 94). In the laboratory trial this delay was in average two seconds (and additional three seconds of adjustment period), but in the field longer delays were noted. In some cases it took up to 15 seconds for the subject to react to the current stimulus. The delay varied within the legs depending on the road roughness and within each subject. The reaction to the vibration during the legs was closer to 2 seconds, thus the delay of 2.5 seconds for the averaging was a good estimate.

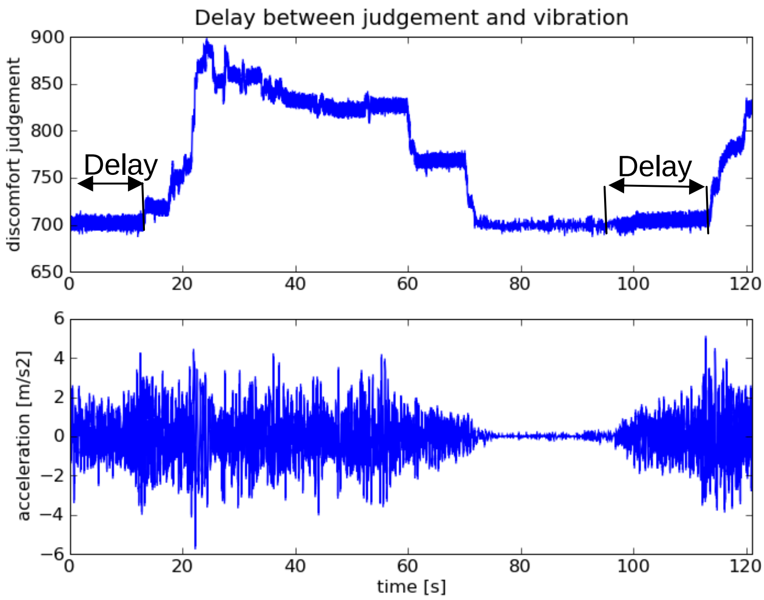

Figure 94. An example of delay between the raw judgment data and the unweighted acceleration for the vertical axis for subject 2 and for leg 3.

9.4.2.2 Analysis of judgment style

The study had several types of road surfaces. Some included shocks (i.e. speed humps and pot holes). Others had more consistent vibration characteristics (i.e. cobblestone and light gravel). It was concluded previously, that because of the different vibration characteristics of the legs, the subjects might change their judgment styles during the measurements. This will most likely affect the correlation when using a fixed averaging size. Even though all subjects were instructed to judge based on their instantaneous discomfort feeling, rather than overall discomfort from the start of a leg, some subjects did judge the vibration more cumulatively than the others (Figure 95). The figure shows differences of judgment styles for group 1, where subjects 5 and 7 judged more cumulatively than the rest (subject 6 was dismissed for technical problems in the judgment data). However all subjects had a fast reaction to the speed humps. Because of the smoothness of the road, the overall judgment level was low, but around the speed humps high (i.e. speed humps dominated the discomfort judgment). This was noticed for both legs with the speed humps (legs 1 and 9).

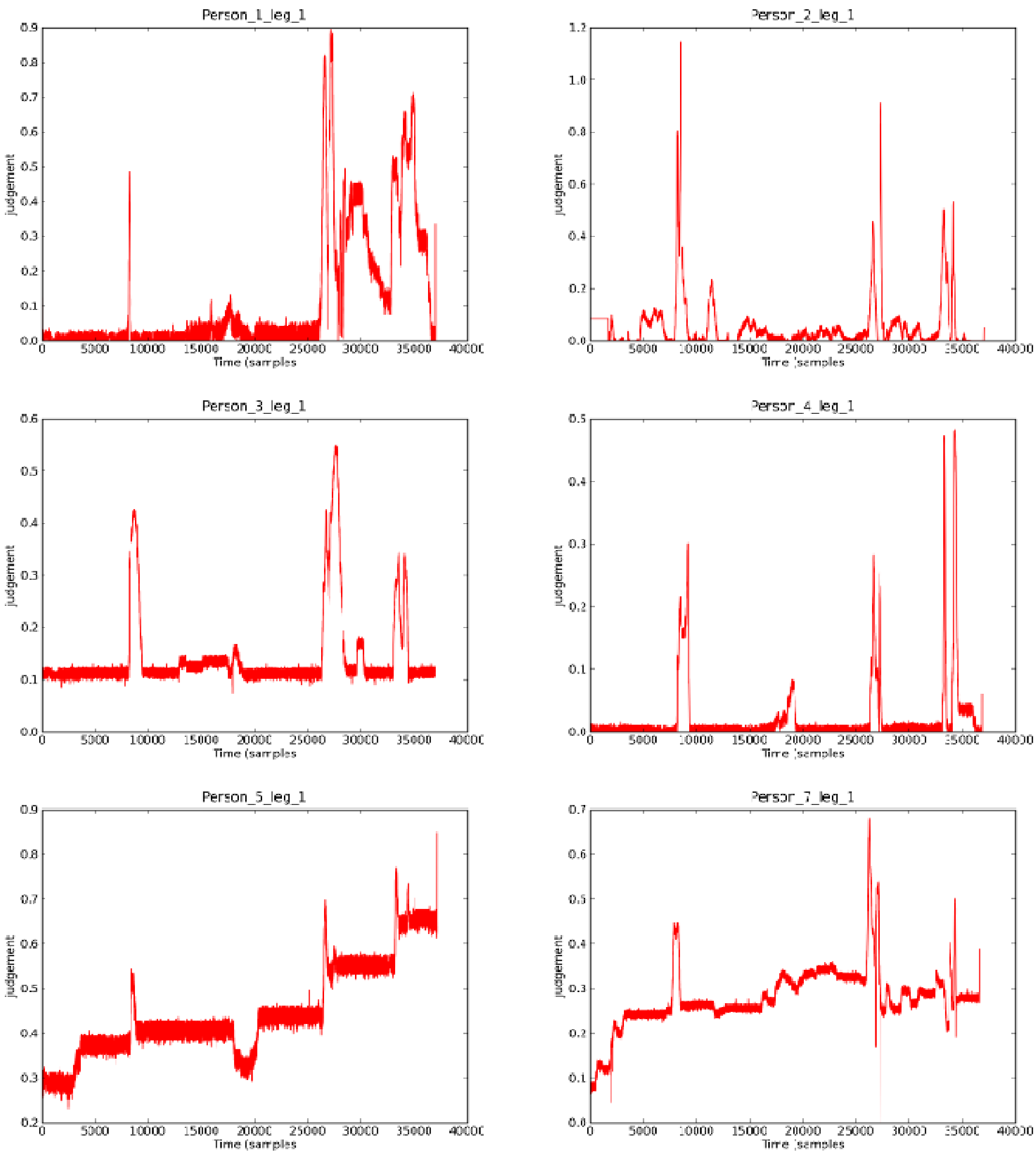

Figure 95. Judgment styles of group 1 for leg 1 with smooth asphalt and speed humps (subject 6 was not included, because of invalid data).

Legs 2 and 5 had smooth asphalt without the speed humps (Figure 96). Because of the low vibration magnitudes throughout the legs the subjects did not show any meaningful reaction to the vibration stimulus.

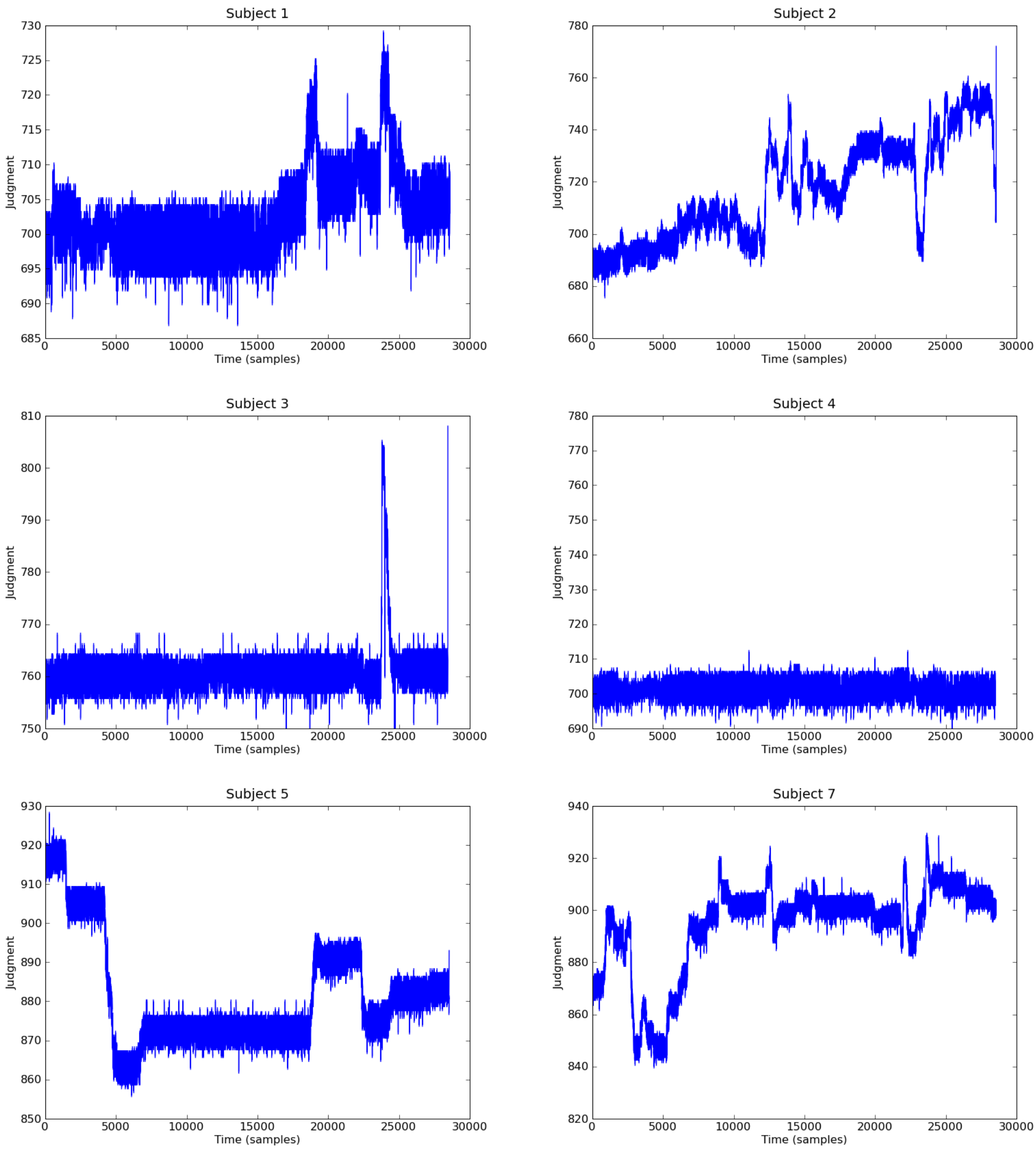

Figure 96. Different judgment styles of group 1 for leg 2 with smooth asphalt (subject 6 was not included, because of invalid data).

In contrast leg 8 had high vibration magnitudes throughout the leg. In this case subjects judged the leg more cumulatively (Figure 97). Again subject 5 had a different judgment style than the rest, but in this case the difference was smaller compared to the other subjects (i.e. the correlation was more similar).

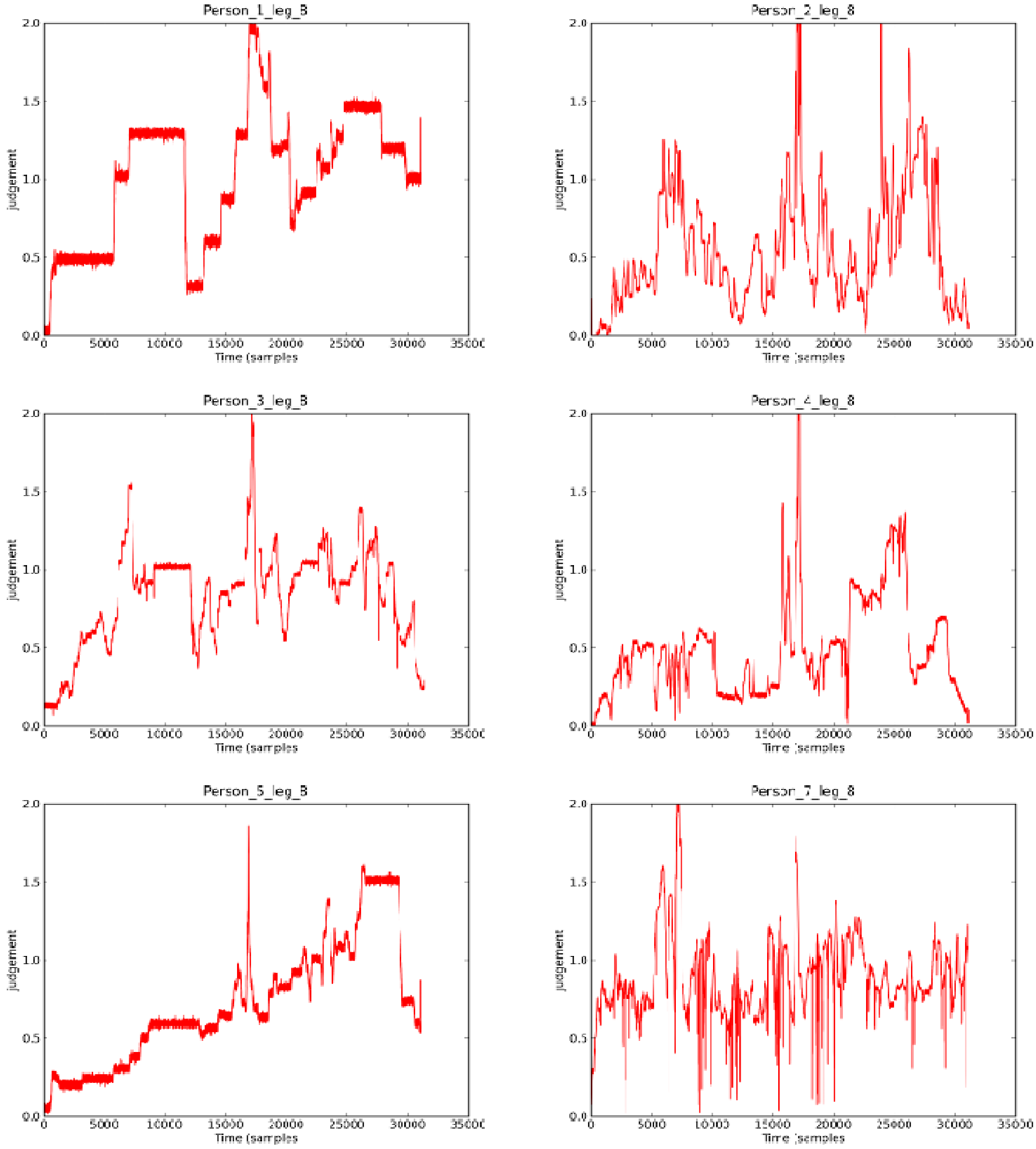

Figure 97. Leg 8 judged by all subjects from the group 1 (subject 6 was not included, because of invalid data).

Based on the legs it was clear that creating optimal windowed data pairs will require different window and overlap sizes for different types of legs or the smallest usable window size should be optimised based on the slowest judgment style. As a conclusion it was noted that the shocks were judged instantly, but the slower the change in the vibration also the more delay was in the judgment response.

The smooth asphalt roads, with and without the speed humps, showed different judgment style than other legs (Table 58). In most cases each subject reacted similarly for each leg, thus clear indication of systematic behaviour was found. The judgments for legs 2 and 5 showed no proper judgments and the legs had too low vibration magnitudes in contrast with the other legs.

Table 58. Summary of all legs and evaluated judgment styles.

Leg	Description	Judgment style
1	Three speed humps on a smooth asphalt	Judgment style was primarily instantaneous as background vibration was low
2	Smooth asphalt	Judgment style was cumulative, but judgment level was too low to use in the analysis. I.e. no real change from “no vibration” case
3	Cobblestone road	Judgment style was cumulative with faster response to high shocks
4	Cobblestone road	Judgment style was cumulative with faster response to high shocks
5	Smooth asphalt	Judgment style was cumulative, but judgment level was too low to use in the analysis. I.e. no real change from “no vibration” case
6	Gravel road with potholes	Judgment style was cumulative
7	Gravel road with potholes	Judgment style was cumulative
8	Off road	Judgment style was cumulative
9	Smooth asphalt with speed humps	Judgment style was primarily instantaneous as background vibration was low
10	Gravel	Judgment style was cumulative
11	Highway asphalt at fast speed (110 km/h)	Judgment style was cumulative

9.4.3 Best setup and data

9.4.3.1 Best window and overlap size and delay for vibration and judgment data

Because of a large number of different scenarios and setups, it was not feasible to analyse and evaluate all combinations. Thus Scenario 2 (seat translational axes with 1.4 multiplying factors for horizontal axes) was chosen for evaluating which setup was the best for the analysis. Scenario 2 was chosen as it had the best average correlation of the standard scenarios.

Data from two subjects (3 and 14) from groups 1 and 2 are shown as an example of visual evaluation (Figure 98 and Figure 99). Both subjects showed that clustering of the data did not become significantly better after setup 4. Correlation of subject 3 did not show any improvement using a delay, but subject 14 did have a small systematic improvement with the delay. However, a visual evaluation showed that no practical difference in clustering was noted with and without the delay for both subjects. Based on the visual evaluation, it was concluded that setup 4b (window size 20 seconds, overlap window 10 seconds, delay 2,5 seconds) would be the best option to conduct analyses of correlation, as an inherent delay was noted also by the previous studies. Even though setups 5a and 5b showed the best correlation values they had too few samples for good confidence levels.

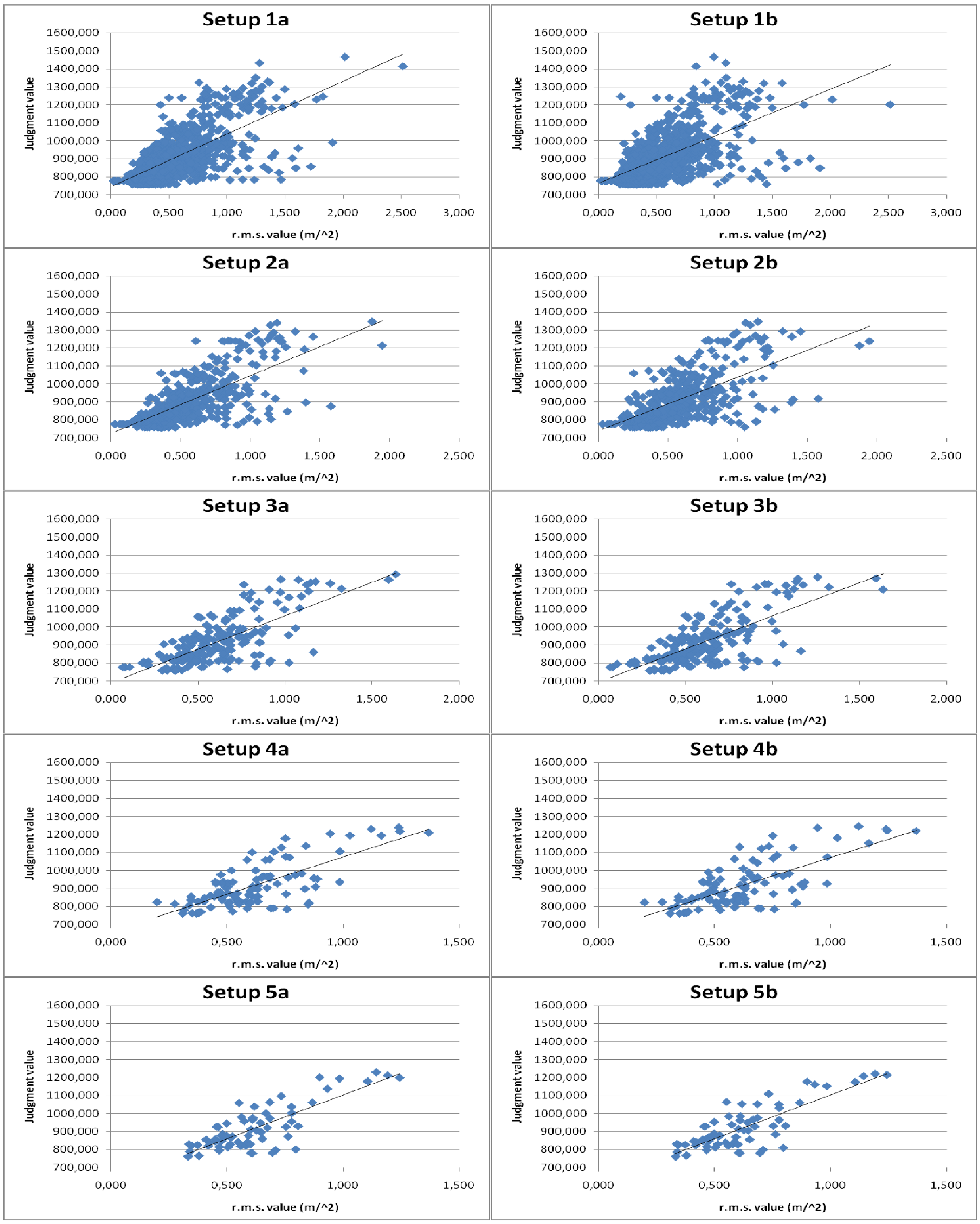

Figure 98. Correlation (Spearman r^2) of different setups to a standard scenario 2 (the seat translational axes with 1.4 multiplying factors for the horizontal axes) for subject 3. Setups are explained in Table 56.

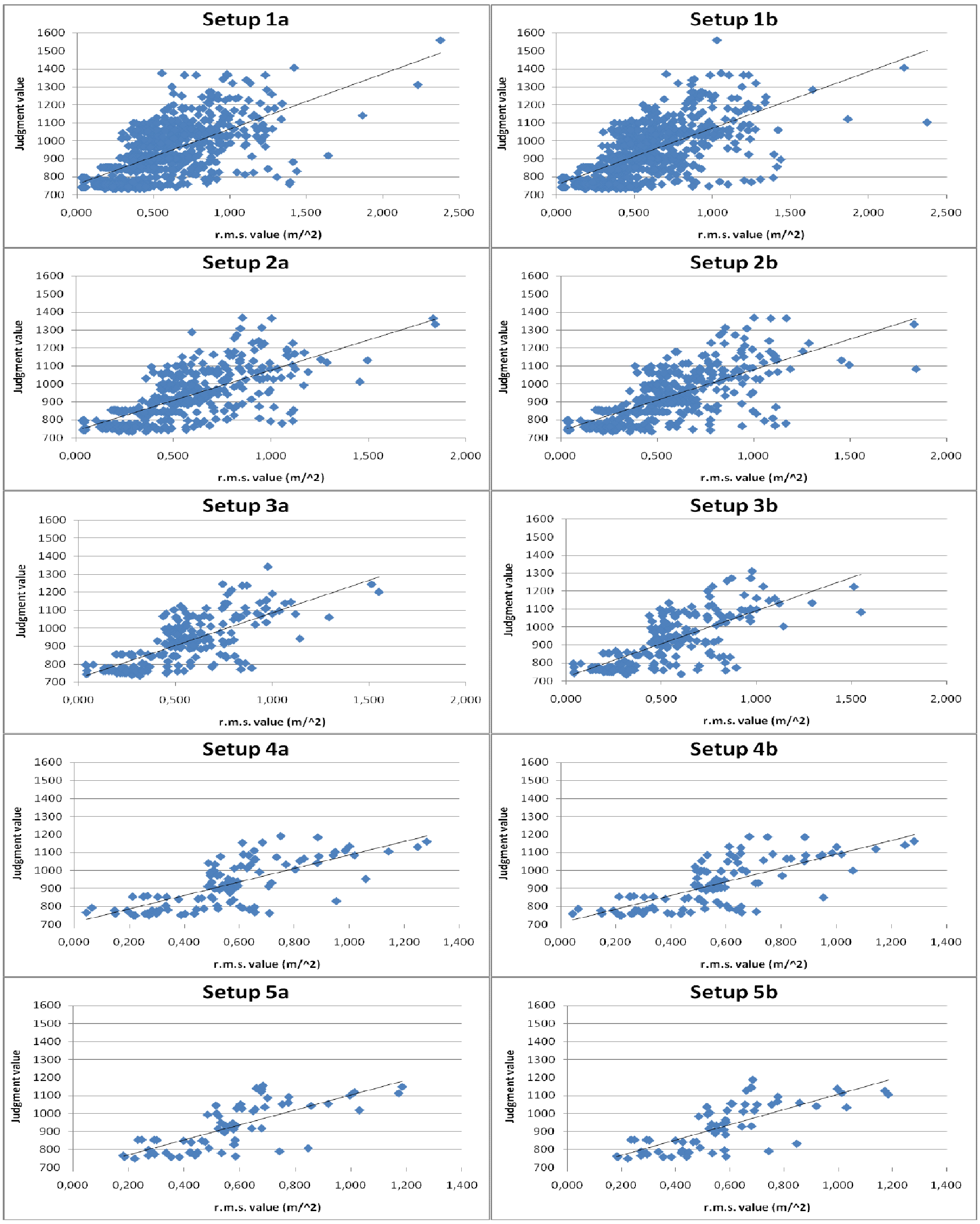

Figure 99. Correlation (Spearman r^2) of different setups to a standard scenario 2 (the seat translational axes with 1.4 multiplying factors for the horizontal axes) for subject 14 (group 2). Setups are explained in Table 56.

Similar analysis was made for all subjects using the Spearman method (Table 59 and Figure 100). The results show that the best setup (i.e. best correlation) varied for the subjects. No systematic improvement was found using the delay, and it was noted that although larger window sizes had higher correlation on average, not all subjects showed improvement with a larger averaging window.

Analysing differences in more detail showed that in practice the correlation did not systematically improve from setup 1a to 4b (W=-45, Z=-1.05 and p=0.294). A low statistical difference was found between setup 1a and 5b (W=-80, Z=-1.88 and p=0.060). Statistical differences between delays were noted only for setups 4 (W=-101, Z=-2.38 and p=0.017) and 5 (W=-120, Z=-3.09 and p=0.002), which confirmed that setup 4b would be the best compromise.

Table 59. Correlation (Spearman r^2) for all setups for each subject using standard scenario 2 (the seat translational axes with 1.4 multiplying factors for the horizontal axes). Group 3 had subjects also from the previous groups 1 and 2.

		Setups									
Subject	**Group**	**1a**	**1b**	**2a**	**2b**	**3a**	**3b**	**4a**	**4b**	**5a**	**5b**
1	1	0.294	0.319	0.313	0.340	0.288	0.327	0.325	0.332	0.317	0.350
2	1	0.413	0.374	0.428	0.424	0.370	0.374	0.317	0.313	0.269	0.267
3	1	0.469	0.395	0.467	0.391	0.449	0.438	0.383	0.359	0.409	0.422
4	1	0.408	0.373	0.386	0.393	0.293	0.309	0.227	0.245	0.196	0.203
5	1	0.077	0.082	0.064	0.074	0.046	0.053	0.038	0.050	0.035	0.054
7	1	0.349	0.330	0.345	0.340	0.313	0.321	0.351	0.353	0.346	0.337
9	2	0.295	0.256	0.342	0.307	0.355	0.347	0.344	0.352	0.357	0.380
10	2	0.182	0.219	0.206	0.235	0.229	0.259	0.209	0.230	0.182	0.209
11	2	0.387	0.427	0.394	0.434	0.392	0.420	0.380	0.405	0.421	0.434
12	2	0.574	0.465	0.601	0.524	0.568	0.531	0.511	0.514	0.528	0.544
13	2	0.437	0.399	0.459	0.439	0.466	0.457	0.457	0.478	0.533	0.548
14	2	0.458	0.484	0.500	0.507	0.496	0.499	0.518	0.526	0.584	0.597
15	2	0.341	0.331	0.361	0.360	0.373	0.384	0.394	0.397	0.434	0.448
16	3	0.489	0.496	0.520	0.529	0.546	0.554	0.607	0.599	0.619	0.619
17	3	0.269	0.322	0.277	0.330	0.298	0.336	0.342	0.374	0.424	0.441
11	3	0.517	0.588	0.548	0.602	0.585	0.602	0.606	0.617	0.644	0.651
5	3	0.320	0.342	0.349	0.368	0.360	0.384	0.396	0.412	0.439	0.468
13	3	0.499	0.457	0.518	0.502	0.523	0.529	0.551	0.562	0.629	0.646
14	3	0.557	0.549	0.599	0.605	0.613	0.634	0.667	0.679	0.695	0.694

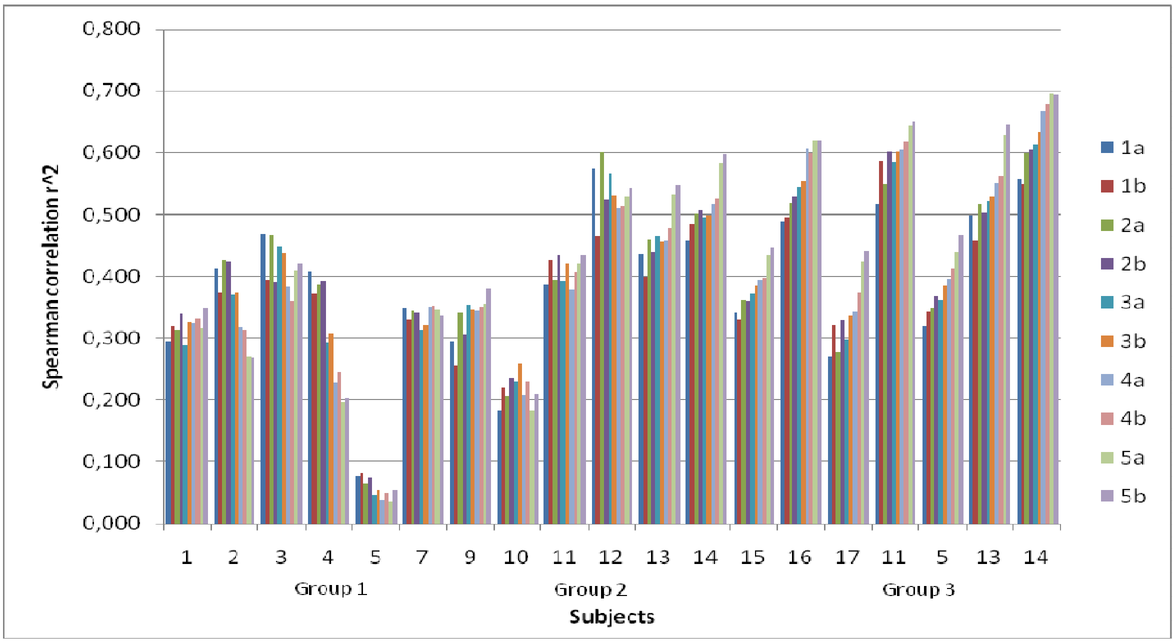

Figure 100. Correlation (Spearman r^2) for all setups for each subjects using standard scenario 2 (seat translational axes with 1.4 multiplying factors for horizontal axes).

9.4.4 Valid subjects and legs for correlation analysis

Based on the evaluation of the correlation of the subjects and the previous evaluation of the legs it was decided that some of the legs and subjects should not be used in the analysis. The legs with mainly smooth asphalt at low speeds were discarded as the subjects did not respond to the vibration level at all (legs 2 and 5). There was no data from one subject due to a technical problem (6), and additionally subjects 5 (judgment in group 1) and 10 (group 2) showed a judgment style, which were different from the other subjects. This was confirmed when calculating the correlation (Table 59).

9.4.5 Normalising judgment data for comparison of subjects and groups

9.4.5.1 Each subject

The judgment data of the subjects were not normalised for calculating correlation for individual subjects, as it did not have any effect on the results (Figure 101). The averaging window size (20 seconds with 10 second overlap and 2.5 second delay) attenuated single peaks, which improved correlation to the vibration (i.e. removed outliers) and comparison between the different judgment styles.

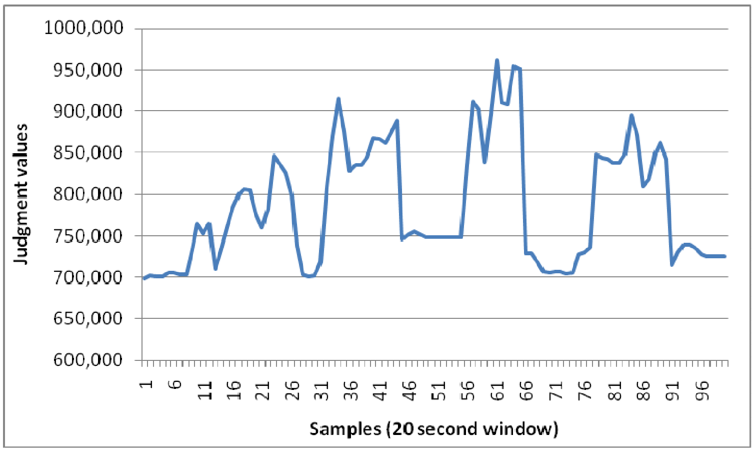

Figure 101. The judgment data averaged using setup 4b (20 second window, 10 second overlap and 2.5 second delay) for the whole route for subject 1.

9.4.5.2 Each group

For comparing the correlation of the groups a normalisation of the judgment data was required for the subjects before averaging was possible (Figure 102). The normalisation was done for each subject using the averaged data from setup 4a. Mean values were calculated from the judgments of all subjects for each group.

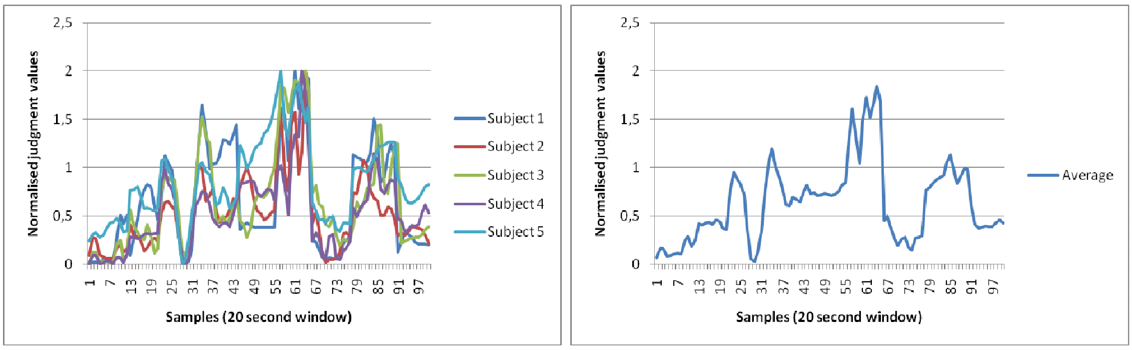

Figure 102. Normalised judgment values of all subjects from group 1 (left) and an averaged judgment value of the group (right) for setup 4b (20 second window, 10 second overlap and 2.5 second delay).

9.4.6 Correlation between vibration magnitudes and discomfort

9.4.6.1 Best standard scenario

The best standard scenario averaged from the correlations of all subjects, using setup 4b, was Scenario 2 (seat translational axes with 1.4 multiplying factors for horizontal axes) although Scenario 1 had practically the same averaged correlation (p=0.682) (Table 60). Even though Scenario 4 had lower averaged correlation, it was the highest for six subjects from groups 1 and 2, and was not statistically different from Scenario 2 (p=0.294). Scenario 3 had lowest correlation from the standard scenarios (compared to Scenario 2: p<0.001).

Table 60. Correlation (Spearman r^2) for all scenarios for each subject. Group 3 had subjects also from previous groups.

		OVTV Scenarios (m/s^2)				
Subject	**Group**	**Sc 8**	**Sc 1**	**Sc 2**	**Sc 3**	**Sc 4**
1	1	0.325	0.257	0.325	0.239	0.244
2	1	0.232	0.313	0.317	0.225	0.284
3	1	0.319	0.365	0.383	0.287	0.342
4	1	0.131	0.244	0.227	0.175	0.242
7	1	0.176	0.400	0.351	0.314	0.411
9	2	0.337	0.331	0.344	0.328	0.330
11	2	0.267	0.413	0.380	0.339	0.429
12	2	0.430	0.509	0.511	0.440	0.477
13	2	0.386	0.434	0.457	0.387	0.494
14	2	0.374	0.531	0.518	0.377	0.476
15	2	0.288	0.426	0.394	0.362	0.437
16	3	0.499	0.606	0.607	0.543	0.590
17	3	0.333	0.290	0.342	0.247	0.258
11	3	0.489	0.589	0.606	0.440	0.509
5	3	0.328	0.400	0.396	0.370	0.388
13	3	0.524	0.504	0.551	0.296	0.347
14	3	0.549	0.706	0.667	0.639	0.703
Average		**0.324**	**0.400**	**0.401**	**0.329**	**0.388**

Correlations for each group showed the same results, where Scenarios 1, 2 and 4 were better than Scenario 3 (Table 61). It is notable that groups 1 and 2 had very similar correlation, although they were driven in reversed order, and group 3 had systematically better correlation. Group 3 did include four subjects from the previous groups. The results were systematic for all groups.

Table 61. Correlation (Spearman r^2) for all scenarios for each group

	OVTV Scenarios (m/s^2)				
Group	**Sc 8**	**Sc 1**	**Sc 2**	**Sc 3**	**Sc 4**
1	0.386	0.554	0.553	0.464	0.534
2	0.398	0.522	0.504	0.451	0.551
3	0.652	0.788	0.766	0.678	0.756
Average	**0.479**	**0.621**	**0.608**	**0.531**	**0.614**

9.4.6.2 Optimised multiplying factors from the laboratory trial

For the field data it was noted that Scenario 8 (best multiplying factors found in the laboratory trial) did not produce any better correlation than the standard scenarios (Table 61 above). In fact the correlation was systematically worse than the best standard Scenario 2 ($p<0.001$). Scenario 8 was also worse for each group (Table 61).

9.4.6.3 New multiplying factors

New multiplying factors were calculated for each subject separately (Table 62) and for each group (Table 63) using setup 4b data. The multiplying factors were optimised using the brute force method with the same principals as in Chapter 8.

The multiplying factors from the subjects showed clear consistency of the seat lateral axis being the most dominant for the discomfort judgment. Even though Subject 17 showed different levels of values, the same trend was evident for all subjects. The seat fore-and-aft had little or no correlation to the judgment compared to the lateral axis. All subjects showed better correlation with the optimised factors than with any previous scenarios. Compared with Scenario 2 the Wilcoxon test showed also statistical difference ($p<0.001$).

Table 62. Optimised multiplying factors and correlation (Spearman) for each subject using the brute force method. Subjects 5 and 6 from group 1, and 10 from group 2 were dismissed from the analyses.

				Multiplying factors for the Frequency weighted r.m.s. values for the seat		
Subject	**Group**	r^2	**p**	**x**	**y**	**z**
1	1	0.659	<0.001	0.0	6.6	1.0
2	1	0.598	<0.001	0.0	11.4	1.0
3	1	0.593	<0.001	0.0	4.4	1.0
4	1	0.459	<0.001	0.0	8.0	1.0
7	1	0.501	<0.001	0.0	1.4	1.0
9	2	0.353	<0.001	0.8	1.8	1.0
11	2	0.545	<0.001	0.2	3.8	1.0
12	2	0.736	<0.001	0.0	3.4	1.0
13	2	0.600	<0.001	0.0	3.8	1.0
14	2	0.656	<0.001	0.0	2.2	1.0
15	2	0.514	<0.001	0.0	2.0	1.0
16	3	0.687	<0.001	0.0	2.8	1.0
17	3	0.611	<0.001	7.2	33.0	1.0
11	3	0.705	<0.001	0.0	2.2	1.0
5	3	0.476	<0.001	0.0	2.4	1.0
13	3	0.646	<0.001	0.0	2.8	1.0
14	3	0.761	<0.001	0.0	1.2	1.0
Average		**0.553**	**<0.001**	**0.1**	**8.6**	**1.0**
Median		**0.600**	**<0.001**	**0.1**	**2.8**	**1.0**

The optimised multiplying factors for each group were similar (Table 63). Again the lateral axis was clearly dominant and the fore-and-aft axis had practically no correlation to the judgments. Group 3 had the highest correlation, which can be linked to having the subjects from the previous groups, which all improved the correlation from their first run.

Table 63. Optimised multiplying factors and correlation (Spearman) for each group using the brute force method.

			Multiplying factors for the frequency weighted r.m.s. values for the seat		
Group	r^2	**p**	**x**	**Y**	**z**
1	0.686	<0.001	0.0	2.0	1.0
2	0.606	<0.001	0.2	2.0	1.0
3	0.846	<0.001	0.0	1.6	1.0
Average	**0.713**	**<0.001**	**0.1**	**1.9**	**1.0**

9.4.6.4 Clustering of the factors

A visual inspection of the correlation of the data points showed linear and positive trend (Figure 103). It was evident that a correlation existed between vibration and judgments for all groups, although Group 2 had somewhat worse agreement than groups 1 and 3.

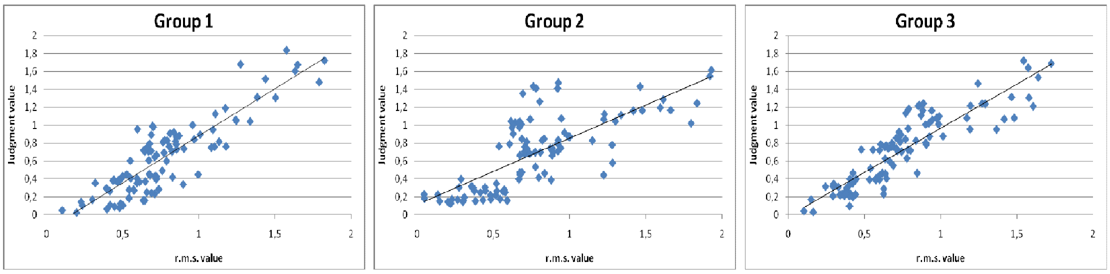

Figure 103. Clustering of data points using new multiplying factors of each group using setup 4a data.

Contour maps show that clustering of factors was similar for groups 1 and 3, while group 2 had a wider range of combinations (Figure 104). All three maps show that a small or zero value for the seat fore-and-aft axis gave the best correlation (i.e. the lateral axis should have clearly larger multiplying factors than the fore-and-aft axis).

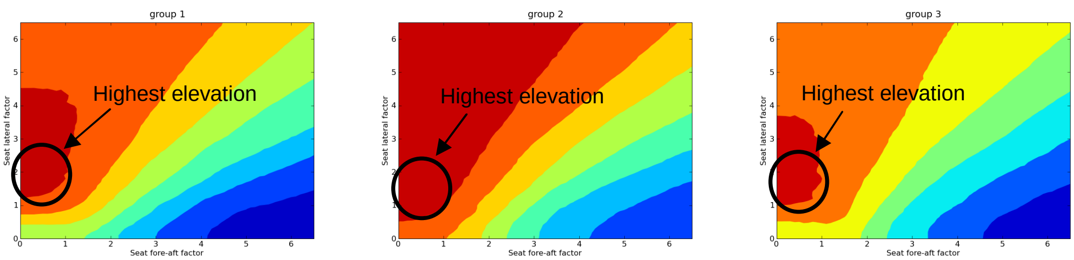

Figure 104. Clustering of multiplying factors for seat horizontal axes (multiplying factor vertical axis is 1.0) for the three groups using a contour map.

9.5 Discussion

The previous results indicated that the multiplying factors of the standard are not optimal for evaluating discomfort from whole-body vibration. A new set of multiplying factors were found to improve correlation in the laboratory trial (Chapter 8). Rarely have results from a laboratory trial of this type been validated in a field. The purpose of this field trial was to validate the standard and the results from the laboratory trial. Similar to the laboratory study, calculation of new multiplying factors were considered the best way to optimise the correlation and evaluate emphasis of axes.

The frequency weighting and r.m.s. averaging was chosen as the methods for producing the vibration magnitudes, because they showed improved results in the laboratory trial and they are required by the standard. Additionally the only reference study conducted in a field (Parsons and Griffin 1983) concluded them to be the best option as well.

9.5.1 Vibration magnitudes and frequency characteristics of the legs

The chosen legs showed typical vibration magnitudes of Finnish roads. The speed humps and pot holes increased amplitudes in the asphalt and gravel roads, while the cobblestone road showed high vibration magnitudes throughout the leg. Each leg was driven in similar conditions for all groups, even though one group was driven 8 months later than the others. No legs with only smooth asphalt were used in the analyses, as they were noted to have too low threshold for any changes in discomfort.

Typical for a car environment, the vertical axis was dominant for all surface types. The vibration magnitudes for the fore-and-aft and lateral axes were similar. The standard deviation between the seat locations was small and systematic (i.e. higher magnitudes showed higher standard deviation). Thus a very good correlation was found between the seat locations. Asphalt roads without speeds humps will produce low vibration magnitudes (less than 0.3 m/s^2), but the speeds humps will clearly increase the r.m.s. values up to 0.6 m/s^2.

The legs were divided into five surface types for analysis of the vibration characteristics. Because of the standard frequency weightings, there were no significant differences in the frequency characteristics of the different surfaces. All legs showed dominant frequencies below 2 Hz when the weighting was applied. This implies that the role of the surface type (i.e. frequency characteristics) only have effects below 10 Hz.

9.5.2 The effect of the additional axes

Based on the analysis the contribution of the seat rotational and floor translational axes were considered small, thus they were not included in the evaluation of the correlation. To simplify the measurements even more the effect of the backrest axes were evaluated. Because of the high correlation to the seat axes, it was assumed that the seat axes alone can be used to find multiplying factors for the optimum correlation. This was based on the results in the laboratory trial (Chapter 8). This simplified the measurements as the location of the sensors can cause errors, especially for the additional axes. It is simpler to use the multiplying factors for the seat lateral axes to compensate the effects of the additional axes.

9.5.3 Analysing different judgment styles and averaging the response

The method of continuous judgment has been used in noise research (Kuwano and Namba 1985), which was used as a reference. However, in evaluating the annoyance of noise only one parameter is considered, usually weighted A-value, thus the correlation evaluation is more straight forward. Evaluating correlation to vibration is more complex as several axes are included (three at minimum) and number of different combinations are possible. This emphasises the need for simplifying the method so that the analysis procedure is not too complex.

Based on the noise references, a 2.5 second averaging with 1 second delay was found the best when analysing correlation. It was previously indicated that a reaction to vibration will have at least 2 second delay (Chapter 6). Thus a 2.5 second reaction delay was chosen to be tested. The results showed that the delay had marginal and inconsistent effect for setups using a shorter window (less than 20 seconds). It improved correlation for setups with 20 and 30 second windows (4 and 5). Setup 4b (20 second window, 10 second overlap and 2.5 second delay) was used as it was a good compromise of reasonable number of data samples and the correlation, and to minimise differences in the judgment styles.

Response to vibration was noted slower when a leg did not show any sudden shocks. The speed humps caused instantaneous change in the judgment, but in most cases the response was between 2 and 10 seconds. This indicated that the data should be calculated using a large enough window size, and overlapping windows. Detailed analysis of each subject’s judgment data showed that some subjects had inconsistent judgment style, thus influencing the results. This was noted for two subjects (5 and 10).

For each individual subject the judgment data was not normalised as a ranking method was used for finding the correlation. However, when the correlation for each group was calculated, a normalisation had to be done. There are no specific rules for this, but it was reasonable to use each subject's judgment from the whole route for normalising it to between 0.0 and 2.0. Now all judgments from each subjects and group were able to be averaged. There was a clear trend for all subjects, but it was still difficult to find a good match for all subjects. However, as the correlation results from each group showed similar trend compared to other groups and each subject separately, a confidence in the method for using the judgment data was good.

It is clear that if using longer exposures in trials then guidance to the subjects on how to evaluate discomfort is important. This requires more training than in laboratory trials. Also it should be accepted that in a field the judgments and results in general will have more errors, and it is important to analyse how to minimise the outliers so that they do not skew the results, and thus conclusions. Averaging the continuous judgment data correctly is an important factor.

9.5.4 Correlation between vibration magnitudes and discomfort

Several scenarios had to be tested as there were no references for continuous judgements of discomfort and linking this to vibration. The scenarios used in the study can be divided in to three categories: 1) scenarios based on the standard guidance, 2) scenarios based on the optimised multiplying factors in the laboratory trial (Chapter 8) and 3) scenarios based on the new optimised multiplying factors in this field trial.

It was found that using the standard guidance Scenario 2 produced best correlation, but only Scenario 3, from the four standard scenarios, produced statistically worse correlation. Scenario 8, which was based on the multiplying factors from the laboratory trial showed similar correlation to Scenario 3, and was also statistically worse than Scenarios 1, 2 and 4. However, the scenario using the new optimised multiplying factors from the field data showed significantly improved correlation compared to any other scenario. The results were systematic for individual subjects and for all groups.

A good correlation (r^2 > 0.5) was found for the most subjects (14 out of 17) when using the new multiplying factors. The correlation using the best standard scenario showed good correlation for only 2 out of 17 subjects. Even though there was a variation amongst subjects, the improvement in the correlation was systematic. A significant improvement was noted also for all groups. The results from the groups showed the same systematic behavior as the individual subjects.

Group 3 included subjects from both groups 1 and 2, and two new subjects. Comparing correlation and judgment of the subjects, which had been exposed to the trial before, even though 8 months apart, the correlation improved in all cases. This was noted for all scenarios. It might be that exposing subjects to training beforehand will improve their ability to judge the data. This has been noted in another study as well (Van der Westhuizen and Van Niekerk 2006).

The reasons for the results of the different scenarios is based on one factor: the multiplying factors of the fore-and-aft axes (the seat and the backrest). Where more emphasis to the fore-and-aft axes was seen, there was worse correlation. This was evident when the new multiplying factors from the field data was derived, which showed zero or close to zero values for the fore-and-aft axes for the best correlation. This was also the reason why the scenario using the multiplying factors from the laboratory trial did not work, as it had high emphasis for the fore-and-aft axis (2.7). The visual analyses of the clustering of the factors confirmed that the highest elevation for the correlation was near zero for the fore-and-aft factor. This was similar for all groups.

The factors found in the laboratory trial suggested higher emphasis of the seat lateral axis, but no emphasis on the fore-and-aft axis. Thus for some reason the subjects did not respond systematically to the fore-and-aft motion. A simple reason for this was not found, but the most likely cause for this is that in a car the fore-and-aft axis is more present when accelerating and braking or going over the speed humps, where the lateral and vertical axes are present more consistently.

9.5.5 Can discomfort be predicted practically using the standard or an optimised method

Because of the implicit guidance of the standard a measurer would most likely use Scenario 1 as a method for predicting discomfort. In this case none of the standard scenarios would give good results, but Scenario 1 and 2 were the best options. The reason was that because of the emphasis of the lateral axis compared to the fore-and-aft axis, and both scenarios emphasise both axes the same. However, there was a possibility to greatly increase the correlation if more adjustable method was used (i.e. the optimisation of the multiplying factors).

The results were not systematic with the findings of the laboratory trial, which suggests that the emphasis of the axes will change depending on the environment and the vibration characteristics. For example in some environments there are no noticeable fore-and-aft vibration, thus the correlation to the axis will most likely show inconsistent results. However, the standard method implies that a fixed set of multiplying factors should work in different environments. This might give a wrong conclusion of discomfort in some environments. It is likely that a underlying factor has causality to discomfort, which is not directly shown in the judgments. This limits the usability of the method to assessing changes in environments which have similar characteristics (e.g. noise and temperature).

Because there are strong indications that no fixed set of multiplying factors work for all environments a guidance on how to measure and calculate new multiplying factors should be given with the technical information. The method of continuous judgment would be a good candidate as well as using the brute force technique as it is the most robust method for finding the best combination of factors.

9.5.6 Recommended methods to evaluate discomfort from whole-body vibration in field

Field environment generates many distractions (i.e. confounding factors), which are not present in a laboratory. It is also harder to control the circumstances, as statistical reliability is lower. Thus the method should be robust and simple enough to work also in the field and give possibility for reasonable statistical reliability and comparability of results.

9.5.6.1 What worked

The chosen method of continuous judgment was concluded to work well both in the laboratory and in the field. It is designed to allow judgement of longer exposures than a few seconds, and it captures the changes of judgment in great detail. It is important to guide subjects for judging the vibration correctly. Based on the developed equipment it was considered rather simple to acquire both vibration and judgment data from multiple subjects simultaneously. The subjects were given short instructions and the route was chosen from the local roads. The measurements took about an hour for each group.

Vibration magnitudes were relatively easy to measure from the seat and backrest locations. Additionally it was noted, that also the 12-axis vibration can be measured in a field with proper equipment. So it is possible to measure all axes in the field in practice.

Exposure durations up to 2 minutes were accepted by the subjects and the concentration was consistent throughout the measurement. However, not much longer exposures are possible, if the subjects have to focus on the vibration constantly.

Spearman rho and Kendall’s tau are proven methods for assessing correlation where normal distribution cannot be assumed. Both methods showed consistent results and are easy to calculate with modern software programs.

9.5.6.2 What did not work

Some subjects will always not judge vibration “correctly”, thus will produce results that are not in line with the other subjects. This requires manual inspection at this point (until an algorithm is developed to automatically remove subjects). The method of continuous judgment allows several judgment styles for the subjects, even though guidance is given. This was evident in the judgment analyses (see Figure 95). It is important to analyse how different judgment styles affect the correlation, as this helps to improve the method in field.

Shorter gaps between the legs are recommended as some of the durations in this trial were up to 10 minutes and it was possible that concentration levels dropped during the final trials.

The route and legs should be considered carefully. In this trial some of the legs were in a city center, thus traffic did influence the stimulus, thus creating differences between the groups. Also exposure to low vibration magnitudes will show inconsistent judgments, thus all surfaces should include at least medium vibration magnitudes (e.g. from 0.3 to 0.6 m/s^2).

9.5.7 Limitations of the results and model

The study covered only one car type with the same legs for each group. Different legs or seats might produce differing results. This has been also noted previously (Griffin 2007). Also the driving style could cause differences, although a same driver was used for all groups in the study. The stimuli were limited to the characteristics of normal Finnish road conditions, thus not directly applicable to all work machine environments. Also the seat was a conventional car seat with rigid body frame, thus not having any suspension system (other than the seat cushion) between the seat and floor. Most work machines have low frequency seat damping, which causes floor motion to be significantly different than the seat or backrest motion.

Based on the earlier assumptions, only the seat and backrest translational axes were measured from each subject, but additionally all twelve axes from the driver were measured to verify the assumptions. The limitation of number of axes was also necessary to allow simultaneous measurements of several subjects. Because of a small number of data, it is still suggested that more 12-axis data is measured and possibly similar measurements analyses in this trial would be repeated for using all axes.

Even though the subjects from each group were exposed simultaneously, the vibration magnitudes were different depending on the seat location. Closer to the axles (front and back) the vibration was higher than in the middle of the car. This was a problem when averaging the judgment values as also the vibration magnitudes from all subjects needed to be averaged. As the correlation method (Spearman) is a ranking method and because of the high correlation of the vibration between the seat locations, it was possible to use the vibration data from one subject for comparison to an averaged judgment value of a group.

The method of continuous judgment has no absolute scaling, thus each subject had their own discomfort range. Because of relative long exposure durations (up to 2 minutes) and duration between legs (up to 10 minutes), the subjects might have forgotten their scaling. However, this was not found to be significant, as correlations for each subject was similar to that for the group.

The test subjects acted as passengers, thus the results cannot be directly used to predict discomfort of the operator/driver. The operator's discomfort can be affected also by the complexity of the task and the work motivation (McLeod and Griffin 1993).

Because of the nature of the trial, noise and other factors could not be controlled. Thus the judgments do include the effect of the other factors. However, as the test route and the legs were same for all subjects, and the other factors remained somewhat constant, the correlation between changes in the vibration characteristics and the discomfort could be evaluated. There were some disturbances during the measurements as some of the legs were in Oulu downtown and traffic changed the experiment. However, as seven subjects were exposed to exactly the same circumstances there was enough statistical data for the analysis.

9.5.8 Further work

The standard method has fixed multiplying factors for all axes without regarding specific characteristics of the different environments. The factors define the emphasis of each axis when calculating OVTV and should improve correlation compared not using the multiplying factors. However, the results in this thesis has shown that consistently multiplying the factors of the additional axes have degraded the correlation.

It is not likely that a fixed set of multiplying factors would work best for all environments, thus a subset of factors for specific environments should be calculated. The results in this trial showed that the optimised multiplying factors could be used to predict discomfort of subjects exposed to similar vibration characteristics. Further trials are needed to evaluate how the optimimum multiplying factors change to conclude more general trend.

This was a first study to acquire both vibration and judgment data in a field using the continuous judgment, cross-modal matching method. Further trials need to be conducted in different environments and surfaces to conclude, if multiplying factors will change depending on the environment, or is there consistency in field. Also this type of study should be conducted for measuring all twelve axes from each subject, although it has been concluded that the effects of the additional axes can be overcome.

The results were not in line with the laboratory study in Chapter 8, where fore-and-aft axis was concluded to be the most significant. The standard method can be used to predict discomfort in a field if optimised multiplying factors are generated to each specific environment. The multiplying factors in the standard have been derived based on comfort contours found using single-axis sinusoidal exposures. Even though this is the most fundamental approach, the results in this thesis have shown that in a multi-axis environment the factors are not optimal. This might be because of several reasons, thus a systematic research in a multi-axis environment using sinusoidal, random and field-like stimuli is necessary.

9.6 Conclusions

A field study was made where both vibration and judgment data was gathered simultaneously from groups of subjects. The conclusions were:

- Systematic trend of the correlation of the individual subjects and the groups were found using the frequency weighted r.m.s. values;
- Significant improvement to the correlations using the standard guidance were achieved using the multiplying factors optimised based on the field data;
    - Higher emphasis to the lateral axis and lower emphasis to the fore-and-aft was noted compared to the findings in the laboratory trial (Chapter 8);
- The results using the new multiplying factors improved correlation systematically for all subjects and groups.

Based on the results of the laboratory and field trials several suggestions for improving the standard method have been found. The complexity of the 12 axis measurements have not been proven to give any practical improvement compared to using just seat translational axes. The effects of the seat rotational and floor translational axes will be small due to the weighting of the acceleration data and the axes. The high correlation of the backrest axes to the seat axes in this type of seat structure will allow using just the seat axes to evaluate discomfort.

10 Chapter 10: General discussion

10.1 Introduction

Exposure to vibration is an intrinsic part of our lives. The modern society is based on moving around using cars, trains, ships, airplanes, etc. The last century has seen an unprecedented growth in travelling. It is very hard to think of a situation or an environment where there is no need to use any means of transport. There is almost no place on earth, where a some form of a machine is not used for transporting people.

Practically all types of transport will cause vibration to a human body. In some cases the vibration affects the human body so that permanent health effects are possible, but luckily in most cases the vibration mainly causes discomfort. However, even low vibration degrades work performance and hinders concentration. More and more people also work while travelling, thus it is important to understand how to reduce vibration in the most effective way.

The effects of vibration to humans can be assessed either subjectively or objectively. Even though comments of a test subject give first-hand information on ride quality, it requires resources and time to arrange tests and understanding of the factors (e.g. physical size, background, motivation, etc) relating to the judgment. Thus, there is a need for an objective method. An objective method can be used to predict the effects in the field, a laboratory or a virtual world. A problem with an objective method is that it is always limited by the methods, which have been used to develop it. It is thus important to understand the background and assumptions of the objective method.

The international research community has acknowledged the importance in understanding the effects of vibration by producing research results and several standard versions. Many researchers use the standard methods or their own version based on the standards to assess the effects on passengers and drivers in different situations. However, since the early 1980’s no new method or any improvements to the standard method have been proposed. For reasons unknown research on understanding the effects of vibration on discomfort has been relatively small since 1986.

10.2 Benefits of understanding discomfort from vibration exposure

Discomfort is becoming more important to manufacturers of machines and vehicles, as the acute health effects have been minimised. The work performance and comfort of passengers can be improved, if the factors affecting the discomfort are known. There is a growing number of people travelling for business and to work, and modern computers have allowed working while travelling. Even small vibration magnitudes can hinder e.g. reading and writing, thus reducing work performance. Currently, based on a perceived lack of proven methods for assessing discomfort objectively, vehicle manufacturers rely mostly on subjective questionnaires and methods, which have not been scientifically proven (Kolich 2008). Thus the data has been difficult to compare and interpret. An objective method will improve, systemise, accelerate and simplify the seat comfort assessment through the development and manufacturing process.

10.3 Problems relating to the current ISO 2631-1 standard

The background behind the ISO 2631-1 (1997) standard method is from the studies conducted in 1970's and early 1980's. The method as a whole was first introduced in 1986 in a SAE paper (Griffin 1986). It also became a British standard in 1987 (BS 6841). The method includes several parts, which translate vibration characteristics to a value, which can be used to assess human reaction: 1) frequency weighting of acceleration of each axis, 2) averaging the acceleration to a single value for each axis, 3) multiplying each axis by a factor and 4) combining the values of the axes to a single value.

Before the BS 6841 standard, the previous standard methods were different and not proven to be effective in practice (Wikstroem, et al 1991). There was very little field validation on the methods. Even though the method in BS 6841 was shown to be superior to the previous methods, it took ten years before a new version of ISO 2631 was agreed. It has been noted in publications that the reasons were more political than methodical (Griffin 1998, Griffin 2007).

Even though the standard method is over 20 years old, there is very little understanding of the practical accuracy of predicting discomfort from whole-body vibration exposure. There are only few studies which have used the method to evaluate discomfort and even fewer that have validated or tested different interpretations of the method. Most validation and effort has been concentrated on the comfort contours, which have been typically studied in a laboratory environment using discrete sinusoidal stimuli, and typically in a single-axis. Other parts of the standard (i.e. multiplying factors and averaging method) have had less validation. The few studies that were found regarding the averaging methods showed inconclusive results, thus it is still not clear whether the r.m.s. or VDV method should be prioritised. Also the studies have been limited to specific environments, thus not allowing generalisation of the results. Only one study was found to suggest higher multiplying factors for the seat horizontal axes (Maeda and Mansfield 2006b), but no study was found, that had analysed the same for all twelve axes.

The problems regarding the standard method relate more to the lack of information rather than the presence of a better method. There is little information on how to select the significant axes for each environment. The standard allows the use of a number of different combinations, without giving any guidance on how to choose the proper one. This may be one reason why so few studies have used all twelve axes. Another reason is that measuring the twelve axes is technically so complex, that few have conducted any in the field. Even if all axes were measured, the standard does not provide practical information to assess the discomfort. Only a very crude table is given in the standard, which is based only on limited data and has overlapping categories without any detailed explanation.

Another interesting issue, which has not been discussed in other publications, is that the size of OVTV is based on how many axes are included. Thus, OVTV will be smaller if less axes are used, and based on the standard, the discomfort will be less. Of course, the other axes do still exist and influence discomfort, but the method does not have any way of compensating the missing axes from the assessment. An analysis in Chapter 5 suggested compensating factors for each missing PVTV for producing OVTV that would be comparable to OVTVs using different number of axes. It was found that a highly linear correlation existed between PVTVs, thus a single compensating factor, based on different numbers of axes, was produced. It is suggested that this type of information is put in to the standard, so that the results would be more comparable. This is not an issue when relative discomfort is assessed in the same environment, but when absolute discomfort is compared to any kind of table with categories or to other measurements.

10.4 Previous research and results

Most of the relevant studies were conducted between late 1960’s to early 1980’s. The studies were mainly conducted in a laboratory using sinusoidal stimuli focusing on the perception threshold and comfort contours. Most of the relevant studies were conducted in the UK or Japan and by a handful of researchers. The findings led to few publications, which defined and introducted the current standard method (Griffin, et al

1982, Griffin 1986, Parsons and Griffin 1983). Since then very little validation and improvement of the method has been conducted.

Only few studies were found which have discussed or validated the standard method for predicting discomfort from whole-body vibration. No studies were found that used a multi-axis test bench linking judgments from subjects to OVTV. Additionally only a few studies had actually measured and published results from 12-axis field measurements.

Only one study was found that measured twelve axes and discomfort judgment from subjects in the field (Parsons and Griffin 1983). The results from that study showed similar findings to the laboratory and field in this thesis: 1) although high individual variability was found within subjects, a similar trend was noted, 2) there was little difference between r.m.s. and r.m.q. methods, 3) more axes will improve correlation and no single worst axis should be used, and 4) the method can be simplified, but needs further understanding of how twelve axes are presented in field.

The literature review showed few studies which have tested the standard method in a field environment using professional drivers (Fairley 1995, Wikstroem, et al 1991). However, even in those cases there was a fixed test track, which emphasised shocks more than those found in environments typical for passengers. The results might be valid for large machinery, but cannot be directly used in other environments. There are no studies where discomfort has been simultaneously acquired from several passengers in an environment close to public transit.

Based on the literature review, it was concluded that more information is needed on how the twelve axes are present in field environments, what are the effects of the frequency weighting curves and multiplying factors, what is the practical correlation between subjective judgments and vibration magnitudes using different numbers of axes, is there a possibility to improve the standards, and do results in the laboratory and in the field show similar findings.

10.5 Measuring vibration and subjective discomfort

An objective method does not require asking subjects to judge discomfort. However, when evaluating the accuracy and statistical confidence of a method, then subjective judgments should be acquired simultaneously with the vibration magnitudes. This is more straight forward in a laboratory environment, but in the field several challenges are faced. Both vibration and discomfort should be measured simultaneously as the vibration exposure is constantly changing. Also it is much more difficult to observe the subjects and control the environments, thus technical tools have more significance.

10.5.1 Measuring 12-axis vibration

The measurements are instructed to be conducted using acceleration sensors from a seat surface, backrest and floor. Measuring all axes will require sensing both translational and rotational accelerations. The translational axes are simple to measure using 3-axis sensors, but the rotational axes need more complex configuration. Because the standard method and guidance have not required the measurement of all axes, there are very few commercial products available for measuring the rotational axes.

The work in Chapter 4 showed that it is possible to produce affordable and simple sensors for measuring all axes. There is no reason not to measure all axes as the software for conducting the analyses is available and the effort to measure and analyse all axes is not different from using just three axes from the seat surface. The work in this thesis did produce a commercial 12-axis sensor system for conducting the health and discomfort evaluation according to the ISO 2631-1 standard.

Based on the results in Chapter 5 it is highly recommended that more 12-axis data is measured in the field from different machines and work phases. There is still very little information on the contribution of the twelve axes, even though the results in Chapter 5 showed that it is most likely that the seat rotational and floor translational axes will have insignificant effects independent of the machine type or an environment.

10.5.2 Acquiring judgment data

Different methods exist to acquire subjective judgements, while subjects are exposed to vibration. However, there are only a few methods, which are suitable for a field study. The methods discussed in the literature review in Chapter 2 were mainly developed and are used in a laboratory, where a researcher can be present and take notes. In the field it is hard to arrange for another person to take the notes, thus a technical device should be used to allow independent recording of the judgments.

Normally the studies have exposed subjects to short stimuli (up to 10-15 seconds), and one judgment for each stimulus has been recorded. This does not suit well for stimuli, which are longer and represents the vibration found in the field better (i.e. non-stationary and continuous). Only one method was found to suit the plans and goals for this thesis. The continuous judgment method has been specifically developed for acquiring judgments in a continuously changing environment. The method allows researchers to analyse and calculate data, which is based on instantaneous and continuous judgments. The device to allow digital recording of the judgment data simultaneously to the vibration was easy to realise for both laboratory and field environments.

The continuous judgement method has not been used in previous vibration research but it has been validated in noise research. The results in Chapter 6 showed that the method produced data which was systematic and did not require complex analysis. The instructions for the subjects were short and an intuitive judging style was natural. In the field trial (Chapter 9), more challenges for data processing was noted, which related to the uncontrolled environment and long exposure time. However, it was possible to optimise the results for analysing the judgment styles. The experience from this thesis gave confidence in the method for future studies, especially relating to field type environments and long exposures.

10.6 Relative contribution of the twelve axes in the field

The results from the field measurements in Chapter 5 showed, that because of weighting for the rotational and floor axes, their contribution will be marginal in practically all environments. This was evident in the laboratory trial (Chapter 7) as well, even though the rotational axes were over emphasised. In practice, this means that there is no need to measure the rotational and floor axes when calculating OVTV. A small compensating factor (i.e. 1.1) can be used to convert OVTV using the seat and backrest translational axes to match OVTV using all axes, as about 10% difference was noted between the scenarios.

Chapter 5 combined results from two previous studies and the new field measurements. The results included data from ten different machines, where some of them were measured by all studies. Although there were large variations in vibration magnitudes between the machines, they all showed similar trends in the dominant axes and locations. Confidence in generalising the results was high, because all three studies showed similar results, even though different equipment and environments were used.

10.7 Using the standard method to predict discomfort

The literature review in Chapter 2 showed that little information exists on assessing the confidence when using the standard method to predict discomfort. The several different interpretations of the method, and the problems relating to the parts of the method, have not given confidence when using it. Two trials were designed, in the laboratory and field, for producing more information on the accuracy of the standard method.

10.7.1 laboratory trial

Based on the results in Chapters 7 and 8, it can be concluded that a high correlation (Spearman r^2 > 0.8) can be achieved between vibration stimuli and subjective discomfort. Especially predicting the relative change in discomfort is possible, as the results showed systematic behavior for all subjects. No differences were found between men and women (i.e. physical size), thus a conclusion can be made that the relative change in discomfort is more universal to all people than the absolute discomfort.

The use of more axes was shown to improve correlation, but it was evident that the seat translational axes alone will provide as good a correlation as all axes, if proper multiplying factors are used. Even though the rotational axes improved correlation, their effect was marginal, thus not justifying using them in most environments.

10.7.2 field trial

Based on the results in Chapter 9, it is possible to use the standard method with optimised multiplying factors and understand discomfort in a field environment. However, the results should be considered only in the environment where the study has been taken, thus no generalisation is possible (i.e. multiplying factors cannot be the same for all environments). There are so many variables in the field, that the correlation will be weaker than in the laboratory. Still the correlation for each group of people was found to be adequate (Spearman r^2 > 0.5). The results showed that data from one group could be used to predict discomfort of subjects in that environment, as other groups showed a similar trend, even though the exposures were not in the same order.

It was found that the axes from the seat and backrest correlated so well, that only the seat translational axes needed to be used to predict discomfort. Similar to the laboratory study, it was found that the rotational and floor axes had marginal effect to OVTV, thus it was concluded that in most cases just the seat translational axes could be used. This makes the field measurements more simple.

10.8 Improving the standard method

The results in Chapter 7 showed that depending on how the standard method was applied, different correlations were produced between OVTV values and discomfort judgments. Use of frequency weightings showed improvements in correlation, while the multiplying factors degraded the correlation systematically. The r.m.s. method showed better results than using the r.m.q. method. The correlation improved systematically for all setups when more axes were included, however it was also noted that the compensating factors did produce practically the same results as including the compensated axes (i.e. using 1.4 multiplying factors to compensate the backrest axes).

10.8.1 Role of the axes

Only one study was found which measured all twelve axes and analysed the correlation compared to different numbers of axes (Parsons and Griffin 1983). However, in this study the only scenarios, that could be compared to the standard method, were either using all axes, or only the worst axis. The results showed that including all axes improved the correlation. The results in Chapter 7 showed similar findings, where including more axes improved correlation for all different setups (i.e. with and without the frequency weightings and the multiplying factors and different averaging methods). It was also found that the axes from the seat and backrest had high correlation, thus a compensating factors was calculated for each PVTV. On the other hand, the role of the rotational and floor axes were found small and not providing enough value compared to the effort of measuring them. Thus the conclusions from Chapter 7 was that the seat translational axes alone could be used for predicting discomfort, if the multiplying factors would be optimised. This was confirmed in Chapters 8 and 9.

Can it be assumed that in every case all twelve axes will improve correlation, or are there environments where some axes would actually degrade correlation with discomfort? The method has its weaknesses, but there is no information, which suggests that some axes will not work. The scenarios used in Chapter 7 showed that the correlation was better in every case where more axes were added, but some axes had more effect than others. The effect of the axes were best with the frequency weighting, but without the multiplying factors, thus the role of the axes are not independent from the frequency weightings and the multiplying factors.

10.8.2 Role of the frequency weighting curves

As most of the research and validation has been directed to the comfort contours (i.e. frequency weightings), there was no evidence on changing them at this point. The frequency weightings manipulate the frequency content of the measured data so, that the effect to discomfort would be the most significant. The weightings for the most axes attenuate frequencies above 4-5 Hz so much, that the frequencies above 10 Hz have practically no effect. Only the weighting for the seat vertical axis and the floor axes (W_k) include higher frequencies up to 20 Hz. It was noted in Chapters 5 and 9, that because of the weighting curves, the frequency characteristics of the different environments were practically similar. This will most likely result in very similar vibration magnitudes as well.

The results in Chapter 7 showed, that very little difference was found in the correlation with or without the frequency weighting the acceleration signals. In the field, the frequency characteristics of a typical machine is similar to that of the frequency weighting curves, thus no significant changes in the characteristics are seen. More significant effects have been noted in laboratory studies, which can be linked to using a sinusoidal or random flat-band stimuli, thus not representing the characteristics of a vehicle in the field.

Based on the results it was concluded that the current frequency weightings have more positive than negative effect to the correlation, thus the role of the multiplying factors and averaging methods should be evaluated and optimised.

10.8.3 Role of the averaging method

As it is more feasible to assess effects of discomfort using a single value, a method to average acceleration signals was introduced. The r.m.s. method, which is used in many applications, was chosen early on as the main method for averaging the acceleration signal. In some studies it was found that more emphasis on shocks should be used, thus the r.m.q. method was proposed as an alternative. Both methods average vibration over the time period, thus do not include information about the duration. The VDV method was derived from the r.m.q. method to include also duration as a factor.

Since creation of the ISO 2631-1 standard in 1997 no conclusive evidence supporting either method was produced, so both methods were included. A crest factor method was chosen to select which method is more appropriate, but even today there is no concensus, of the best method. There is little information on the usability of the methods relating to discomfort, especially outside a laboratory environment.

The results in Chapter 7 indicated no improvement in the correlation when emphasising shocks. Even though the stimuli did not include extreme shocks, it had a wide range of typical stimuli, which is found in the field. The few studies, which have suggested using the r.m.q. (or VDV) method, have not analysed the correlation to discomfort, or have purposely used stimuli with a high shock content. It has been also concluded that more important than calculating the shock level is to understand the vibration in a more statistical way.

10.8.4 Role of the multiplying factors

The purpose of the multiplying factors is to change the relative emphasis of each frequency weighted vibration magnitude. The reason for introducing the factors were the results from the comfort contour studies, where the same level of discomfort was experienced for different levels of vibration magnitudes for different axes. To equalise the effects, the multiplying factors were introduced, so that the axes could be combined to a single value. However, the author was not able to find a publication where this process was explained and the values for the factors derived. Thus the origin of the multiplying factors is an interpretation of the author. The multiplying factors change the emphasis of the different axes when calculating an OVTV. Each factor and vibration value is taken to second power, thus the factors have great influence for PVTVs and OVTV.

The results in Chapters 7, 8 and 9 showed that the role of the multiplying factors is great when improving the standard method and understanding the relative contribution of the axes. More emphasis on the horizontal axes from the seat were noted compared to the vertical axis. Especially in the case where only the seat translational axes are used, the horizontal factors should be higher than the suggested 1.4.

10.9 Implications of the findings for improving the standard method

This study used field-like stimuli both in the laboratory and in the field to validate and optimise the standard method. This is a different approach than other studies, where more controlled, simple and short stimuli were used. The results in Chapters 7, 8 and 9 suggested that the best approach for improving the correlation was to change the multiplying factors.

Different sets of multiplying factors were derived from the laboratory and the field trials. In both cases the emphasis on the lateral axes were found to be greater than in the standard, but differences were noted for the fore-and-aft axis. In the laboratory a factor of 2.7 was produced, where in the field practically zero value showed the best correlation. The results implied two issues: 1) the multiplying factors for the axes will not be the same for all environment and 2) in the field, the vibration to some axes is either missing or produced from sources, which have inconsistent effects on discomfort (e.g. speed humps, accelerating, turning, etc).

Even though there is validity in the fundamental approach of using sinusoidal stimuli in a laboratory to minimise the other factors, the trials in this thesis showed that the factors do not work in practice in a multi-axis environment and using field-like stimuli. It is most likely that one general method does not work for all environments (actually it has not been proven to be the best for any environment so far), so practical and optimised versions of the method should be produced for different environments.

There is a difference in what type of behavior is behind the vibration magnitude value. If the vibration is based on one high level movement (i.e. shock) or on more average movement, it will change the judgment of the stimulus. The stimuli in the laboratory trial (Chapters 6, 7 and 8) was generated to expose all to axes as many combinations as possible. However, the stimuli in the field trial was not controlled in any way. The results in the field trial showed, that there are environments, where one axis might have different type of vibration characteristics than other axes, thus resulting in an inconsistent correlation.

It might be that the comfort feeling from vibration exposure is so complex that it is not possible to isolate the characteristics of it, or even isolate vibration from other factors like noise. However difficult, there still needs to be an effort to further the knowledge, because new information can significantly improve work environments. For doing this it becomes critically important that the guidance for conducting the experiments is simple, logical and universal, so that the information can be easily measured and analysed, systematically compared and discussed.

10.10 An improved method for predicting discomfort from whole-body vibration

Unfortunately this thesis did not conclude a single improved model for predicting discomfort from whole-body vibration. However, it was concluded that a set of tools can be used to optimise parts of the methods (i.e. the multiplying factors) for specific environments and then using the derived factors to predict discomfort in that environment. Thus the improved method includes steps first to produce the method used for the prediction.

The following procedure is suggested for optimising the standard method to a specific field environment:

1. A field trial is conducted for acquiring judgments and vibration simultaneously;
    a. At least 21 subjects and selection of typical environments for producing the vibration;
    b. Exposures should be at least one minute long, and preferably over ten different surfaces;
    c. Three groups of seven subjects should be exposed to the stimuli in different order;
    d. Continuous judgment and vibration from the seat and backrest axes should be measured simultaneously at 256 Hz sampling rate;
2. Analysing the correlation and finding the optimal multiplying factors;
    a. The judgment data from each subject should be trimmed from the beginning and end (5-10 seconds) and the rest of the data should be averaged using different window sizes (10 to 20 second window size with 2.5 second delay is a good start);
    b. The averaged judgment data from all stimuli for each subject should be normalised so that the minimum value is 0.0 and maximum is 2.0;
    c. Vibration magnitudes should be calculated using the frequency weightings and the r.m.s. method;
        i. The same window sizes and trimming should be used to calculate the r.m.s. values to pair the judgment and vibration data;

d. Data for a group can be averaged using the normalised judgments from the subjects and using vibration magnitudes from one subject;

e. The best possible correlation should be calculated using a brute force method between all measured axes and the values for each subject and group;

    i. Number of different multiplying factors should be tested when combining the vibration magnitudes of the axes to OVTV using r.s.s. method;

f. The best correlation found for each subject and group should be documented as well as a contour map produced on how the correlation changes when the factors are changed;

    i. Also the best correlations found using the standard multiplying factors should be documented to assess the level of improvement;

3. Assessing and using the improved method;

    a. The new multiplying factors show the relative emphasis of the axes to provide best correlation to discomfort;

    b. The multiplying factors of the standard can now be replaced by the new factors and objective measurement can be taken from similar types of environments to predict discomfort.

10.11 Contribution of the thesis work

Even though the standard method has been available in practice since 1986, the full method has been rarely used, thus little information is available on the practical use of the method. The purpose of this thesis was not to develop a completely new method for predicting the discomfort, but to understand, validate, improve and guide the use of the standard method. The work in this thesis was intended to provide information from all aspects of the discomfort assessment, from technical considerations for measuring the vibration and judgment for optimising the method for a field use. Based on the literature review, all parts required more information and analysis.

Since starting the thesis work in early 2006, few studies have been published on this issue, but none of the studies have provided overlapping information or information which would make parts of the results in this thesis obsolete. This thesis has provided insight on the matter and can be used by other studies to compare the results and understand how discomfort is changed under vibration exposure.

11 Chapter 11: Limitations and future work

11.1 Limitations

Because of the chosen methods and hypotheses, and the scope of the trials, the results in this thesis are limited. Also the method of the standard is limited, which was the basis for this thesis. Despite the known problems relating to the standard method, it was considered important to study and validate the method, and to find out how to improve it. This is a valid goal as there are literally thousands of assessments done using the method and all current commercial equipment is based on it.

Claims that a method has been validated are usually based on limited evidence of consistency with some observation or impression in a specific situation and not evidence that the method is appropriate over the full range of conditions to which it can be applied (Griffin 2007). It is important also for the findings in this thesis to be limited to the results and critically evaluate the usability of the results. The work in this thesis is not related to a separate method, but is part of the research relating to validation of the standard method.

11.1.1 Limitations of the standard method

It is possible that ISO 2631-1 does not provide a good model of subjective feeling relating to vibration. Studies have found issues relating to frequency weightings (Maeda and Mansfield 2006a, Maeda and Mansfield 2006b), multiplying factors (Maeda and Mansfield 2006a), averaging methods and the guidance of the standard (Griffin 1998). Griffin (1998) pointed out the problems and lack of references regarding the use of W_k weighting and 1.4 multiplying factors for the horizontal axes. There seems to be no valid studies behind them.

It has been shown that the current frequency weightings underestimate discomfort at higher frequencies (above 30 Hz) and at higher magnitudes (i.e. larger errors at lower magnitudes) (Griffin 2007). So the weightings are only reasonably valid in a specific magnitude range, and they might be underestimating discomfort at magnitudes found typically in a car or a train. The weightings are also derived from a large number of results using statistical means, thus they are more representative of a population rather than an individual (Mansfield 2005). It seems that weightings for the fore-and-aft and lateral axes from seats underestimate the discomfort and should have higher multiplying factors (Maeda and Mansfield 2006b). Also depending on the frequency content of the vibration the discomfort scaling will most likely change (Maeda 2005). This implies that no general absolute scaling can be provided, like it is provided in the standard. The table provided in the standard (Annex C) provides an overlapping scale of range of OVTV values that can be associated with a discomfort level (e.g. “high discomfort”). The studies, which have been the basis for creating the table have all used similar methods and have an inherent problem of producing overlapping categories (Maeda 2005).

The multiplying factors derived for the twelve axes are mostly based on single-axis experiments, where each axis and location has been separately analysed. There are indications that a multi-axis environment will produce different results. This was also shown by the laboratory and field trials in this thesis. However there are very few results concerning multi-axis vibration and correlation to discomfort, especially using field-like stimuli. Further experimental work is required in order to establish whether there could be scenarios where it is necessary to measure rotational vibration.

Based on the earlier studies there is no consensus on the best averaging method. It is interesting to note that the r.m.s. method seems to be better for low shock vibration, but the r.m.q. and VDV for vibration including shocks. This limits the scope of the standard method and separates it in to two versions.

11.1.2 Limitations of the theory behind the standard and applying the standard in practice

The assumption is that discomfort relating to the vibration exposure can be evaluated and predicted, and extracted from other factors like noise. This has to be assumed, as otherwise there is no possibility to develop a method for evaluating the discomfort from the vibration. However, it is not explicitly clear that this assumption is correct. It might be that human decision making processing is too complex and non-linear to be modeled using current approaches, especially in the field.

If assessment of discomfort also includes a behavioral component, such as changing to different transport or vehicle, the calculated vibration values will not provide the answer. This depends on the availability of the other transportation, costs and so on. Thus the method can provide information on how to improve discomfort, but not to assess the behavior of humans in a broader sense.

It was already speculated in the 1970's that several receptors in a human body perceive different characteristics of vibration, thus depending on the dominant frequencies the receptors are different (Miwa and Yonekawa 1974). This might be one reason for the vibration magnitude and frequency dependence of perception. In hand-arm vibration research several receptors, which sense vibration at different frequencies have been found (Mansfield 2005). In whole-body vibration a similar model of receptors has not been suggested.

The applicability of the same method for different environments has been questioned from the beginning of the first standard draft (Griffin 1978). It is more likely that the discomfort is also linked inherently to other environmental variables than vibration, so that just by examining vibration will produce differing results depending on the environment. For example it is logical to assume that a paying customer (i.e. passenger) will have different judgment criteria than a paid worker.

11.1.3 Limitations of the results

11.1.3.1 Laboratory experiments for validating the equipment

The equipment and sensor configuration for detecting rotational axes were validated in the laboratory using a six-axis test bench and commercial equipment. A number of different stimuli were used to verify the accuracy of the equipment at practical levels. The experiments did not include a more detailed testing of the sensor dynamic response at different frequencies, as it was assumed that the data provided by the sensor manufacturer was correct. The same sensor was also tested in a different study at the Technical Research Centre of Finland, but this was not done in a such detailed manner, which is normally required for a measurement equipment.

11.1.3.2 Field measurements

Because of the limited time and resources only a number of work machines were measured using all twelve axes. Additionally only a few repetitions were possible for each work phase, because the measurements were made during the actual work. Thus there was only limited data for concluding the results. This was noted also with the previous publications having results of the twelve axes.

11.1.3.3 The laboratory trial

A laboratory study included 22 subjects and 30 different types of stimuli. Even though the number of the subjects and stimuli were adequate for providing statistically meaningful results, the test should be conducted in different environments and using subjects from different backgrounds. The subjects in this trial were university students and department staff, thus not accustomed to vibration exposure. Most of the subjects were also young, which could affect the results.

The stimuli were different than normally used in laboratory experiments, as it was non-stationary and based on field measurements. Thus the frequency characteristics of the stimuli were dictated by realistic stimuli rather than theory. Each stimulus lasted 15 seconds, including continuously changing vibration characteristics. A similar kind of study should be conducted using different equipment (i.e. test bench) and different stimuli to conclude if the results can be generalised, or are specific to the environment.

Only one type of seat was used, which represented a typical car seat. The stimuli did include vibration from work machines, but the seat might have changed the results so that the results cannot be assumed to work as well in a work machine environment. The subjects kept their feet on a non-moving platform, thus not all twelve axes were used. Even though previous study using the same environment did not show any differences when keeping the feet on the moving platform, the role of the feet should be further studied.

The laboratory trial was limited to understanding the relative change in discomfort, thus no absolute discomfort levels can be derived from the results.

11.1.3.4 The field trial

The standard method was tested using a car with subjects exposed to typical vibration characteristics of Finnish roads. The trial was planned to validate the findings of the laboratory trial. Several limitations had to be accepted to allow a trial in the field.

Only one car type was used in the trial. The car represented more of a taxi than a normal car. The seats at the back where the subjects were seated, had less foam than typical car seats. Thus the vibration was likely felt more than in a normal car. During the measurements the weather was warm and sun was shining so that the airconditioning was working at full. Depending on the seating location the effectiveness of the air conditioning changed, thus some subjects might have been more warm than others.

As already noted in the laboratory study, also subjects in this trial were young students with few exceptions. The judgment styles showed that more detailed instructions should be given and training of the subjects should be more emphasised.

11.2 Further work

The following list describes the suggested further work to validate and verify the results in this thesis and to improve the understanding of the standard method:

- **More 12-axis measurements in the field**. It is necessary to validate and verify if the effect of the seat rotational and floor translational axes is universal, and whether there are some classes of vehicles where rotational motion could be more significant (e.g. small boats). The measurements should be made using all twelve axes and the frequency weighted vibration magnitudes using the r.m.s. method should be published.

- **Laboratory trials to verify the correlation between discomfort and vibration magnitudes based on the standard method**. Trials using different type and duration of stimuli should be used to verify if similar results are found than in the laboratory study in Chapter 7. Subjects with different background and experience should be used to evaluate the characteristics of different groups.

- **Laboratory and field trials to verify the optimised multiplying factors and the effects of the frequency weightings and the averaging methods**. The trials should be conducted using different types of stimuli from land and sea vehicles to find the differences when optimising the multiplying factors. This should lead to understanding similarities and differences between the environments.

- **Field trials to verify the need for different sets of multiplying factors**. The optimised multiplying factors derived from different environments should be evaluated.

- **Development of the method to acquire both vibration and judgment data simultaneously and to calculate new optimised parameters for each environment**. Based on this thesis it seems most likely that the multiplying factors (i.e. finding best possible correlation) will change for different environments. Thus a simple method and technology should be provided for the researchers to allow for the study of the environments.

- **Revision of the standard guidance**. The guidance needs to be simplified and more information on assessing the results should be given. Also examples of expected correlations should be presented as well as a general practical guidance for the whole process.

12 Chapter 12 – Conclusions

12.1 Conclusions

This thesis has shown several important results, which will give a better insight for using the standard ISO 2631-1 method to evaluate discomfort from whole-body vibration in an optimal way. This thesis included two laboratory experiments to develop and validate measurement equipment, a field study to measure all twelve axes from several machines, and a laboratory and field trial to analyse discomfort from exposure to multi-axis vibration. The following list shows the main conclusions derived from the work (in the order of appearance in the thesis):

- **There are very few studies and little information on how to use the standard method to predict discomfort in practice.** An extensive literature review was conducted and showed the need for providing more information about the standard method. The review found that there is no information on the level of confidence expected for predicting discomfort in the laboratory or field. Furthermore, several parts of the standard method and the theory behind it still needs clarification and new information. Especially the information relating to the applicability of the method in a field environment was missing.
- **Affordable and simple equipment can be used to evaluate discomfort from vibration using the full method.** Several experiments and tests were conducted for validating the sensor configuration for measuring rotational accelerations. Also software was produced to allow simple evaluation of the discomfort. The results showed that the full method can be used in practice and does not require much more effort than measuring and analysing the three axes from the seat.
- **Seat and backrest translational axes are practically dominant in all field environments when using the standard method**. The most dominant axes were seat vertical and backrest fore-and-aft. Additionally seat horizontal axes showed high contribution, but less than the most dominant axes. The standard method emphasises these axes so that it is likely that they are dominant in all types of environments.
- **Seat rotational and floor translational axes can be neglected for most environments**. The axes had only marginal (10 to 15 %) contribution to the overall vibration total value when the standard frequency weighting and the

multiplying factors were used. As the contribution of the axes were within a small range, the axes can be replaced by a compensating factor.

- **The applicability of the r.m.s. method based on the crest factor is small if all twelve axes are used**. It was found that if all twelve axes are used, then it is very likely that at least one axis will show a higher crest factor than the standard limit for the r.m.s. method. For all twelve axes only a few measurements showed crest factors below 9, but if the seat translational axes were used alone, then only one-third of the measurements exceeded the limit. However, the validity of the crest factor method can be suspected, especially for a longer measurement duration, as it is based only on a single peak value.
- **Different axes are dominant at different frequency ranges**. It was found that different axes are dominant depending on the frequency. Typically the seat and backrest axes were dominant below and floor axes above 10 Hz. The dominant axis changed multiple times from 0.5 to 80 Hz, thus the averaging of the time signal might not provide enough information for accurate prediction of discomfort.
- **The effect of additional axes (i.e. point vibration total values) can be compensated by using a single factor.** Compensation factors were calculated when less than twelve axes were included to calculate OVTV. The results showed high collinearity between PVTVs, thus it was reasonable to compensate missing PVTVs using a single factor. It is suggested to use a compensating factor to allow direct comparison of overall vibration total values with a different number of axes.
- **The method of continuous judgment of line length can be used to evaluate discomfort from whole-body vibration**. The cross-modal method was selected as a number of studies showed it to work well for non-stationary long stimuli in noise research. It was also found to work well in vibration research as the subjects easily adopted the technique to judge vibration, the instantaneous judgment does not require long term memory, and the data can be evaluated using different approaches. A delay was noted between judgments and vibration magnitudes, which suggested a trimming of the data and a small offset fix.
- **There were no differences between men and women for judging relative discomfort from non-stationary field-like stimuli**. The results showed that

gender nor physical size were a factor when evaluating discomfort. Even though previous publications have noted differences in gender, at least the relative discomfort (i.e. change in discomfort when vibration characteristics were changed) did not seem to be affected by gender.

- **Correlation between vibration and discomfort improved when more axes were used**. Including all measured axes produced the best correlation for each subject and for the whole group. All axes improved correlation, thus it is important to include as many axes as possible. However, in most cases only small improvement was noted compared to using seat translational axes, thus greater complexity in analysis does not necessarily guarantee a better correlation between the measured vibration magnitude and ratings of discomfort.
- **Frequency weighting curves improved correlation systematically**. The use of the frequency weighting was validated by comparing the frequency weighted vibration magnitudes to the unweighted values. In each case, where more than the seat translational axes were used, the weightings improved correlation.
- **The r.m.s. method showed better correlation than the r.m.q. method**. The results showed no evidence that using the r.m.q. method would improve correlation between vibration magnitude and discomfort. The r.m.s. method was better systematically for all cases with and without the frequency weightings and the multiplying factors.
- **The multiplying factors degraded correlation for the additional axes**. The multiplying factors for the backrest and seat rotational axes degraded the correlation for all setups. This was concluded based on the laboratory and field trials. This was systematic for all subjects.
- **Seat translational axes alone can be used to evaluate discomfort**. It was found that in both laboratory and field trials, practically the same correlation between discomfort and vibration was achieved using only the seat translational axes with multiplying factors. In the laboratory the 1.4 multiplying factors to compensate the backrest axes provided practically the same correlation than using all measured axes. The same scenario was also the best standard scenario in the field trial. Thus it was concluded that the optimisation of the multiplying factors should focus on the seat translational axes.

- **Optimised multiplying factors improved the correlation to discomfort and vibration exposure**. The new optimised multiplying factors were calculated using two different approaches (a brute force method and multiple linear regression models) and the results were similar: the seat fore-and-axis should be multiplied by 2.7 times and the seat lateral axis 1.8 times compared to the vertical axis. The factors were higher than suggested by the standard when only the seat translational axes are used (i.e. 1.4).
- **The brute force technique and contours maps allowed easy optimisation of the multiplying factors for different environments.** The methods can be used to calculate optimised multiplying factors for any environment where judgment and vibration data have been previously recorded. The methods can also be used to test how many axes are necessary to be measured.
- **A developed device for simultaneously measuring vibration and subjective judgments from multiple subjects was shown to work both in laboratory and in field**. Based on the requirements of the continuous judgment method, a device was developed, which can be used to acquire instantaneous judgments from subjects. The device can be used as an additional sensor, thus synchronising the judgment with the vibration data. The subjects were able to judge vibration effortlessly. This makes it possible to have stimuli, which is longer (several minutes or hours) and less training of the subjects.
- **A systematic trend in predicting correlation was found in the laboratory and field**. Even though the results from the laboratory and field trials showed different sets of multiplying factors, the method itself provided similar trends for each subject and group: the use of different multiplying factors improved correlation.
- **Significant improvement was achieved in correlation compared to the standard method**. In both laboratory and field trials a statistically significant improvement was achieved using the optimised multiplying factors compared to the best possible combination of axes based on the standard guidance. This was evident for each subject and all groups.
- **Discomfort can be predicted in the field using the standard method**. The predicted discomfort and the trend in optimising the correlation were the same for different groups, even though the stimuli and route was not exactly the same

and one group was driven 8 months later. This shows high confidence that the method can be used to predict relative discomfort in a specific environment.

- **Discomfort should be evaluated only relatively within an environment**. The current standard implies that discomfort can be evaluated in an absolute scale for a variety of environments. There is no evidence that supports this. The results and conclusions in this thesis suggested that the current standard guidance for evaluating discomfort should be changed to compare relative discomfort within an environment.

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