Ride comfort difference thresholds for a vehicle on a 4-poster test rig

by

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Abstract

To improve ride comfort a reduction in the acceleration experienced by occupants is required. Simulation software and test equipment are able to measure reductions in acceleration that are too small for humans to perceive. It is therefore important to know how large the reduction in vibration should be for occupants to perceive an improvement in comfort. This study determined difference thresholds (DTs) for ten automotive engineers seated in a vehicle on a 4-poster test rig. Participants were exposed to all six axes of vibration. DTs were determined for two road profiles using vertical acceleration measured on the seat and seat rail. The two road profiles were obtained by scaling the magnitude of the vertical displacements of a test track used for ride comfort evaluations. The two roads had different magnitudes, but the same spectral shape, and were therefore used to investigate the validity of Weber's Law. The BS 6841 weighted r.m.s. magnitude of the vertical acceleration measured on the seat were 0.58 and 1.01 m/s^2 for the two roads. An up-down-transformed-response (UDTR) test procedure was used with a three-down-one-up rule to determine DTs. There was no statistically significant difference found in the medians of the relative difference threshold (RDT), calculated from the vertical seat acceleration, over the two roads. The median RDT for the two roads were 10.1 % and 8.6 % respectively. Results were consistent with Weber's law.

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List of symbols

Symbol	Description	Units
A	Reference stimulus magnitude	m/s^2
a	Growth function	-
a_t	Tangential acceleration	m/s^2
C	Relative difference threshold (RDT)	%
C_i	Relative difference threshold for the i-th set	%
c	Constant	-
$F(x)$	Probability of correct response at a stimulus magnitude x.	-
i	Set number in UDTR procedure	-
I	Stimulus magnitude	m/s^2
ΔI	Absolute difference threshold (ADT)	m/s^2
ΔI_i	Absolute difference threshold for the i-th set	m/s^2
k	Number of first set to be used in difference threshold calculation	-
m	Number of sets in UDTR procedure	-
n	Number of correct responses	-
P_i	Average of the r.m.s. magnitudes of n alternative stimulus at the i-th peak	m/s^2
P_{ref_i}	Average of the r.m.s. magnitude of reference stimulus at the i-th peak	m/s^2
$P_{ref_{ij}}$	Magnitude of the j-th reference stimulus at the i-th peak	m/s^2
r	Radius	m
r_x	Roll-axis	-
r_y	Pitch-axis	-
r_z	Yaw-axis	-
S	Sensation magnitude	-
T_i	Magnitude of alternative stimuli at a trough for the i-th set	-
T_{ref_i}	Magnitude of reference stimuli at a trough for the i-th set	-

Symbol	Description	Units
t	Trial	-
W_b	BS 6841 (British Standards Institution, 1987) frequency weighting function applicable to the three orthogonal axes at the feet and vertical acceleration at the seat-surface.	-
W_c	BS 6841 (British Standards Institution, 1987) frequency weighting function applicable to longitudinal acceleration at the seat-back.	-
W_d	BS 6841 (British Standards Institution, 1987) frequency weighting function applicable to longitudinal and lateral acceleration at the seat-surface as well as lateral and vertical acceleration at the seat-back.	-
W_e	BS 6841 (British Standards Institution, 1987) frequency weighting function applicable to the three rotational accelerations about the orthogonal axes at the seat-surface.	-
x	Stimulus magnitude	m/s^2
X_r	Alternative magnitude at which there is a specific chance r of obtaining a correct response.	m/s^2
α	Angular acceleration	rad/s^2

List of abbreviations

Abbreviation	Description
ADT	Absolute Difference Threshold
BS	British Standards Institution
DL	Difference Limen
DOF	Degrees Of Freedom
DPSD	Displacement Power Spectral Density
DT	Difference Threshold
EVE	Innovative Engineering of Ground Vehicles With Integrated Active Chassis Systems
IQR	Inter Quartile Range
ISO	International Organization for Standardization
JND	Just Noticeable Difference
P	Peak
RDT	Relative Difference Threshold
r.m.s.	Root Means Square
T	Trough
UDTR	Up Down Transformed Response
2AFC	Two-alternative forced choice

List of definitions

Term	Description
Absolute difference threshold (ADT)	Smallest change in vibration magnitude that a person can perceive measured in m/s^2.
Anatomical/Anatomy	Relating to bodily structures.
Biological/Biology	Related to the processes that takes place within a living being.
Biomechanical/Biomechanics	The study of how skeletal and musculature systems work under different conditions.
Cognitive	Related to the mental process of understanding.
Difference threshold (DT)	The difference threshold is used as an umbrella term referring to both the absolute and relative difference thresholds. It has the same meaning as the JND.
Just noticeable difference (JND)	The JND is used as an umbrella term referring to both the absolute and relative difference thresholds. It has the same meaning as difference thresholds.
Kinesthetic	Learning through feeling body movement, weight, muscle movement.
Perception threshold	The smallest vibration that a human can perceive.
Physiological/Physiology	Related to bodily processes on a macro and microscopic level.
Psychological/Psychology	It is the science of behaviour and mind embracing all aspects of conscious and unconscious experience as well as thought.
Psychophysics	A branch of psychology that deals with relationships between stimuli and the sensations and perceptions evoked by these stimuli.
Psychometric function	Models the relationship between a stimulus level and the probability of a correct response at the stimulus level.

Term	**Description**
Relative difference threshold (RDT)	Smallest change in vibration magnitude that a person can perceive relative to the stimulus magnitude defined as a percentage.
Somatic system	Is responsible for carrying motor and sensory information to and from the central nervous system.
Vestibular	Relating to the sense of balance situated in the inner ear.
Visceral	Internal organs.
4-Poster	Test system consisting of four actuators designed for vehicle testing. A vehicle's four wheel are placed on top of the actuators. The actuator's movement simulates the road surface and forces exerted by the road on the wheels.

Chapter 1

Introduction

1.1 Ride comfort and human response to vibration

The ride comfort of vehicles is a complex field that incorporates psychological effects, ergonomics, climate, noise and vibration exposure. The purpose of a vehicle's suspension is to provide comfort to occupants by isolating them from road inputs. Less vibration results in improved comfort. Understanding how people respond to vibration is the key to designing more comfortable vehicles.

Mansfield (2005) introduces his textbook, Human response to vibration, with a splendid overview. He introduces the origin of human response to vibration as follows: "Mankind has always had the desire to build, create, and explore. Each of these activities involved some kind of vibration that was transmitted to the human. From primitive axes to hand saws to power tools and industrial machines. From riding in carts to automobiles and trains and planes. As modern man was able to harness energy more efficiently, the apparatuses used to build, create and explore, have used more energy and as a result increased quantities of energy have been dissipated in the form of vibration, of which some are transmitted to people."

I share the view expressed by Mansfield (2005) when he mentions what attracts him to this field of research: "One of the most rewarding aspects of studying human response to vibration is its truly multidisciplinary nature. For example, the authors listed in the references have various backgrounds including engineering, psychology, the natural sciences, clinical medicine, and ergonomics. If the phrase 'human response to vibration' is de-constructed into its components then we can consider that a complete grasp of the discipline requires an understanding of the human (biological, anatomical, and physiological aspects), their responses (psychological and biomechanical aspects) and the nature of vibration (in terms of the engineering and underlying physics)." The multi-disciplinary nature of the research (see Figure 1.1) and the large effect that the human factor has on results were also what attracted me to this field of research.

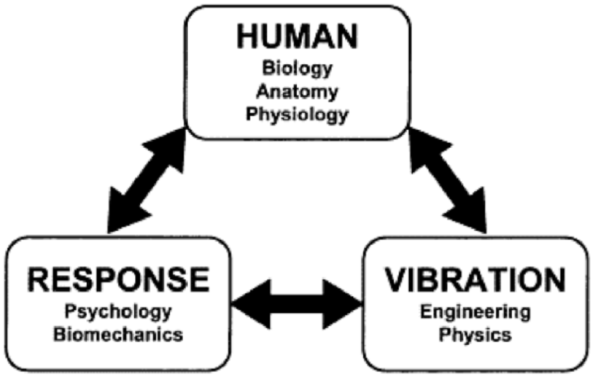

Figure 1.1: Components of the discipline "human response to vibration" as explained by Mansfield (2005).

1.2 The smallest change in vibration that a person can detect

The smallest change in vibration that a person can detect is of great value in the pursuit of more comfortable vehicles. Vehicles manufacturers are continually improving the suspension systems of their vehicles in order to reduce the vibration that is experienced by occupants. Morioka and Griffin (2000) mentions that research over recent years have been based on the assumption that a reduction in vibration magnitude will result in an improvement in comfort. The problem at hand, as stated by Morioka and Griffin (2000), is that it is not known when a reduction in vibration magnitude will result in a noticeable improvement in comfort, as a too small reduction in vibration magnitude will not be perceivable by an occupant. It is therefore of value to know what the smallest change in vibration magnitude is, that will result in a perceivable change in comfort.

The smallest change in vibration magnitude that a human can detect is also known as the difference threshold (DT) or just noticeable difference (JND). The term DT will be used to avoid confusion. The DT comprises of a relative difference threshold (RDT) and an absolute difference threshold (ADT). The RDT is the percentage by which a stimulus magnitude should be increase/decreased in order for the difference to be just noticeable. The ADT is the difference in magnitude between two stimuli (in m/s^2) which is just sufficient for the difference to be detected.

Mansfield and Griffin (2000) state that occupants' subjective evaluation or judgement of the vibration might influence their opinion of a vehicle. Vibration may be measured during experimental testing, or in simulation, in order to predict whether design changes will improve comfort. It is further mentioned that methods of measure are capable of measuring changes that humans can not detect. With regards to the design process, Mansfield and Griffin (2000) report that if the effect of the change is too small for a human to detect it might be decided that such a change is not of importance although, a few imperceptible changes may contribute towards a total difference that may be perceived. Therefore, Mansfield and Griffin (2000) state that knowledge of the smallest change in magnitude of vibration that can be detected has relevance towards the decision on the implementation of design changes and the selection of methods to predict vehicle ride comfort. Mansfield and Griffin (2000) further report that although frequency weightings have been established to predict relative discomfort and compare different vehicles, there has been little research in the DTs of whole-body vibration.

Pielemeier et al. (1997) also discusses the importance of DTs in determining the required intensity accuracy of vibration simulators when performing subjective testing. They mention that the DT is an important psychophysical parameter in understanding subjective vibration assessment. Griffin (1990) states that, "the change in magnitude of whole-body vibration required before the change is observed has rarely been investigated."

Published literature on DTs for whole-body vibration has subjected participants to vertical vibration of various wave forms, therefore determining DTs for vertical vibration only. When driving in a vehicle occupants are exposed to not only vertical acceleration, but also lateral, longitudinal, roll, pitch and yaw acceleration. There is uncertainty as to how much the vibration magnitude in a vehicle should change for the participants to perceive a change in comfort while being exposed to all six components of acceleration. Morioka and Griffin (2000), who determined DTs for vertical vibration, emphasized in their conclusion that, "...further information is required in order to confidently predict the sensitivity with the full range of complex motions in vehicles."

Chapter 2

Literature Study

2.1 Introduction

Occupants in passenger vehicles are exposed to seated whole-body vibration. DTs for seated whole-body vibration can play a significant role in the vehicle design process. The literature study investigates DTs determined for seated whole-body vibration found in literature as well as other important factors that contribute to subjective-objective correlation of data in order to identify a void in current research.

2.2 Research approaches for investigating human response to vibration

Griffin (1990) states that the study of human response to vibration is concerned with establishing relationships between various effects and their causes. Effects, as in this case of this study, are reduced comfort, but can also include impaired activities or health. Causes are factors such as vibration conditions (frequency, amplitude, duration, input position etc.), environmental conditions (noise, visual stimulation, temperature etc.) or participant characteristics (age, cohort, dimensions of body, posture etc.). Due to the complexity of the cause-effect relationship Griffin (1990) states that two distinct methods of research have emerged: either the systematic study considering each variable separately or the simulation of real conditions (such as driving over a rough road) and the study of real effects (such as reduced comfort) on actual tasks (such as driving).

Griffin (1990) claims that the systematic approach is more likely to advance knowledge of the cause-effect relationship, explaining why effects occur and providing solutions. He acknowledges that systematic research will never lead to a perfect solution to the human response to vibration "equation". He further states that for a particular set of conditions a precise solution might only be obtained by simulating the real conditions and observing the effects and studying how changing the conditions alters the effects. This approach is often characterised by cost, complexity and the impossibility to simulate environments in a laboratory. In conclusion, Griffin (1990) is of opinion that both types of research are of importance and that the results can be highly complimentary.

2.3 Difference threshold

Griffin (1990) defines the difference threshold as: "The difference in value of two stimuli which is just sufficient for their difference to be detected." For vehicle vibration on a seat Mansfield and Griffin (2000) defines the difference threshold as: "...the minimum change in the magnitude of the whole-body vibration required for the seat occupant to perceive the change in magnitude." The DT, also called the JND (Pielemeier et al., 1997), comprises of an absolute and relative difference threshold. The DT is always determined for a certain acceleration magnitude called the reference magnitude. The ADT is the magnitude, by which the reference acceleration should change for a person to notice a change. The RDT is the percentage by which the reference magnitude of a stimulus should increase for a person to detect a change. Both the ADT and RDT are linked to the characteristics of the psychophysical method (discussed in Section 2.9) used during testing.

The DT should not be confused with the vibration "threshold" or "perception threshold". The "threshold" or "perception threshold" are defined by (Griffin, 1990) as: "The value of a stimulus which is just sufficient for its presence to be detected." Any vibration magnitude below the "threshold" value can not be detected by a human.

2.4 Weber's law

The German psychologist, E. H. Weber, proposed that the ADT is proportional to the magnitude of the stimulus and that the RDT remains constant (Morioka and Griffin, 2000). The formulation of Weber's law is presented by Equation 2.1, where ΔI is the ADT, I is the magnitude of the stimulus and C is the RDT. Therefore, when Weber's law holds, the absolute difference required, between two stimuli, for a person to perceive a change in vibration magnitude will increase/decrease at the same rate as the stimulus increase/decrease. It would reduce the amount of experimental work required as the DT would not have to be determined at every required stimulus magnitude.

$$C = \frac{\Delta I}{I} \tag{2.1}$$

Weber's law is defined for the detection of magnitude changes in vibration stimuli. According to ISO 2631-1 (International Organization for Standardization, 1997), a vibration with a r.m.s. magnitude larger that another will be perceived as being relativity less comfortable. Within this study, DTs will specifically be defined as the smallest change in vibration magnitude that causes a change in comfort that a person can detect. Weber's law will therefore be used for the detection of a change in comfort.

2.5 Inter- and intra- participant variability

Inter- and intra- participant variability are both of great importance during experimental testing when making use of humans as participants. Griffin (1990) defines inter-participant variability as the differences between people. These include body size, age and gender, MBI, age, disability, clothing, fitness and expectations. The author is not aware of any study that reported significant differences between genders with regards to DTs. Griffin (1990) defines intra-participant variability as factors that can change over a short period of time with regards to the participant. The main factors include orientation (backrest inclination and facing direction within vehicle), position (selected vehicle seat, feet position, knee angle and hand position) and posture.

2.6 Mechanisms of perception

Mansfield (2005) provides a good overview of all the mechanisms used by humans to perceive vibration. It is useful to keep the following information in mind when designing an experiment and when interpreting results, especially subjective feedback. The following section is a summary which has been adapted from Mansfield (2005).

The body combines signals from the visual, vestibular, somatic, and auditory systems in order to sense vibration. For high displacement and low frequency vibration, one can clearly see movement by changes in the relative position of objects on the retina, such as the movement of a vehicle's body in relation to the environment. Higher frequencies can also be sensed by observing blurry images or movement of certain objects such as the vibration of the rear view mirror of a vehicle. The vestibular complex of the inner ear includes the semicircular canals and the vestibule, which are sensitive to rotational and linear acceleration (gravity), respectively. The vestibular complex makes a leading contribution to a human's sense of balance and spatial orientation.

The somatic system can be divided into three elements: the kinesthetic, visceral (relating to the internal organs), and cutaneous (relating to the skin). The somatic system is responsible for relaying sensations from the body and sending commands to the body. "Kinesthetic sensation uses proprioceptors from the joints, muscles and tendons to provide feedback to the brain on the position and forces within the elements. Similarly, visceral sensation uses receptors in the abdomen. Cutaneous sensation consists of four types of nerve endings in the skin." Together they are sensitive to frequencies between 5 and 500 Hz. The fourth and last sensory system for whole-body vibration is the auditory system. While driving in a vehicle noise from the road as well as suspension (during shocks) can be heard in the vehicle.

According to Mansfield (2005): "The combination of sensory signals must be assimilated by the brain to produce a cognitive model of the motion environment. Therefore, psychophysical techniques are appropriate for the investigation of human perception to vibration." Steven's power Law (a psychophysical function) states that sensation magnitude increases proportionally to the stimulus magnitude raised to some power:

$$S = cI^a \tag{2.2}$$

where S is the sensation magnitude, c is a constant, I is the stimulus magnitude, and a is the value of the exponent or the growth function. It is important to note that the relation between sensation magnitude and stimulus could be non-linear with a change in frequency as show by Morioka and Griffin (2000). Although Morioka and Griffin (2000) concludes that the "...sensation magnitude increases in approximately linear proportion to the acceleration magnitude."

2.7 The use of whole-body vibration standards to evaluate comfort

The use of machinery exposed people to vibrations of various kinds. Vibration has numerous effects on the human body. It can cause discomfort, fatigue as well as short and long term health related problems (Griffin, 1990). A scientific method was required by which these vibrations could be evaluated based on the effect it has on people with regards to health, human activities, discomfort and perception, as well as motion sickness. Various whole-body vibration standards were developed such as BS 6841 (British Standards Institution, 1987) and ISO 2631-1 (International Organization for Standardization, 1997). (From here on BS 6814 will always refer to British Standards Institution (1987).) Griffin (1990) provides a thorough review of the BS 6841 and ISO 2631-1 (International Organization for Standardization, 1997) as well as various other standards on whole-body vibration. The BS 6814 was selected as the preferred standard to be used to interpret data and will be described in more detail here. BS 6841 was used in order to compare RDT results with the valuable work done by Mansfield and Griffin (2000), although ISO 2631-1 has a newer publication and has been adapted as the current benchmark. (Appendix D provides a comparison between BS6841 and ISO2631-1 for key results.)

BS 6841 prescribes that when evaluating vibration for comfort, excluding motion sickness, vibration with a frequency range of 0.5 to 80 Hz should be considired in all six axes on the seat-surface (three translational and three rotational), as well as the three translational axis at the seat-back and feet. The manner in which vibration affects comfort are dependant on the frequency of the vibration. The standard uses frequency weightings to take into account human sensitivity to different frequencies. Frequency weighting curves are shown in Figure 2.1. These functions reduces the energy in frequency bands that humans are less sensitive to and therefore reduces its effect on the overall r.m.s magnitude of the vibration. Table 2.1 indicates which frequency weighting applies to which axis and location.

The basicentric co-ordinate systems used for seated whole-body vibration are presented in Figure 2.2. The co-ordinate systems are defined relative to the surfaces that comes in contact with the body and originates at the point from which vibration is considired to enter the body. Measurements on the bottom seat surface should be made under the ischial tuberosities. Measurements on the seat back should be made in the area of principal support of the body. Measurements at the feet should be made on the surface that most often supports the feet. BS 6841 presents various techniques to quantify a stimulus by a single value. The r.m.s. of the frequency weighted acceleration are often used if there is no large shocks in the stimulus and therefore when the crest factor is below 6. The BS 6841 also includes a method to combine r.m.s accelerations measured in different axis at different locations into a single overall vibration value taking in to consideration that the human is not equally sensitive to vibration in all axis.

The applicability of frequency weightings in the prediction of DTs are debatable as Mansfield and Griffin (2000) conclude that: "Additional experimental work is required to investigate the applicability of frequency weightings to predict difference thresholds." There are also some limitations that apply to weighting functions. Mansfield (2005) mentions two limitations of frequency weighting curves relating to comfort and perception:

1. Frequency weightings are derived from meta-analysis (statistical approach to combining data) of studies of equal sensation curves. They are therefore representative of a population rather than an individual.
2. They assume linearity, i.e. there is only one weighting used for low and high magnitude environments.

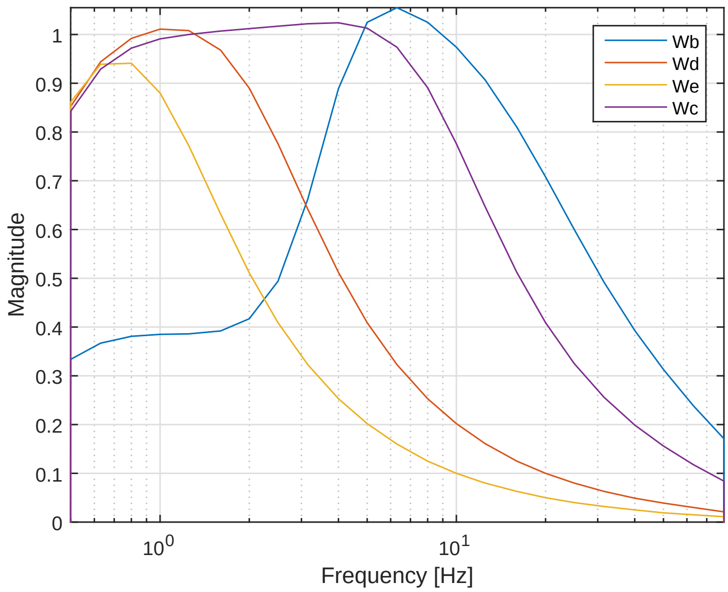

Figure 2.1: Frequency weighting curves from the BS 6841 standard.

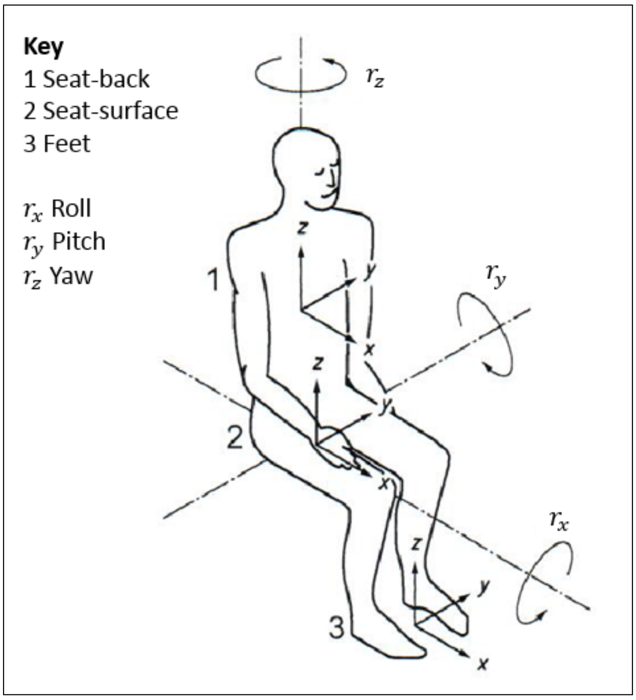

Figure 2.2: Basicentric co-ordinate system used by BS 6841 when measuring seated whole-body vibration. Image obtained from ISO 2631-1, Amendment 1 was used as image in BS 6841 is not as clear. (International Organization for Standardization, 2010).

Table 2.1: Frequency weighting functions from BS 6841 and to which location and axis they are applicable to.

Frequency weighting	Location	Axis
W_b	Feet	x-axis
		y-axis
		z-axis
	Seat-surface	z-axis
W_c	Seat-back	x-axis
W_d	Seat-surface	x-axis
		y-axis
	Seat-back	y-axis
		z-axis
W_e	Seat-surface	r_x -axis
		r_y - axis
		r_z - axis

2.8 The psychometric function and psychophysical testing techniques

Methods used to determine the DT were adopted from the field of psychoacoustics, which is the study of sound perception. Within the field of psychoacoustics a lot of research has been done on estimating points on a psychometric function. Methods from psychoacoustics are used in the field of whole-body vibration to estimate points on the psychophysical function and thus estimate the smallest change in vibration magnitude that a human can perceive. An assumption is made that an increase in the magnitude of vibration that participants are exposed to will result in reduced comfort (British Standards Institution, 1987). Based on this assumption, the change in vibration magnitude will be link to a change in comfort.

Wetherill and Levitt (1965) state that a psychometric function provides the relationship between a stimulus level, x, and the probability of a correct response, $F(x)$, at the stimulus level. A psychometric function is shown in Figure 2.3, where X_{50} is the stimulus level, x, where a person has a 50 % chance of giving a correct/positive response. The definition of a correct/positive response is different for each study and how to interpret the magnitude x (on x-axis of the psychometric function) would depend on whether the perception threshold or DT is being determined. If the perception threshold is being determined and a person is exposed to a vibration x and asked if they can feel it, a positive response would be when they can feel the vibration. In such a case where there is a yes/no response and a stimulus level from X_0 to X_{100}, a person has a 0 % to a 100 % chance of detecting the stimulus. If the difference threshold was determined for a reference stimulus of magnitude A, X_{75} would be larger than A such that when a person is exposed to a vibration of magnitude A and X_{75}, he would have a 75 % chance of selecting the largest of the two.

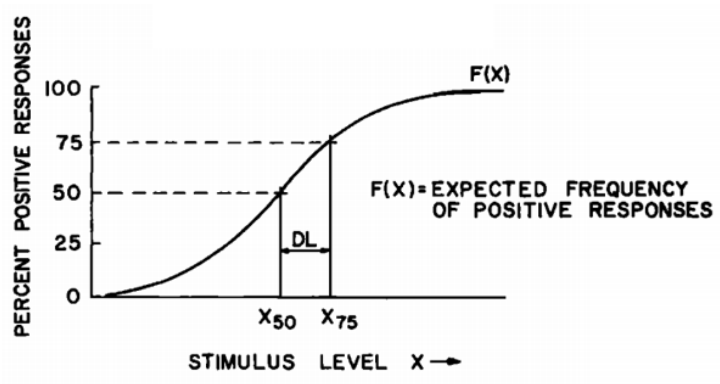

Figure 2.3: Typical psychometric function of the expected frequency of positive responses from Levitt (1971).

In psychoacoustic literature there exists various psychophysical testing techniques that can be used to estimate points on a psychometric function. These techniques are divided into two groups: classical and adaptive procedures. Procedures discussed here are those used in published literature relating to difference threshold testing for seated whole-body vibration. Classical techniques include the method of constants. Adaptive techniques include the simple up-down method, up-down transformed response method (UDTR) as well as the method of limits. In difference threshold testing all three these methods make use of a two-alternative forced choice (2AFC) method whereby the participant is presented with two stimuli, a reference and an alternative, and has to select one. This is called a trial. The reference stimuli stays constant while the alternative stimuli undergoes change in its magnitude during the test procedure. For each trial the reference and alternative stimuli are always presented in a random order. If the participant does not know which stimuli to select they have to take a guess. Levitt (1971) states that with psychophysical testing there are two important factors in obtaining good results: the first is the placement of observations and the second is the analysis of data. Levitt (1971) further states that observations should be placed as close as possible to the point which is of interest on the psychometric function.

An example test procedure of the **method of constants** are shown in the top left graph in Figure 2.4. With the method of constants, several alternative vibration stimuli (x_2, x_3 and x_4) larger that the reference stimulus (x_1) are chosen. These chosen magnitudes will for example range from being just larger than the reference to being much larger than the reference. For every trial a participant would be exposed to a reference stimulus and an alternative stimulus and asked to identify the largest (or most uncomfortable) of the two. For each trial a random alternative (either x_2, x_3 or x_4) are selected. The participant's response therefore has no effect on the course of the procedure. A fixed number of tests are performed at each magnitude. The data is analysed by fitting a psychometric function to the data in order to estimate the point of interest (e.g. X_{75}) as shown in the top right graph in Figure 2.4. The advantage of this method is that the data covers a wide range of magnitudes. Levitt (1971) states that a shortcoming of this method is that if the researcher is only interested in one point on the psychometric function (e.g. X_{75}) the method is inefficient as a large portion of the observations are placed at some distance from the point of interest. Levitt (1971) states that a second shortcoming is that the procedure does not allow gradual changes in the DT during the test procedure to be noticed.

The **method of limits** starts with presenting an alternative stimulus that differs a lot from the reference in magnitude and therefore has a high probability of correct response. The bottom left graph in Figure 2.4 shows an example test procedure. The alternative stimulus is reduced in step sizes until an incorrect response is obtained. The average of the last two alternative stimuli are used as an estimate for X_{50}. The procedure can also be inverted starting with a small difference and increasing until a correct response is obtained. Levitt (1971) states this method can be used where a rapid estimate of X_{50} is required. The shortcoming is that observations are badly placed with most observations being a distance from X_{50} (Levitt, 1971).

The **simple up-down** procedure is an efficient method in estimation the X_{50} level according to Levitt (1971). The bottom middle graph in Figure 2.4 shows an example test procedure. It differs from the method of limits in that it continues beyond a single incorrect response increasing the difference between the reference and alternative at an incorrect response and decreasing the difference between the reference and the alternative at a correct response. Advantages are that most test magnitudes (or observations) are situated close to X_{50} and that gradual drift in observations are noticeable and taken into account. Levitt (1971) states that disadvantages are that observations are not placed in a way so that a level other than X_{50} can be estimated and secondly selecting a too large step size will result in badly placed observations and a too small step size will waste a lot of time. Levitt (1971) states that there are various methods to analyse data and that Wetherill (1963) developed a method in which all peaks (denoted by P)

and troughs (denoted by T) are averaged to provide an estimate for X_{50}. According to Levitt (1971) the method proposed by Wetherill (1963) is extremely simple and robust.

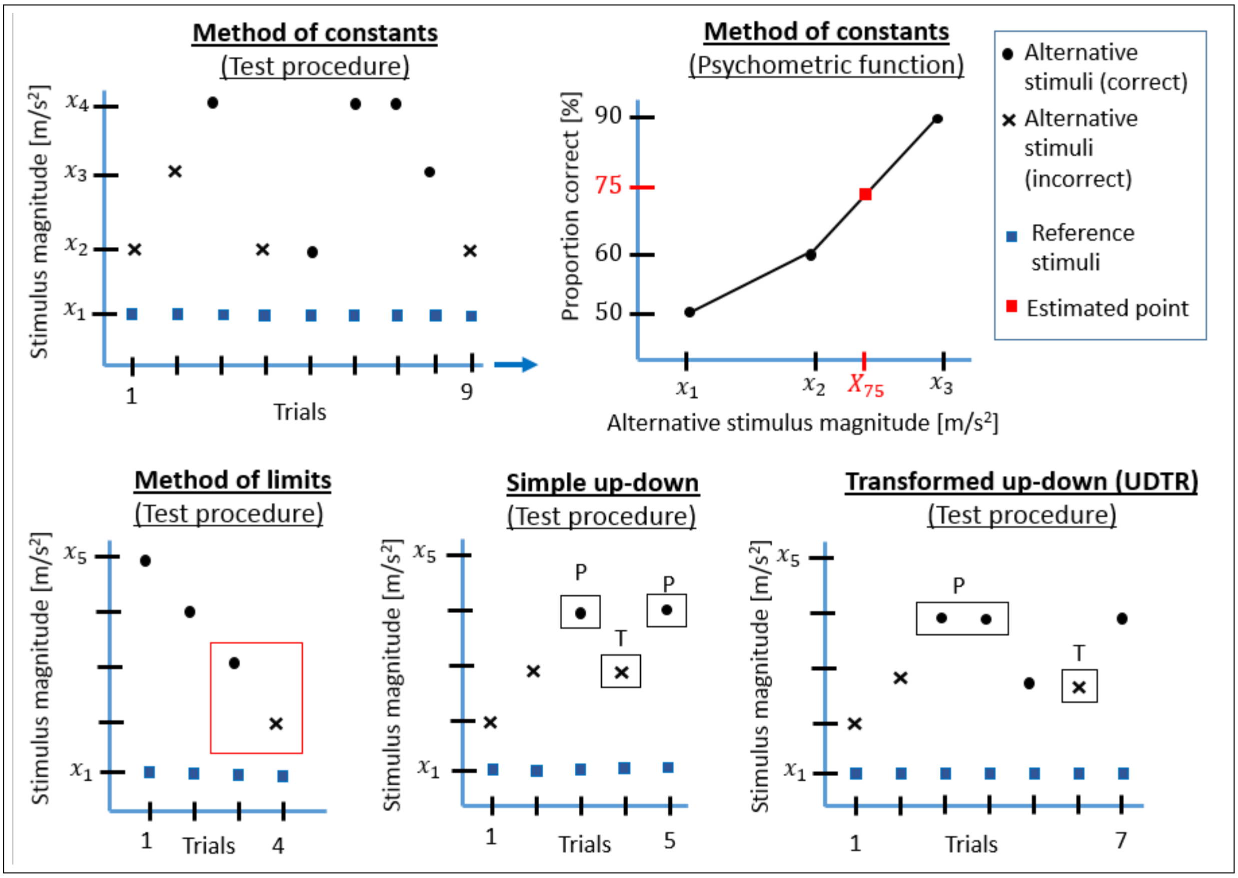

Figure 2.4: Top left: example of the first few trials of a test making use of the method of constants. Top right: psychometric function of the data obtained from the method of constants. Bottom left, middle and right: example test procedures for the method of limits, simple up-down and transformed up-down respectively.

The **up down transformed response (UDTR)** procedure is similar to the simple up down procedure, but has the advantage that it allows the estimation of points other than X_{50}. The bottom right graph in Figure 2.4 shows an example test procedure. The procedure for controlling the stimulus magnitude is similar to that of the simple up-down, except that a certain sequence of responses are required before the stimulus level is increased/decreased. For example, in order to estimate X_{70} two consecutive correct responses are required before decreasing the alternative stimulus magnitude. To estimate X_{79}, three consecutive correct responses are required before decreasing the alternative stimulus magnitude. In both these cases the stimulus magnitude is increased for an incorrect response and remains constant for any other scenario. The method proposed by Wetherill (1963) also applies tot the UDTR method. A thorough explanation of the UDTR procedure follows in Section 2.9 explaining the statistics behind obtaining X_{50}, X_{70} and X_{79}.

In selecting a psychophysical testing technique there are two important considerations: the available time of participants and the point of interest on the psychometric function that has to be estimated. The UDTR procedure was selected as it is efficient in estimating a probability of correct response higher than 50% (X_{50}). Although the method of constants are also able to estimate a probability of correct response higher than 50% it was impractical due to its inefficiency. DT results from published studies making use of various psychophysical testing methods will be discussed later. The effect of each psychophysical method on the DT obtained is complex and mostly unclear at this stage.

2.9 Up down transformed response (UDTR) method

The UDTR method was selected as the method of choice to govern the test procedure for each participant in order to determine the DT within a reasonable time and with a certainty level of above 50%. For the application of the UDTR method a participant is exposed to two stimuli, a reference and an alternative. This is called a trial. The magnitude of the alternative stimulus can be smaller or larger than that of the reference stimulus. In this study the alternative is larger than the reference. The participant is asked to identify the larger or most uncomfortable of the two stimuli. Based on the participant's response the magnitude of the alternative stimulus is increased or decreased by a fixed step size. If the participant incorrectly (−) identifies the larger stimuli of the two the magnitude of the alternative stimulus is increased. Only after n consecutive correct (+) responses are the magnitude of the alternative stimuli decreased. Although reference is made to correct and incorrect responses, the participant is never at fault and can never be wrong in his response. Incorrect refers to the fact that the participant was not able to correctly identify the largest or most uncomfortable stimulus and therefore the difference between the stimuli was below his threshold. The reference stimulus undergoes no changes during the testing procedure. Reference and alternative stimuli are always presented to the participant in a random order.

Figure 2.5 provides a visual layout of an example test procedure making use of the three-down-one-up rule. Circles and crosses indicate the magnitudes of the alternative stimuli, where circles indicate correct responses and crosses incorrect responses. Squares indicate the magnitude of the reference stimuli. At trial one, a correct response was given, therefore the alternative magnitude did not change. After trial two an incorrect response was given and the alternative magnitude increased. Trial three, four and five yielded correct responses and therefore, after three consecutive correct responses, the alternative magnitude was decreased. The two correct responses in trials six and seven resulted in the magnitude of the alternative stimulus remaining unchanged. The single incorrect response in trial eight lead to an increase in alternative stimulus magnitude.

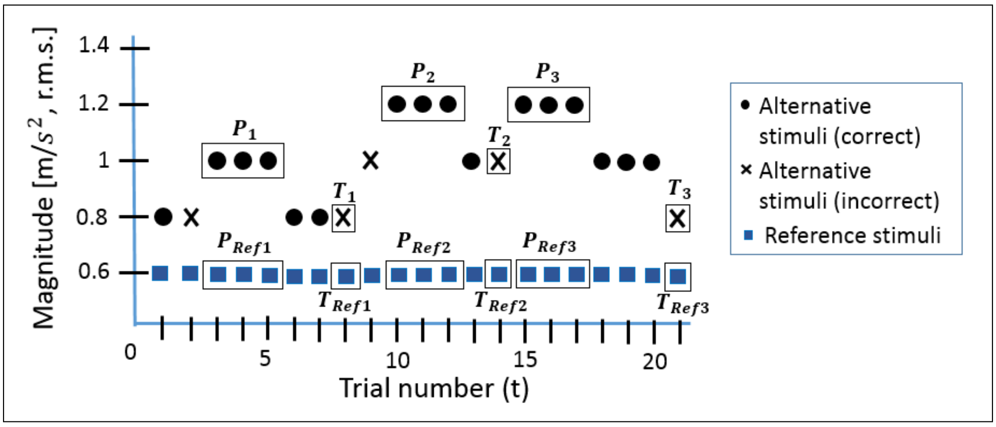

Figure 2.5: Example of the test procedure followed for the UDTR method with the three-down-one-up rule.

Levitt (1971) states that responses obtained during the procedure can be divided into up groups and down groups. A sequence of responses resulting in the magnitude of the alternative stimulus being increased is called an up group and a sequence of responses resulting in the magnitude being decreased is called a down group. The point on the psychometric function that will be estimated by the procedure depends on how these groups are compiled. Levitt (1971) states that the UDTR procedure tends to converge at the stimulus level where the probability of obtaining a down group is the same as obtaining an up group. For the UDTR method where $n = 1$ (therefore simple up down procedure) a single incorrect response would form the up group and a single correct response would form the down group. As the procedure tends to converge at the reference magnitude x where there is an equal probability of obtaining a down or an up group, the probability of obtaining a correct or incorrect response is equal. Therefore P(x) = 0.5, where P(x) is the probability of obtaining a single correct response at magnitude x. If $n = 2$ the probability of a down group (+ +) and a up group (− or +−) is equal. Therefore $[P(x)^2] = 0.5$ for two correct responses resulting in $P(x) = 0.707$. For $n = 3$ the probability of a down group (+ + +) is equal to the probability of an up group (− or + − or + + −) and therefore $[P(x)]^3 = 0.5$ and $P(x) = 0.794$. If a procedure is used where $n = 2$ it is referred to as a two-down-one-up procedure. If $n = 3$ it is referred to as a three-down-one-up procedure. Table 2.2 provides a summary of the various possible values of n and the result thereof.

In estimating the DT from the UDTR procedure the method proposed by Wetherill (1963) is discussed as it is simple and robust according to Levitt (1971). Wetherill (1963) identifies peaks and troughs and calculates the average between them to determine the magnitude of the alternative stimulus that would give a certain chance (determined by n) of obtaining a correct response. A peak (sections P_1, P_2 and P_3) is formed when the gradient of the procedure changes from an increasing alternative stimulus to a decreasing alternative stimulus. A trough (points T_1, T_2 and T_3) is formed when the gradient changes from a decreasing alternative stimulus to an increasing alternative stimuli. The first two reversals are often excluded from the calculation to eliminate starting errors (Mansfield and Griffin (2000) and Morioka and Griffin (2000)). The ADT is calculated by subtracting the mean of the peaks and troughs from the reference stimuli magnitude to obtain ΔI. The RDT (C) is calculated by dividing the ADT (ΔI) by the reference magnitude (I) as shown by Equation 2.1. Peaks and troughs are also referred to as reversals. A test would continue until a certain amount of reversals are obtained - in the case of the example it was 6 reversals.

Table 2.2: Different strategies for the UDTR procedure to obtain a certain probability of a positive response (Levitt, 1971).

n	Down Group	Up Group	Probability of sequence from down group	Probability of positive response at convergence
1	$-$	$+$	$P(x)$	$P(x) = 0.5$
2	$+-$ or $-$	$++$	$[P(x)]^2$	$P(x) = 0.707$
3	$++-$ or $+-$ or $-$	$+++$	$[P(x)]^3$	$P(x) = 0.794$

2.10 Previous studies on the difference thresholds for seated whole-body vibration

This section is focused on giving an account of the DT data for seated whole-body vibration that is currently available in literature. Special attention is given to studies that focused on the field of vehicle engineering. These studies played a key role in the planning of the experimental work and understanding human response to vibration.

Studies by Mansfield and Griffin (2000) and Pielemeier et al. (1997) were the only two studies found which simulated inputs experienced by occupants in a vehicle. In both of these studies participants were seated on an automobile seat on an actuator subjecting participants to vertical vibration only. Mansfield and Griffin (2000) exposed participants to vibration signals recorded from a real vehicle, while Pielemeier et al. (1997) exposed participants to certain frequency bands of white noise. Other DT studies such as Morioka and Griffin (2000) and Matsumoto et al. (2002) exposed participants seated on a flat rigid surface with no backrest to sinusoidal vibration. The studies made use of different psychophysical testing methods, but all employed the 2AFC method where participants always had to make a choice between two options.

Mansfield and Griffin (2000) set out to determine the ADT and RDT for participants seated on an automobile seat, fixed to an actuator, being exposed to real vibration stimuli recorded in a vehicle. The stimuli were reproductions of the vertical acceleration measured on the seat guide of a vehicle. The vibration was measured as the vehicle drove over a tarmac and a paved road. To minimise the effect of inter-participant variability, caused by the response of the seat, the stimuli were scaled for each participant such that the BS 6841 weighted acceleration measured on the seat surface showed the desired acceleration output. Ten male and 10 female participants were exposed to 4 different reference stimuli. The tarmac stimuli were scaled and played to participants at weighted r.m.s. magnitudes of 0.2, 0.4 and 0.8 m/s^2 and the paved road vibration stimulus were scaled to a weighted r.m.s. of 0.4 m/s^2. Both the tarmac and paved road stimuli contained frequencies from approximately 0 to 30 Hz. The upper value of 30 Hz was limited by the actuator's performance.

Participants were exposed to a 10 s reference stimulus followed by a 2 s pause and then a 10 s alternative stimulus. The reference and alternative stimuli are given to the participant in a random order. White noise at 80 dB was played to participants through earphones in order to reduce the effect of the noise from the actuator. The UDTR method was implemented with a three-down-one-up rule. A step size of 4 % of the reference stimulus was used. After being exposed to a reference and an alternative stimulus participants were asked the question: "Did you feel more uncomfortable during the first or the second stimulus?". Precautions were taken to ensure that a true threshold was measured. If the mean magnitude of the first 3 test stimuli for the first measured set of correct responses was lower than than that of the second set of correct responses the first was rejected as possibly being a false-positive response. After this, tests continued until three sets of three consecutive peaks had a standard deviation in their average magnitude of less than 5% of the reference magnitude and where three consecutive troughs had a standard deviation in their magnitude of less than 5% of the reference magnitude. Six reversals were used in the data analysis.

Mansfield and Griffin (2000) report that participants made use of various strategies in order to select the most uncomfortable stimuli. Many participants compared the beginning of the first stimulus to the beginning of the second stimulus or the end of the first to the end of the second. Some participants made their judgements by evaluating discomfort caused by movements of specific body areas such as thighs, viscera, knees or head. Other strategies included comparison of the impulses in the stimuli as well as comparing the end of the first stimulus to the beginning of the second stimulus.

Mansfield and Griffin (2000) found that there was no significant difference between the absolute (Wilcoxon matched-pairs, $p < 0.005$) and RDTs (Wilcoxon matched-pairs, $p < 0.05$) for the three tarmac stimuli. This data implies that Weber's Law holds for DTs obtained with the same spectral shape. As there was no significant difference between the DTs for the tarmac stimuli with weighted r.m.s. of 0.4 m/s^2 and the pave stimuli with weighted r.m.s. of 0.4 m/s^2 it might be concluded that the W_b frequency weighting made an appropriate allowance for the effect of frequency for the discomfort of the different road surfaces. However, if it is assumed that Weber's Law holds and W_b is suitable then the RDTs should be the same for all magnitudes, irrespective of frequency spectrum. As the data showed a significant difference between the RDTs for the tarmac 0.8 m/s^2 and pave 0.4 m/s^2, but no difference between all other combinations the results are inconclusive. It is stated that additional experimental work is required to investigate the applicability of frequency weightings to the prediction of DTs. It was also found that there were no consistent differences between the results for male and female participants. Mansfield and Griffin (2000) conclude that the RDT was approximately 13%. RDT results for every reference stimulus are summarised in Table 2.3.

Table 2.3: Summary of published RDT data.

Author (s)	**Excitation**		**RDT[1] (C) [%]**				
	Type	**Ref r.m.s. [m/s^2]**	**Min**	**25th**	**Median**	**75th**	**Max**
Mansfield and Griffin (2000)	Tarmac	0.2*	6.0*	11.0*	12.8*	16.9*	34.9*
		0.4*	6.9*	10.9*	13.8*	16.1*	36.1*
		0.8*	5.9*	8.8*	11.8*	14.4*	30.4*
	Pave	0.4*	9.3*	12.2*	14.1*	19.1*	29.5*
Morioka and Griffin (2000)[2]	5 Hz Sinusoid	0.1	7.3	10.2	12.3	14.7	20.4
	20 Hz Sinusoid		6.8	7.4	11.0	13.8	20.3
	5 Hz Sinusoid	0.5	5.9	7.0	10.3	13.1	24.5
	20 Hz Sinusoid		3.2	5.9	8.1	14.5	24.9
Matsumoto et al. (2002) [3]	4 Hz Sinusoid	0.7	-	4.0	5.3	5.9	-
	8 Hz Sinusoid		-	4.6	5.7	7.3	-
	16 Hz Sinusoid		-	5.4	6.0	8.1	-
	31.5 Hz Sinusoid		-	5.9	6.6	8.7	-
	63 Hz Sinusoid		-	5.3	5.9	6.1	-
	80 Hz Sinusoid		-	4.4	6.1	6.7	-
Pielemeier et al. (1997) [4]	2.8 – 5.7 Hz [5]	0.079	7.5	-	13.8	-	22.5
	5.7 – 11.3 Hz [6]		9.8	-	16.3	-	17.5
	11.3 – 22.7 Hz [7]		7.0	-	11.3	-	13.8

Morioka and Griffin (2000) investigated DTs for whole-body vertical vibration looking at the effects of frequency and magnitude. Twelve participants were exposed to four sinusoidal reference vibrations: two frequencies of 5 and 20 Hz and each at an unweighted r.m.s. magnitude of 0.1 and 0.5 m/s^2. Participants were seated on a flat wooden surface with no backrest. The UDTR procedure was used with step sizes of 2.9 %. Each reference stimulus was 4 s long, followed by a 1 s pause and a 4 s alternative stimulus. After each run the following question was asked: "Did you judge the first or the second to be the greater?" The focus was thus on intensity perception and not necessary comfort. Measurements continued until 10 reversals were obtained. The first two reversals were omitted, making reference to Levitt and Rabiner (1967), thus using eight reversals to calculate the DT.

Morioka and Griffin (2000) mention that some participants reported that they judged the difference between the reference and alternative stimuli by feeling the movement of a particular part of the body. At 5 Hz the movement of the head, knee, shoulders, or viscera (internal organs) was used and for the 20 Hz stimulus movement of the upper leg or back.

[1]Accelerations weighted according to the BS 6841 standard are indicated by a "*".

[2]Minimum, 25th percentile, 75th percentile and maximum are not provided and were obtained from data supplied.

[3]Some variation may exist as exact data were not supplied and values had to be read off a supplied graph. Minimum and maximum values were not published.

[4]Note that sample size consisted of three participants, therefore the minimum, median and maximum are three data points from three participants for a certain excitation. The RDT was not published and had to be calculated.

[5]Octave band with geometric mean of 4 Hz.

[6]Octave band with geometric mean of 8 Hz.

[7]Octave band with geometric mean of 16 Hz.

Morioka and Griffin (2000) report that there was no significant difference (Wilcoxon, $p > 0.3$) between the ADT obtained at 5 and 20 Hz for both magnitudes. There was also no significant difference (Friedman, $p > 0.5$) between the RDTs for the four stimuli. Although a trend was observed that the median RDT reduced for an increase in vibration magnitude, this result is approximately consistent with Weber's Law. Although not significantly different, it was also observed that the median RDT tend to be lower for the higher frequency at both magnitudes. It was stated that this could indicate that detection of vibration sensitivity is larger at 20 Hz than at 5 Hz, implying that it is not recommended to use frequency weightings that assume vertical vibration at 5 Hz to produce significant greater discomfort than vertical vibration at 20 Hz. In conclusion Morioka and Griffin (2000) found the RDT to be approximately 10 % (refer to Table 2.3), not differing significantly between the two frequencies and magnitudes of vibration. Morioka and Griffin (2000) also mention that, "further information is required in order to confidently predict detection sensitivity with the full range of complex motions in vehicles".

Matsumoto et al. (2002) investigated the effect of frequency on DTs for vertical sinusoidal whole-body vibration. Participants were exposed to six different frequencies over a broad range: 4, 8, 16, 31.5, 63 and 80 Hz. All vibrations had the same unweighted r.m.s. magnitude of 0.7 m/s^2. Sixteen male volunteers were used. Participants were seated on the top face of the shaker without a backrest. Participants wore ear defenders to prevent them from perceiving the vibration by accompanied noise from the shaker. This study did not apply the UDTR procedure, but rather used the method of limits. As discussed, the method of limits estimates the DT such that a participant would have a 50 % chance of correctly identifying the largest of two stimuli. Participants were exposed to a reference and alternative stimulus and asked to judge the vibration magnitude of the stimuli by using one of the following phrases: "The first vibration was greater", "The second vibration was greater" or "I did not perceive a difference between the two stimuli". The difference between the magnitude of the reference or the alternative would increase with a step size of 2.9 % until a correct response is obtained. This would be called a series of trials. The alternative and reference stimulus was presented in four ways (see Figure 2.4) defining if the reference or alternative is presented first and whether the test vibration increased or decreased. The test was terminated after looping three times through the four presentation types. The magnitude of the reference stayed constant with only the alternative changing. Morioka and Griffin (2000) provides an example of such a test procedure which is presented in Figure 2.6.

Table 2.4: Four ways of presenting the reference and alternative stimuli (Matsumoto et al., 2002).

	Alternative magnitude larger than reference	Alternative magnitude smaller than reference
Reference →Alternative	Type 1	Type 2
Alternative →Reference	Type 3	Type 4

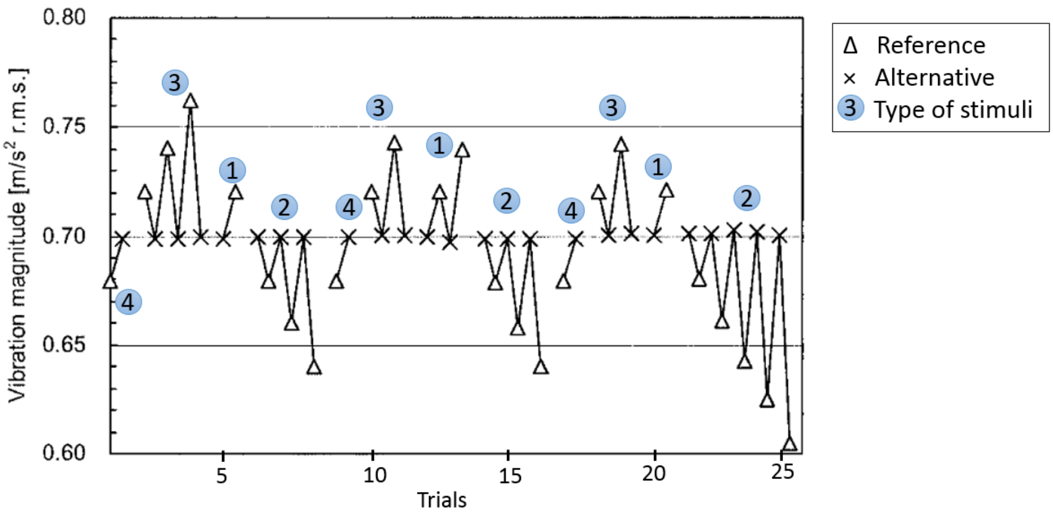

Figure 2.6: Example of the test procedure followed by Morioka and Griffin (2000). The figure was adapted from Morioka and Griffin (2000).

Matsumoto et al. (2002) state that it is generally known that when the magnitudes of two stimuli, of any type, in a series are compared the magnitude of the second stimulus tends to be judged relatively greater than the magnitude of the first stimulus. This effect was observed in the results of this experiment. Figure 2.7 shows the ADTs obtained when the magnitude of the vibration presented first was greater than the second and when the magnitude of the vibration presented second was greater than the first. When the first stimulus was greater people tended to choose the second as greater, selecting the incorrect stimulus to be the greatest, resulting in a higher difference threshold. The ADT for a series of trials when the first was larger than the second is significantly different from when the second was larger as the first for all frequencies (Wilcoxon, $p < 0.05$ at 4, 63 and 80 Hz, $p < 0.01$ at 8, 16 and 31.5 Hz). This indicates that participants might judge the magnitude of the second vibration relatively larger than the first.

Matsumoto et al. (2002) found that ADTs were dependant on frequency with 4 Hz being significantly lower than that at 16, 31.5 and 63 Hz and the RDT at 31.5 Hz was significantly greater than that at 4, 8 and 80 Hz. Median RDTs across the various frequencies were found to be between 5.2 and 6.5 % (refer to Table 2.3). The effect of the psychophysical method used is stated as a possible cause for the RDTs being much lower than that of other comparable studies.

Pielemeier et al. (1997) set out to estimate the ADT for low level stimuli of vertical vibration at three octave frequency bands with centres 4, 8 and 16 Hz for frozen Gaussian noise on an automobile seat. The three octave bands had ranges of 2.8 - 5.7 Hz, 5.7 - 11.3 Hz and 11.3 - 22.7 Hz. All three frequency bands have the same r.m.s. magnitude. The frequency bands were chosen based on their importance for vertical whole-body vibration sensitivity according to Griffin (1990). These frequency bands are also similar to frequencies important for road vibrations transmitted to automobile occupants. Participants were seated on an automobile seat in the Ford Vehicle Vibration Simulator. The simulator has 12 degrees of freedom (DOF), but only the seat was vibrated in a vertical direction. The reference stimulus had an unweighted magnitude of 0.079 m/s^2 r.m.s. (8 mg, r.m.s.). Participants were exposed to four alternative stimuli having r.m.s. values 3.125% (0.25 mg), 6.25% (0.5 mg), 12.5% (1.0 mg) and 25% (2.0 mg) larger than the reference. The psychophysical method used was the method of constants. With the method of constants the participant's response does not govern the test procedure. Participants were presented with a reference and alternative stimulus and asked to identify the one with the highest intensity. The various alternative stimuli were presented in random order and the same amount of trials were completed at each alternative magnitude. The threshold where participants would have a 75 % chance of correctly identifying the largest of two stimuli was estimated. Three participants were used and trained with feedback until their performance stabilised for each frequency. Training required 100 - 200 trials at every frequency. The feedback was given by a control system with a user interface where the participant could press a button to indicate his answer. The control system would then provide instant feedback indicating if the answer is correct.

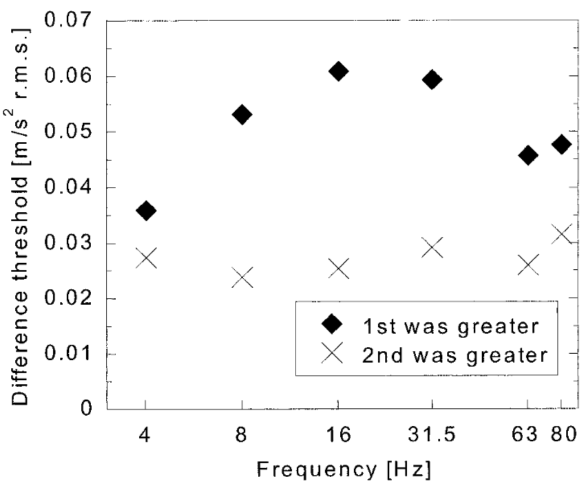

Figure 2.7: Median difference thresholds (as a fraction) obtained when the magnitude of the vibration presented first was greater than the second and when the magnitude of the vibration presented second was greater than the first from Matsumoto et al. (2002).

Pielemeier et al. (1997) mentions that with a 4 s reference/alternative stimulus and a 1 s pause at 4 Hz, participants struggled to determine exactly when the one ends and when the other starts. By using an interface that indicates when stimulus 1 and 2 is playing the pause could be reduced to 0.5 s. This also eliminated bias towards the second stimuli that was observed. The vertical seat transmissibility was determined by using a 0.196 m/s^2 (20 mg) broadband uncorrelated Gaussian vertical excitation. Between participants at a single frequency the maximum difference was 0.8:1. The r.m.s acceleration was measured on the seat and scaled for every participant for every stimulus to counter the effect of the seat transfer function. The total scaling range was 4:1 given an amplification of 2:1 at 4 Hz and an attenuation of 0.4:1 at 16 Hz. Tests were conducted in blocks of 25 pairs. In total 150 - 200 trials were preformed per participant per frequency resulting in 3000 trials per person over a period of a month. Figure 2.8 provides an example of the psychometric function of proportion correct versus r.m.s. stimulus difference for the 4 Hz signal. The sample size was restricted due to the large number of trials required to get a good estimate. Each data point on the graph indicates the proportion of correct responses at that reference magnitude. By fitting a curve to these points the reference magnitude where a participant would have a 75 % chance of correctly identifying the largest stimulus was estimated.

Pielemeier et al. (1997) reports that the variations with frequency are not large enough to conclude that there is frequency dependence. Pielemeier et al. (1997) reports further that most of the estimates for the ADTs lie between 0.006 m/s^2 and 0.014 m/s^2 which is close to the perception threshold for similar frequency ranges. It is stated that it will be interesting to see the results of future experiments at higher reference magnitudes and to observe the dependence of DT on the magnitude of the reference stimulus. Pielemeier et al. (1997) does not present RDT data. Using ADT data and the stimuli magnitudes the RDTs were calculated to be between 7 % and 22.5 % (refer to Table 2.3).

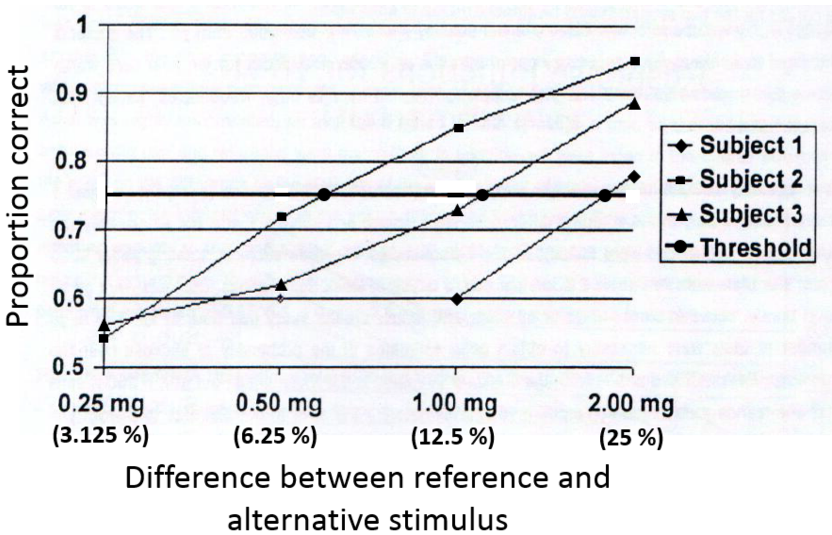

Figure 2.8: Psychometric function of proportion correct versus difference in r.m.s. magnitude between reference and alternative stimulus for the 4 Hz signal. (Figure adapter from Pielemeier et al. (1997).)

2.10.1 Summary of previous difference threshold studies

This section provides a summary of previously published studies on DTs. Table 2.5 provides details on the methods and experimental procedure used by each study. Table 2.6 provides the title of each study, the environment it was done in, the input stimuli used and the participants used. A summary of the RDTs are presented in Table 2.3, together with a visual comparative box plot in Figure 2.9. A few box plots will be used to indicate the spread of certain data sets. All box plots are defined in the following manner: the lowest and highest horizontal stripes indicate the minimum and maximum values respectively, while the lower and upper ends of the box indicates the 25th and 75th percentiles respectively, the line within the box indicates the median.

It is interesting to note that, except for data from Matsumoto et al. (2002), medians are in the region between 8 and 14 %. RDTs from Matsumoto et al. (2002) are a bit lower than the rest of the studies ranging from 5.3 to 6.6 %. Matsumoto et al. (2002) mentions that their RDTs are lower than expected and mentions the psychophysical method used as a possible cause, stating that the effect of the psychophysical methods should be investigated. It is also interesting to note that all the DT studies discussed here use participants younger than 30 years old. Investigating the effect of age on DTs by using older participants could possibly yield interesting results.

Mansfield and Griffin (2000) asked participants to identify the most uncomfortable stimulus while Morioka and Griffin (2000) and Matsumoto et al. (2002) asked participants to identity the greater stimulus and Pielemeier et al. (1997) asked participants to identify the stimulus with the highest intensity. Mansfield and Griffin (2000) therefore determines the smallest change in vibration magnitude that will result in a change in discomfort, while the other three studies determines the smallest change in vibration magnitude that will be perceived by the participant as a change in intensity/magnitude. When comparing the results from these studies the assumption was made that the same result will be obtained if participants are asked to identify the most uncomfortable or higher intensity, although it is possible that these two case yield different results.

Table 2.5: Summary of test procedures used in published DT studies.

Author (s)	**Aural consideration**	**Method**	**Step size**	**Signal duration**	**Stop criteria and selection of data for analysis**	**Question**
Mansfield and Griffin (2000)	White noise at 80 dB played through earphones	UDTR with three-down-one-up rule.	4 %	10 s reference, 2 s pause, 10 s alternative	If the mean magnitude of the first three test stimuli for the first measured set of correct responses was lower than than that of the second set of correct responses the first was rejected as possible being a false-positive response. After this measurement continued until three sets of three consecutive peaks had a standard deviation in their average magnitude of <5 % of the reference magnitude and where the three corresponding troughs had a standard deviation in their magnitude of <5 % of the reference magnitude. Therefore using six reversals in analysis.	"Did you feel the more discomfort during the first or the second stimulus?"
Morioka and Griffin (2000)	Ear defenders with integrated speaker 70 dB white noise.	UDTR with three-down-one-up rule.	2.9 %	4 s reference, 1 s pause, 4 s alternative	Stop after 10 reversals. Neglect first two reversals during data analysis to reduce starting errors according to Levitt and Rabiner (1967).	"Did you judge the first or the second to be greater?"
Matsumoto et al. (2002)	Ear defenders	Method of limits	2.9 %	4 s reference, 2 s pause, 4 s alternative	The test procedure continued until the cycle of four presentation types was completed three times. The ADT for a series of trials were calculated by taking the average of the magnitude difference at the last trial and at the single last trial. An average is then calculated across the three cycles for each type.	Indicate if the first or second stimulus is the greatest or if no difference is perceived.
Pielemeier et al. (1997)	Not mentioned	Method of constants	3.125, 6.25, 12.5 and 25 %	4 s reference, 0.5 s pause, 4 s alternative	After training participants, 150 to 250 trials were done per participant at each frequency. The number of trials are based on a statistical analysis. All data gathered after training was used.	Indicate which stimulus is of higher intensity.

Table 2.6: Summary of DT studies with respect to the experimental environment, input signal and number of participants used.

Author (s)	Title	Environment	Input signal	Partici-pants
Mansfield and Griffin (2000)	Difference thresholds for automobile seat vibration	Vehicle seat on shaker	Actual vibration recorded on vehicle seat rail	10 men and 10 women
Morioka and Griffin (2000)	Difference thresholds for intensity perception of whole-body vertical vibration: Effect of frequency and magnitude	Flat wooden surface on shaker with no backrest	Sine wave	12 males
Matsumoto et al. (2002)	Influence of Frequency on Difference Thresholds for Magnitude of vertical sinusoidal vibration	Flat top surface on shaker with no backrest	Sine wave	16 males
Pielemeier et al. (1997)	Just noticeable difference in vertical vibration for participants on an automobile seat	Vehicle seat in the Ford Vehicle Vibration Simulator	Frozen Gaussian noise in specific frequency bands	3 trained males

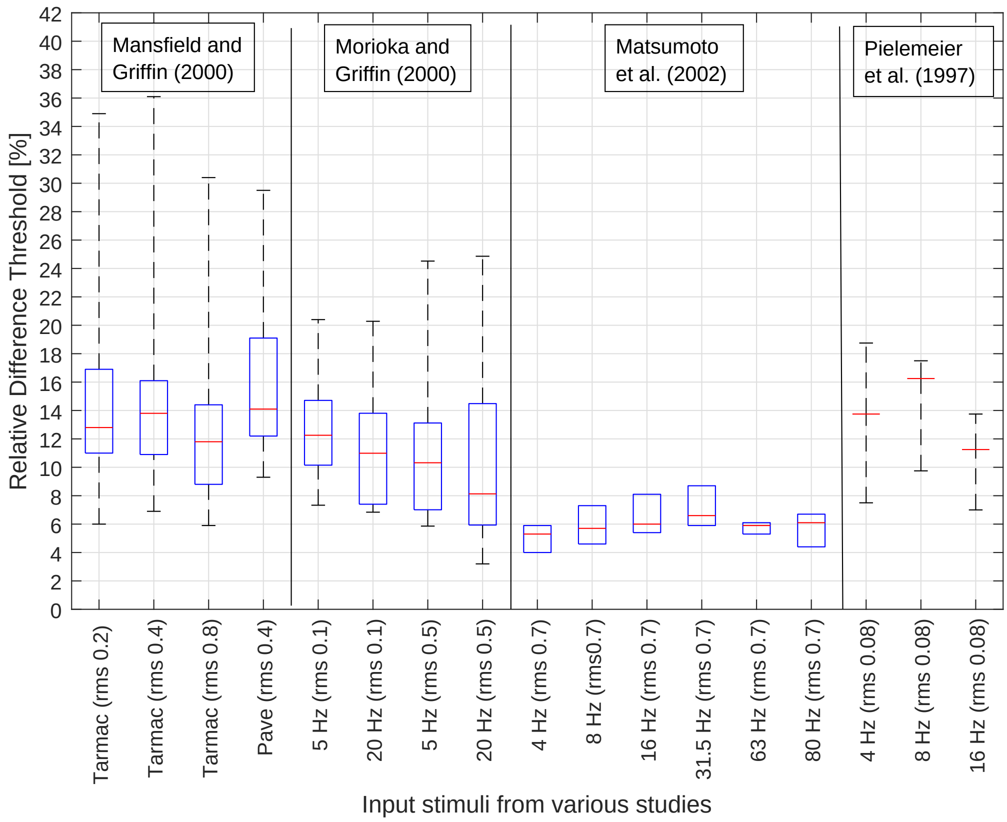

Figure 2.9: Box plot of the RDTs from published data.

2.11 Conclusions from the literature study

Mansfield and Griffin (2000) state that the vibrations that a person perceive in a vehicle may influence their opinion of the vehicle. They continue to state that accelerations can be measured in a vehicle in order to try and predict if design changes will improve comfort. Measuring equipment can detect changes in acceleration not perceivable by a human and therefore Mansfield and Griffin (2000) state that it is of importance to know what the smallest change in vibration magnitude is that a human can perceive. Mansfield and Griffin (2000) is of the opinion that knowledge about the smallest change in magnitude of vibration that a human can detect, can assist engineers to decide which design changes would result in a perceivable improvement in comfort. They set out to determined a DT for participants seated in a vehicle seat exposed to vertical vibrations which are similar to those experienced in a real vehicle.

Morioka and Griffin (2000) state that: "... it is useful to know how much a vibration has to be reduced for it to be perceived as being less uncomfortable." Morioka and Griffin (2000) state further that although it is assumed that a reduction in vibration magnitude will result in reduced discomfort, it is not known when a reduction in vibration magnitude will not result in a noticeable improvement in comfort. Therefore it is implied that if a change in magnitude is smaller that the perceivable threshold of a human no change in comfort will be perceived. Morioka and Griffin (2000) set out to determine DTs for various sinusoidal vibration inputs to solve the problem. Participant were exposed to vertical sine wave excitations at two magnitudes and two frequencies while seated on a flat rigid surface with no backrest.

Pielemeier et al. (1997) state that the smallest change in vibration magnitude that a human can detect was important during the design of simulator aimed at ride comfort simulations. They determined DTs for participants seated in a vehicle seat exposed to 5 frequency ranges of Gaussian noise to investigate the effect of frequency on the DT.

From Mansfield and Griffin (2000), Morioka and Griffin (2000) and Pielemeier et al. (1997) it is clear that knowledge about the DT of humans will add value to the vehicle design process and understanding the human's perception to vibration. Research done by Mansfield and Griffin (2000), Morioka and Griffin (2000) and Pielemeier et al. (1997) exposed participants to purely vertical acceleration. The question arose what the DT would be should participants be exposed to all six components of acceleration and if Weber's law would hold in such a case.

2.12 Problem statement, research question and aim

The literature study has shown that DTs have been determined for vertical sinusoidal inputs at various frequencies and amplitudes (Morioka and Griffin (2000) and Matsumoto et al. (2002)). It has also been determined for actual vertical accelerations recorded in a vehicle over different roads and then played to participants on an actuator (Mansfield and Griffin, 2000). Further more, DTs have been determined for certain frequency bands of interest consisting of Gaussian noise (Pielemeier et al., 1997).

There is a void in current research as it is not known what the DT would be if participants were to be seated in a real vehicle subjected to all six components of acceleration. Without knowing the smallest change in vibration that causes a change in comfort for occupants seated in a vehicle exposed to all six components of acceleration, suspension changes aimed at reducing discomfort or various suspension settings (such as sport and comfort) could be implemented without the end user being able to notice a difference. The first research question would therefore be, "What are the DTs for drivers seated in a vehicle, on a 4-poster test rig, if exposed to all six components of acceleration?". The study aims to answer this question by calculating the DTs based on vertical accelerations while participants are seated in a vehicle on a 4-poster test rig being exposed to all six components of acceleration - as if driving in a straight line over a rough road.

DTs are always determined at a specific excitation level. Weber's law states that the ratio between the excitation and the change in excitation that will be just noticeable are at a constant ratio. If Weber's law holds it would reduce the number of experiments required at different magnitudes of excitation. The second question is therefore, "Does Weber's law hold for a RDT calculated from vertical acceleration when a driver is exposed to all six components of acceleration within a vehicle?". The study aims to answer this question by conduction DT tests over two road profiles that differ only in magnitude and not in frequency content.

2.13 Dissertation overview

Figure 2.10 provides a layout of the dissertation. Chapter 1 gave an introduction to ride comfort, human response to vibration and difference thresholds explaining the significance of each. Chapter 2 provided an overview of published literature in order to locate a void in current research. Special attention is given to previous studies determining DTs for whole-body vibration. Chapter 3 will provide the necessary details on the experimental work done to determine the DTs. It is divided in to three parts where the first states important parameters and considerations in designing the experiment, the second section depicts the experimental setup and the third describes the complete experimental testing procedure in detail. Chapter 4 presents all the DT results and aims to answer the two questions. The dissertation ends with Chapter 5 concluding on the research done and providing recommendations for future work.

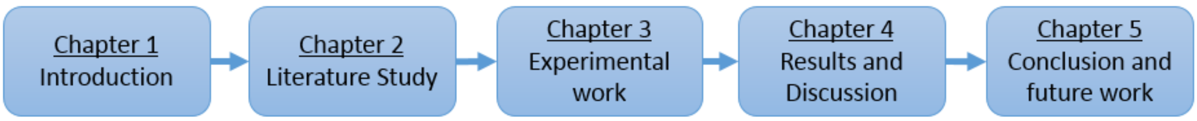

Figure 2.10: Dissertation overview by chapter.

Chapter 3

Experimental Work

3.1 Introduction

Experimental work was conducted with the purpose of determining the DTs for drivers seated in a vehicle on a 4-poster test rig while exposed to all six components of acceleration. DTs were determined for two reference road profiles while participants were seated in the driver seat of a Range Rover Evoque. These two road profiles are magnitude scaled version of each other and therefore differ only in magnitude, containing the same sequence of events. The validity of Weber's law was also investigated from DTs obtained over the two road profiles of different magnitude. Ten participants partook in the study. The participants were all male and working or studying in the field of vehicle engineering. The UDTR procedure was used to estimate the DT of each participant by governing the vertical acceleration of the driver seat rail. The UDTR procedure relies on the principle that the vertical acceleration must be decreased or increased by a certain percentage based on the participant's response. In order to increase the vertical acceleration at the seat rail by a certain percentage during the test procedure, the relationship between the displacement input from the 4-poster and the seat rail vertical acceleration output had to be determined. The road input was multiplied by various multiplication factors in order to obtain the required r.m.s. change in the vertical acceleration at the driver seat rail in order to produce the required alternative stimuli.

This chapter is divided in to three sections as shown in Figure 3.1. The first section (Design of experiment) contains the fundamental parameters and considerations for the psychophysical testing method and for the processing of data. Section two (Experimental setup) contains all necessary information regarding the 4-poster test rig, vehicle, data acquisitioning, as well as road profile inputs. The third section (Difference threshold testing) describes the testing procedure followed in order to determine the DT of each participant from the participant's briefing before the test starts tot calculating the DT at the end of a test.

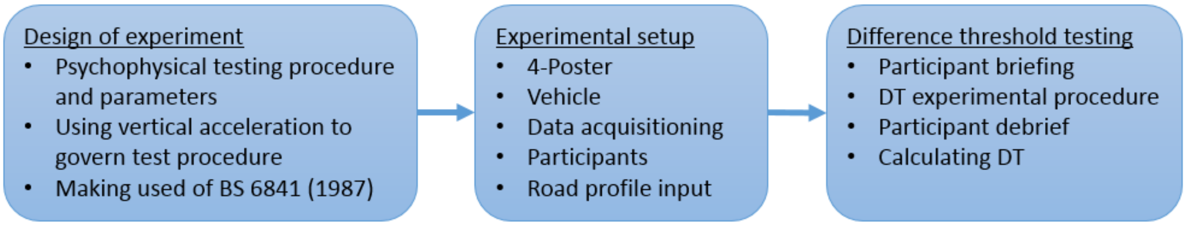

Figure 3.1: Process flow diagram of Chapter 3.

3.2 Design of experiment

The design of experiment outlines some of the important aspects with regard to the psychophysical testing method, selecting a sensor to govern the increase and decrease of the acceleration magnitude, and whether to make use of the BS 6841 to interpret measured accelerations.

3.2.1 Psychophysical testing procedure and parameters

The UDTR procedure was selected as the psychophysical testing procedure to estimate the DT. It was selected based on the principal that it estimates a DT for a participant at a 79 % certainty level and the fact that it has also been used by Mansfield and Griffin (2000) as well as Morioka and Griffin (2000) with success. The UDTR procedure has various parameters that has to be defined. These parameters include the duration of the reference and alternative stimuli, duration of pause between stimuli, step size used to increase/decrease the difference between the reference and alternative stimuli, the order of presenting the reference and alternative stimuli, the number of reversals required, and the question asked to the participant after a trial. All parameters for the procedure used to determine the DT as well as the ground which these parameters are based on are presented in Table 3.1.

An evaluation of the sensory information available to the participant in conjunction with the aim of the experiment was done. The aim of the experiment is to determine DTs for a change in vibration magnitude perceived by participants through their body, attempting to exclude the effect of sound and visual stimuli as far as possible. Table 3.2 provides and overview of considerations with respect to visual and aural inputs.

Table 3.1: Parameters used for tests conducted to determine the DT.

Parameter	**Specification**	**Reason**
Method	UDTR procedure with three-down-one-up rule	When a person is exposed to two stimuli which differ in magnitude by the person's DT, there will be a 79.4% chance of the person correctly identifying the most uncomfortable of the two stimuli. This method was also used by Mansfield and Griffin (2000) and Morioka and Griffin (2000).
Neglecting reversals in DT calculation	Neglect first 2 reversals	Mansfield and Griffin (2000) rejected the first three correct responses if their mean was lower than the second set of correct responses; Morioka and Griffin (2000) refers to Levitt and Rabiner (1967) which states that the first two reversals should be omitted in order to reduce starting errors; Morioka and Griffin (2008) neglected the first two reversals referring to Levitt (1971).
Reference / Alternative duration	20 s	Mansfield and Griffin (2000) used 10 s, Morioka and Griffin (2000) used 4 s, Matsumoto et al. (2002) used 4 s and Pielemeier et al. (1997) used 4 s. The test track used was 444 m long and was negotiated at 80 km/h resulted in a 20 s stimulus.
Pause	2 s	Mansfield and Griffin (2000) used 2 s, Morioka and Griffin (2000) used 1 s, Matsumoto et al. (2002) used 2 s and Pielemeier et al. (1997) used 0.5 s with feedback.
Step size	3 %	Based on Mansfield and Griffin (2000) using 4 %, Morioka and Griffin (2000) using 2.9 % and Matsumoto et al. (2002) using 2.9 %. Wetherill and Levitt (1965) suggests that an initial step size of half of the difference threshold or the difference threshold can be used. For a second set of tests the step size can be reduced to 0.25 or 0.5 of the expected difference threshold. The expected median RDT is 10 to 20 % based on literature. Using the 0.25 step size it results in 2.5 to 5 % step size.
Reversals	8	Mansfield and Griffin (2000) and Morioka and Griffin (2008) tested until 6 usable reversals were obtained and Morioka and Griffin (2000) tested until 10 reversals were obtained. Levitt (1971) refers to Wetherill and Levitt (1965) that recommends that at least six to eight reversals should be obtained.
Question asked	"Did you feel more discomfort during the first or the second stimuli?'	The question used is identical to that used by Mansfield and Griffin (2000).
Sequence of Reference and Alternative signals	Random	It is essential to use a random order.

Table 3.2: Considerations with respect to the sensory inputs of a human.

Sensory input	**Used**	**Literature**
Visual	It was considered to blindfold participants so that they would not use the movement of the vehicle body in relation to external objects to gauge the roughness of a road. It was decided not to blindfold participants as limiting sight could cause participants to feel uncomfortable.	Previous studies on vertical whole body vibration do not particularly pay attention to visual inputs.
Aural	During preliminary testing, researchers explored the use of white noise played either though the vehicle's sound system or head phones. It was found that in order to mask suspension and actuator noise, the white noise had to be sufficiently loud that it could cause discomfort. Therefore participants were asked to wear earplugs. The earplugs used were in-ear deformable ear plugs. This worked well in reducing noise from the suspension and actuators.	Mansfield and Griffin (2000) played 80 dB white noise, Morioka and Griffin (2000) played 70 dB white noise, and Morioka and Griffin (2000) played 75 dB white noise to participants through headphones. Matsumoto et al. (2002) also made use of ear defenders.

3.2.2 Using vertical acceleration to govern the UDTR procedure

In order to make use of the UDTR procedure to estimate the DTs of participants, the magnitude of acceleration that the participants are exposed to must be adjustable. Previous studies discussed in Section 2.10 exposed participants to only vertical acceleration and therefore the magnitude of the vertical acceleration was adjusted. In this study participants were exposed to all six components of acceleration. Various methods existed in order to quantify the acceleration magnitude that participants will be exposed to in order to govern the UDTR procedure (increase and decrease of vibration magnitude). In order to simplify the procedure, although participants were exposed to all six components of acceleration while seated in the vehicle, the UDTR procedure was governed by adjusting the vertical acceleration of the seat rail without using a transfer function. The accelerometer situated on the FL corner of the driver seat rail was used.

Previous studies making use of vehicle seats, such as Mansfield and Griffin (2000) and Pielemeier et al. (1997), individually scaled the vibration stimulus measured on the seat. This was done to ensure that every participant would experience the same magnitude of vibration irrespective of the seat's transfer function for that participant. Due to certain time/resource constraints it was not possible to scale the inputs individually for every participant such that each participant would experience a similar magnitude stimulus measured underneath the ischial tuberosities. Therefore the procedure was governed by using the vertical seat rail acceleration not taking the variation in acceleration that would be experienced by participant due to the effect of the seat into account.

3.2.3 Interpreting accelerations by making use of BS 6841

Mansfield and Griffin (2000) reports BS 6841 weighted acceleration data and uses this data to calculate DTs. The results from Mansfield and Griffin (2000) were inconclusive regarding the applicability of the W_b weighting curve, from BS 6841, on the prediction of difference thresholds. Mansfield and Griffin (2000) recommends, "Additional experimental work is required to investigate the applicability of frequency weightings to the prediction of difference thresholds." The applicability of the W_b weighting curve can also be questioned by observing the results of Morioka and Griffin (2000), Matsumoto et al. (2002) and Pielemeier et al. (1997). These results do not indicate the same perception to vibration for different frequencies as the W_b weighting curve is understood to predict.

Although there are some uncertainty regarding the applicability of weighting functions in DT testing all acceleration data measured within the vehicle were interpreted using weighting functions to account for the human's sensitivity to various frequencies.

The asymptotic approximation of the frequency weighting function with frequency band limitation, supplied in Table 3 of BS 6841, was used. All frequency content below 0.5 Hz and above 80 Hz was discarded as it falls outside the range of interest as well as to discard content that falls outside of the sensors' specifications. The filter was applied in the frequency domain during post processing using MATLAB. Figure 3.2 displays the filter in the frequency domain.

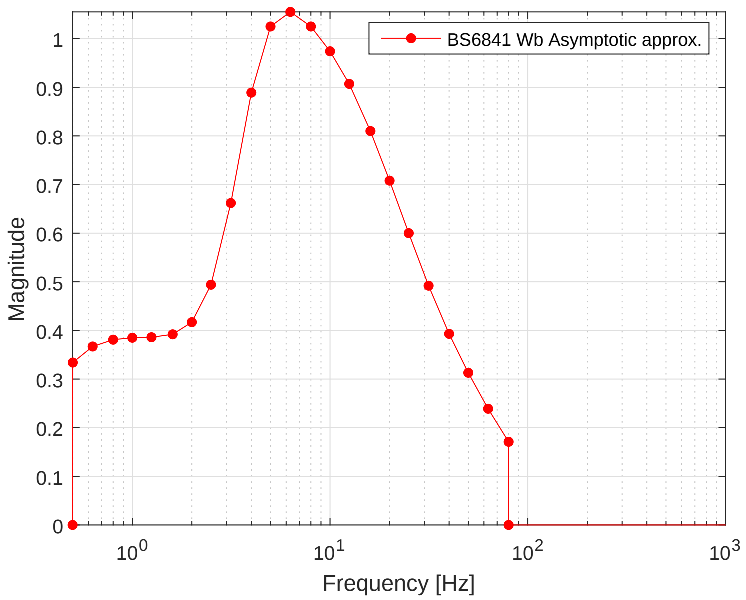

Figure 3.2: The asymptotic approximation of the frequency weighting function with frequency band limitation which is supplied in Table 3 of BS 6841. The weighting function was forced to be zero below 0.5 Hz and zero above 80 Hz.

3.3 Experimental setup

The experimental setup consisted of four components: the 4-poster test rig, the vehicle, the data acquisition systems and the participants. Figure 3.3 provides a schematic layout of the experimental setup. The four components are indicated by different colours and their names are underlined. Details surrounding each components are discussed in the subsections to follow.

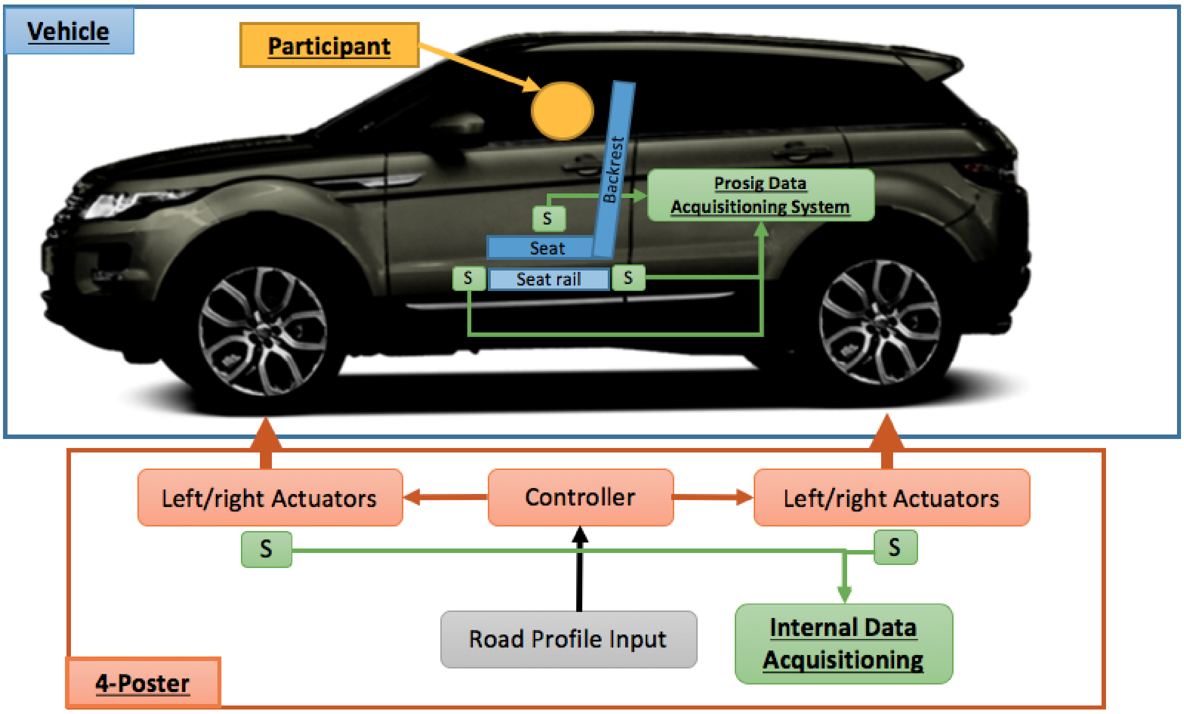

Figure 3.3: Schematic layout of the experimental setup.

3.3.1 4-Poster test rig

Experimental work was conducted at Tenneco Automotive Europe BVBA, located in Sint-Truiden, Belgium. Tenneco's 4-poster test rig was used. The test rig has more powerful actuators in the rear than in the front. Due to the fact that the Evoque has a 57:43 (front:rear) weight distribution the heavier part of the vehicle was placed on the more powerful actuators to attain the required displacement at the higher frequencies of the road profiles. Therefore the front of the vehicle was placed on the rear of the 4-poster. When reference is made to the 4-poster it will be in the 4-poster configuration and when reference is made to the vehicle it will be in the vehicle configuration (see Figure 3.4). Road profiles, defined by vertical and longitudinal displacement, were loaded for each of the four actuators. Figure 3.5 provides a visual diagram of the 4-poster testing laboratory with the vehicle on the actuators. The 4-poster could excite frequencies up to 40 Hz at the required displacements.

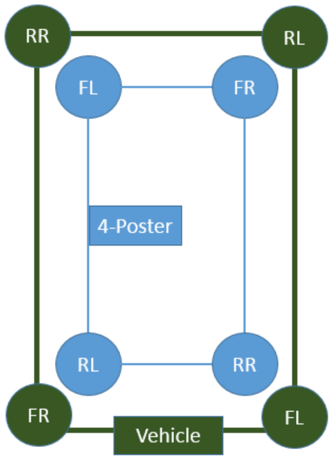

Figure 3.4: Relationship between 4-poster orientation and vehicle orientation.

3.3.2 Vehicle

A Range Rover Evoque was used as the testing platform to determine DTs. The road profiles used represent off-road driving conditions making the Evoque a suitable platform. The necessary technical information of the vehicle is supplied in Table 3.3. Testing was carried out with two occupants (participant and researcher) in the vehicle. The axis system used to define the orientation of all sensors are shown by Figure 3.6.

The driver seat was placed in the centre of its longitudinal range of movement on the seat rail, the steering wheel was in the most upright and least extended position while the backrest was at an angle deemed comfortable. Heat generated inside the vehicle by the participant, operator and the Prosig data acquisition system caused the temperature in the vehicle to rise. The vehicle's climate control was used to keep the temperature constant at $21.5°C$. Therefore the vehicle's engine was running while conducting tests. The vehicle's dampers rely on airflow to dissipate heat. A cooling system was placed underneath the vehicle in order to cool the dampers (shown on Figure 3.5). An extraction fan installed for the purpose of extracting exhaust gasses was used to keep the air in the 4-poster room uncontaminated. For safety purposes the 4-poster room is also fitted with a sensor to detect air contamination.

Table 3.3: Test vehicle information.

Parameter	**Description**
Make and model	Range Rover Evoque eD4 (2014)
Driver side	Left hand drive
Weight distribution (Front:Rear)	57:43
Weight (Including driver and passenger)	2023 kg (+/- 20 kg)
Suspension	Original
Tyres	Pirelli Scorpion Verde 235/55R19
Tyre pressure	2.5 bar

Figure 3.5: Visual of 4-post test rig with the test vehicle on the actuators.

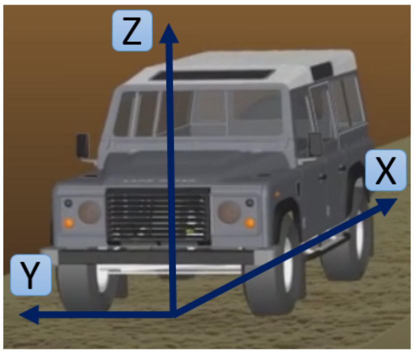

Figure 3.6: Vehicle axis system used.

3.3.3 Sensors and data acquisition

The vehicle was fitted with seven accelerometers in order to measure the accelerations experienced by the participant in the driver seat. BS 6841 suggest that vibration should be measured at locations where vibration enters the body. For a seated participant in a vehicle it would therefore be at the feet, hands, seat bottom and seat back. In order to simply the approach, acceleration were only measure at the location that was deemed to be the main point of vibration entry to the body. Figure 3.7 indicates the locations of these sensors and the axes that were measured, while Table 3.4 provides details regarding the types of accelerometers used. The locations front left (FL), front right (FR) and rear left (RL) are located on the seat rail. On the FL location of the seat rail a tri-axial accelerometer was placed, on the FR two single axis accelerometers, and on the RL of the seat rail a single axis accelerometer. Figures 3.8 and 3.9 in conjunction with Table 3.5 show how the accelerometers on the seat rail were mounted. Figure 3.10 shows the positioning of the seat pad accelerometer. The seat pad was placed underneath the ischial tuberosities (sit bones) of the participant and fixed to the upholstery by making use of adhesive tape. In order to mask the presence of the seat pad it was covered by a double layer of bubble wrap as shown in Figure 3.10. This provides a normal feel when sitting on the seat.

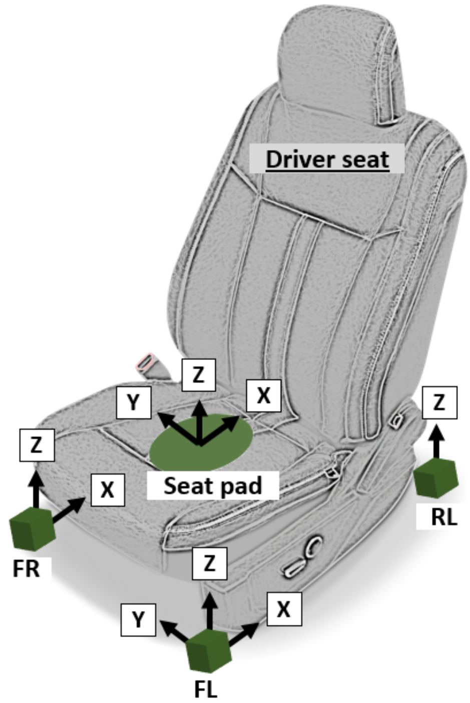

Figure 3.7: Location and orientation of accelerometers at the driver seat.

The required data was recorded by making use of two data acquisitions systems. The 4-poster has a built in data acquisition system with displacement and acceleration sensors on each actuator. Each of these accelerations and displacements were recorded by the 4-poster's data acquisition system. All accelerometers on the vehicle were recorded by the Prosig data acquisition system (model P8020) within the vehicle. In order to synchronise the data from both data acquisition systems during post processing the displacement of the rear right actuator was recorded by both.

According to BS 6841 - Section 6, the range of frequencies of importance for the investigation of discomfort and perception are 0.5 to 80 Hz. Data was sampled at 2000 Hz. By sampling at 25 times the highest frequency of interest the error between the analogue signal and the digital signal constructed of samples were reduced significantly. An anti-aliasing filter was used with a cut off frequency of 400 Hz.

Table 3.4: Details of accelerometers fitted to the vehicle.

Measured Parameter	Type	Manufacturer	Series	Range	Frequency range
Seat rail longitudinal acceleration (Front Left)	MEMS	Measurement Specialties (China). Ltd.	4630-005-180	+/-5 g	0 - 100 Hz
Seat rail lateral acceleration (Front Left)					
Seat rail vertical acceleration (Front Left)					
Seat rail longitudinal acceleration (Front Right)	Piezo	PCB Piezotronics	M352C68	+/-50 g	0.5 - 10 kHz
Seat rail vertical acceleration (Front Right)	MEMS	Measurement Specialties (China). Ltd.	4000A-005-060	+/-5 g	0 - 100 Hz
Seat rail vertical acceleration (Rear Left)	MEMS	Measurement Specialties (China). Ltd.	4000A-005-060	+/-5 g	0 - 100 Hz
Seat pad longitudinal acceleration	Piezo	PCB Piezotronics	356B40	+/-10 g	0.5 - 1 kHz
Seat pad lateral acceleration					
Seat pad vertical acceleration					

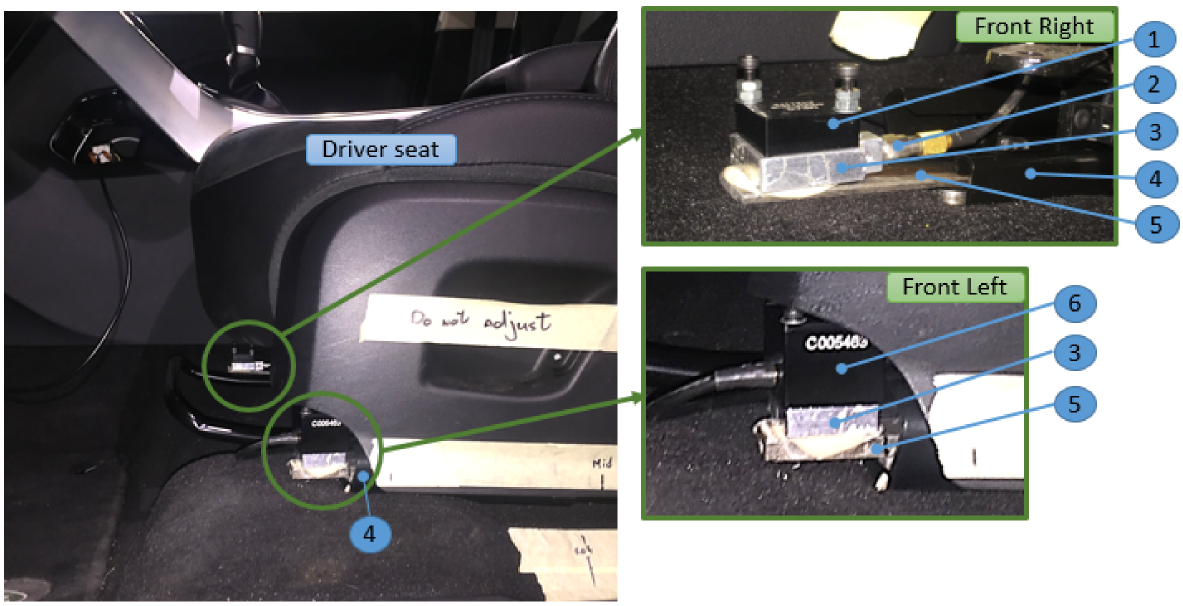

Figure 3.8: Front accelerometer mountings on the front left and front right part of the driver seat rail.

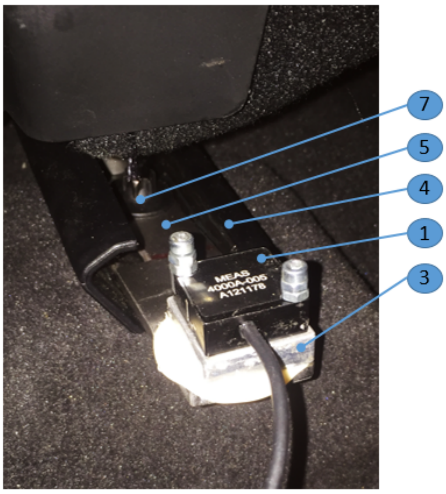

Figure 3.9: Left rear accelerometer mounting on the driver seat rail.

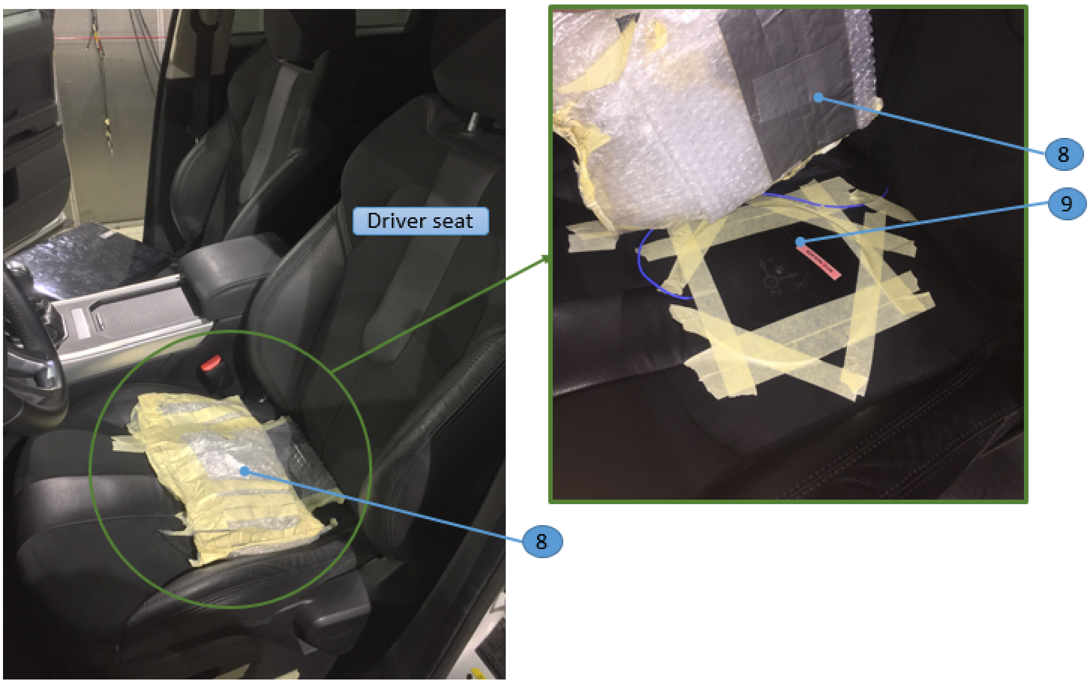

Figure 3.10: Seat pad accelerometer on the driver seat.

Table 3.5: Description of items in Figures 3.8 to 3.10.

Item	**Description**
1	Single axis accelerometer (Measurement Specialties)
2	Single axis accelerometer (PBC)
3	Accelerometer mounting block
4	Seat rail
5	Mounting plate bolted to seat rail (2 mm thick)
6	Tri-axial accelerometer (Measurement Specialties)
7	Seat rail mounting bolt
8	Seat pad cover
9	Seat pad accelerometer (PCB)

3.3.4 Participants

Ethical clearance was required as humans were used as participants in this study. The required ethical clearance was obtained from the Engineering, Built Environment and IT (EBIT) faculty Research Ethics Committee of the University of Pretoria. The participants consisted of 10 male engineers that all work or study in the field of vehicle engineering. Els (2005) found that the cohort, as defined by occupation, has an influence on the subjective perception of comfort. The age, length, weight, fitness level and occupation of each participant are shown in Table 3.6. Table 3.6 also provides the distribution of the various measures.

Table 3.6: Participant characteristics with respect to age, length, weight, fitness level and occupation.

	Age [years]	**Stature [m]**	**Weight [kg]**	**Fitness level [hours exercise per week]**	**Occupation**
Participant 001	32	1.74	83	5	Engineer
Participant 002	38	1.70	63	5	Engineer
Participant 003	39	1.82	90	3	Ride Engineer
Participant 004	43	1.82	89	1	Ride Engineer
Participant 005	36	1.85	80	6	Engineer
Participant 006	25	1.93	80	1	Engineer
Participant 007	35	1.78	71	4	Engineer
Participant 008	23	1.74	85	6	Engineer
Participant 009	24	1.82	83	6	Engineer
Participant 010	33	1.71	74	3	Engineer
25^{th} Percentile	25	1.74	74	3	
Median	34	1.80	81.5	4.5	
75^{th} Percentile	38	1.82	85	6	

A session of maximum 1 hour and 44 minutes was estimated to be required for each of the two reference road profile tests. Figure 3.11 provides a breakdown of the estimated maximum required time to test a single reference road. Based on literature it was estimated that no more than 50 runs would be required to complete the UDTR procedure. Note that the procedure could theoretically be completed within 17 runs.

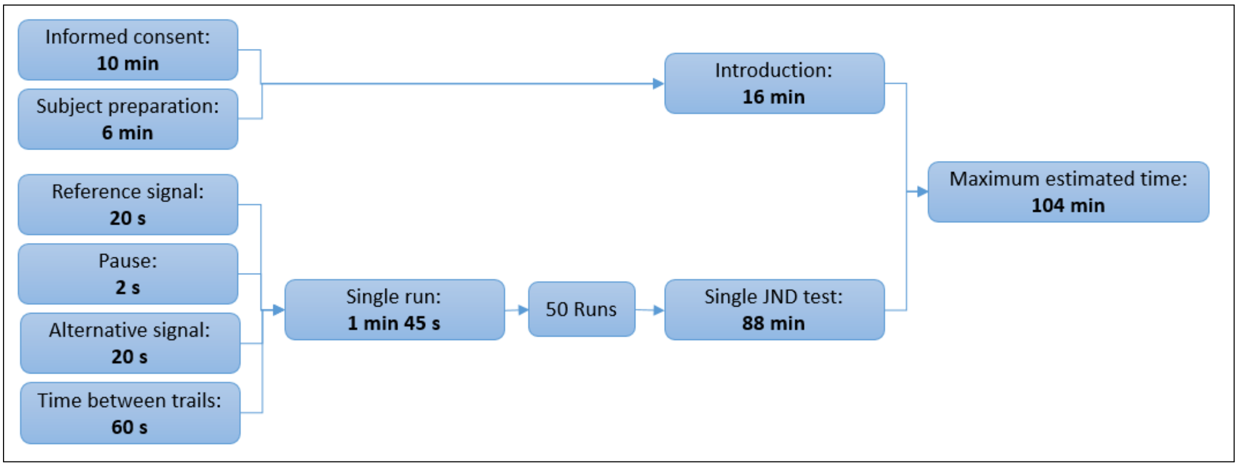

Figure 3.11: Breakdown of estimated maximum duration per DT test for a single reference road.

3.3.5 Road input and seat rail acceleration

Participants were exposed to accelerations which are similar to those experienced when driving over a rough road. A road profile generated for the purpose of ride comfort evaluation was used to excite the vehicle on the 4-poster test rig. The road profile is called Test Track 1 and excited the vehicle as if the vehicle is negotiating the road at 80 km/h.

In order to investigate if Weber's law would hold at different magnitudes of excitation the DTs were determined at two different magnitudes of excitation. In order to produce reference and alternative stimuli the vertical displacement of Test Track 1 (on all 4 actuators) was multiplied by various constants, therefore making no change to the frequency content. For the UDTR procedure the reference stimuli was selected to be larger than the reference. The displacement of Test Track 1 was therefore scaled down to 71 % (named Road 0p71) allowing a 40 % increase for the alternative stimuli without increasing the vertical displacement of the alternative stimuli above that of Test Track 1 to limit vibration severity. A second reference stimulus was required that would resemble a less rough road. Test Track 1 was therefore scaled down to 30 % in its displacement magnitude to form Road 0p30. Figure 3.12 shows the displacement power spectral density (DPSD) plot of Test Track 1 together with ISO 8608 (International Organization for Standardization, 1995) road profile classifications. It is clear that Test Track 1 has significant more low frequency content than high frequency content. Road 0p30 and Road 0p71 resulted in BS 6841 weighted accelerations of 0.6 m/s^2 and 1.1 m/s^2 respectively, measured with the FL seat rail accelerometer.

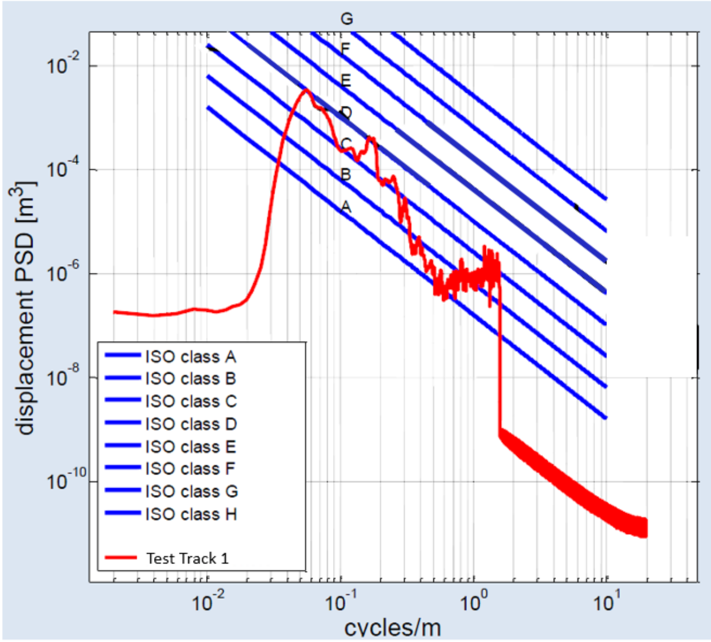

Figure 3.12: Displacement power spectral density plot of Test Track 1 in relation to the ISO 8608 (1995) road profiles of class A to G.

The UDTR procedure requires that the alternative stimuli be increased and decreased in steps while going through the procedure. As mentioned in Subsection 3.2.2 it was decided to govern the UDTR procedure by monitoring the vertical acceleration of the driver seat rail. A relation was established between the displacement input from the 4-poster and the acceleration output on the seat rail (FL z-axis seat rail sensor) with no occupants seated in the vehicle. An iterative process was followed were the displacement road profile (of each actuator) was multiplied by a constant and played on the 4-poster. The vertical acceleration at the FL corner of the driver seat rail was then measured. The goal was to find road profile multiplication factors (constants) that would result in a 3% step size on the BS 6841 weighted vertical acceleration of the FL corner of the driver seat rail. The reasoning behind choosing the desired step size as 3% is described in detail in Section 3.2.1.

A list of the reference and alternative road profiles used are given in Table 3.7. The naming convention used is as follows. Test Track 1 was multiplied by a group multiplication factor (GMF) of 0.30 and 0.71 in order to obtain two reference stimuli (Road 0p30 and Road 0p71 respectively). Each reference road was then multiplied by an individual multiplication factor (IMF) to obtain an alternative stimuli. The overall multiplication factor (OMF) is obtained by multiplying the GMF by the IMF. The OMF indicates how much each stimuli was scaled from the original Test Tack 1. The relationship between the change in displacement of the road profile and the weighted r.m.s. of the vertical acceleration measured at the seat rail showed a near linear relationship as shown in Figure 3.13. For Road 0p30 the alternative stimuli shown in Table 3.7 resulted in mean step sizes of 2.6 % on the seat rail and for Road 0p71 the mean step size was 2.7 %. (The mean step size was calculated across the 10 alternative stimuli for each reference road.) Mean step sizes of 2.6 and 2.7 % was deemed close enough to the goal of 3 %.

Figure 3.14 displays the frequency content of reference Road 0p30, alternative Road $0p30_{10}$, reference Road 0p71 and alternative Road $0p71_{10}$ measured in the vertical direction on the FL seat rail. It confirms that the frequency content changes only in magnitude across the various reference and alternative road profiles. There is no shift of energy visible across the spectrum. The magnitude of the frequency content increases/decreases across the complete frequency range by an equal amount.

Table 3.7: List of reference and alternative road profiles used in the UDTR procedure.

Road Name	**GMF**	**IMF**	**OMF**
Reference Road 0p30	0.3	1	0.300
Alternative Road $0p30_1$	0.3	1.06	0.318
Alternative Road $0p30_2$	0.3	1.12	0.336
Alternative Road $0p30_3$	0.3	1.16	0.348
Alternative Road $0p30_4$	0.3	1.225	0.368
Alternative Road $0p30_5$	0.3	1.28	0.384
Alternative Road $0p30_6$	0.3	1.32	0.396
Alternative Road $0p30_7$	0.3	1.365	0.410
Alternative Road $0p30_8$	0.3	1.39	0.417
Alternative Road $0p30_9$	0.3	1.42	0.426
Alternative Road $0p30_{10}$	0.3	1.5	0.450
Reference Road 0p71	0.71	1	0.710
Alternative Road $0p71_1$	0.71	1.04	0.738
Alternative Road $0p71_2$	0.71	1.08	0.767
Alternative Road $0p71_3$	0.71	1.12	0.795
Alternative Road $0p71_4$	0.71	1.16	0.824
Alternative Road $0p71_5$	0.71	1.2	0.852
Alternative Road $0p71_6$	0.71	1.24	0.880
Alternative Road $0p71_7$	0.71	1.28	0.909
Alternative Road $0p71_8$	0.71	1.32	0.937
Alternative Road $0p71_9$	0.71	1.36	0.966
Alternative Road $0p71_{10}$	0.71	1.4	0.994

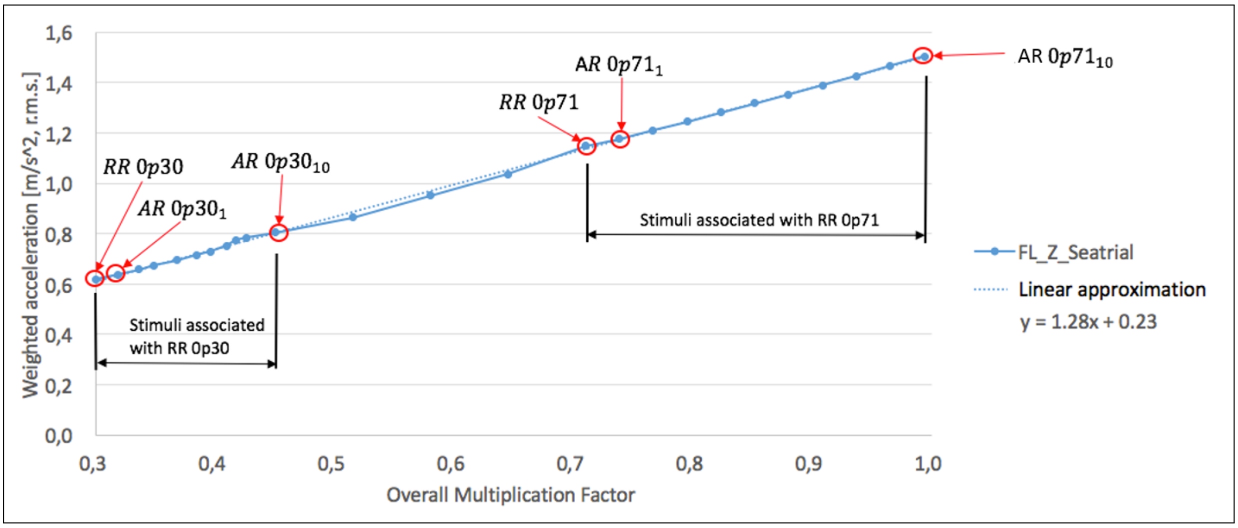

Figure 3.13: Relationship between BS 6841 weighted r.m.s. of vertical acceleration at the FL seat rail accelerometer and OMF. RR refers to reference road and AR refers to alternative road.

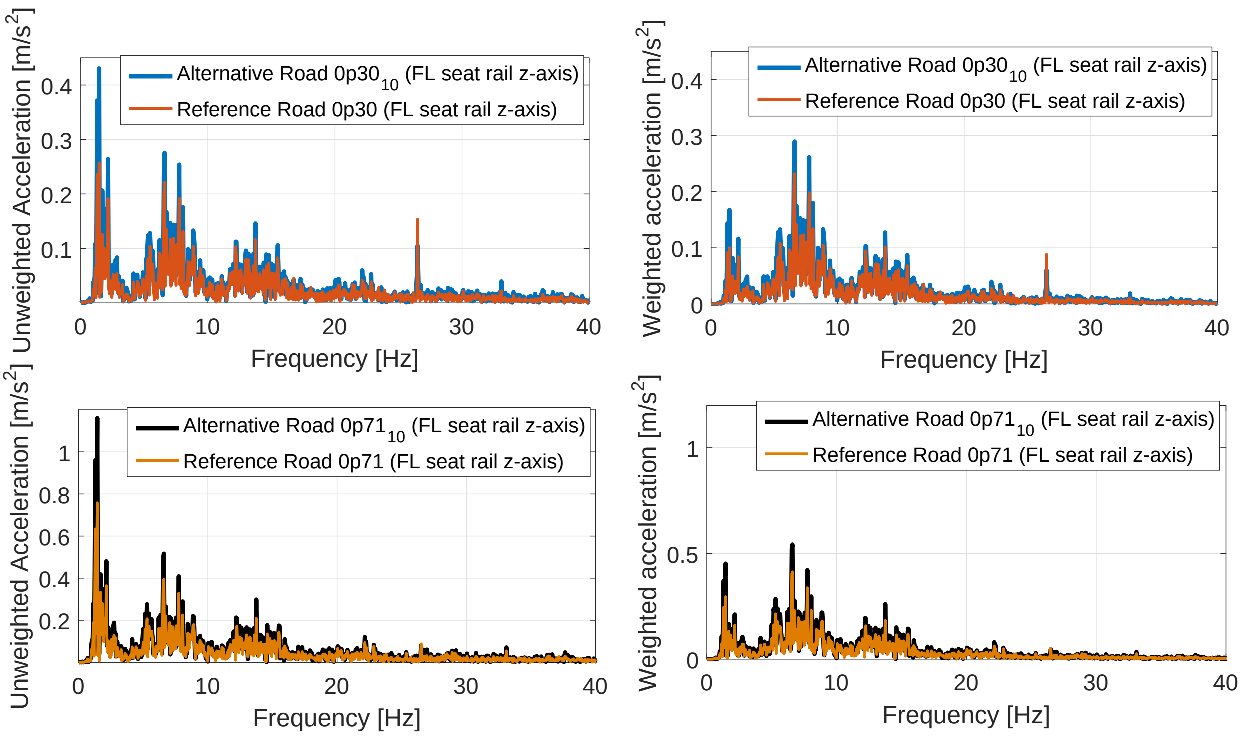

Figure 3.14: BS 6841 weighted and unweighted frequency content of the reference Road 0p30, alternative Road $0p30_{10}$, reference Road 0p71 and alternative Road $0p71_{10}$.

3.4 Difference threshold testing

Various strategies can be used to obtain the RDT. A layout of the process followed in determining the RDT is shown in Figure 3.15. Each of these process blocks are discussed in detail within this section.

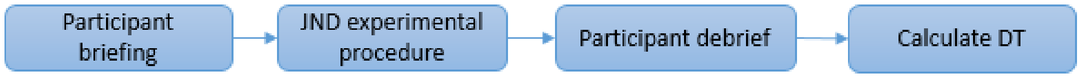

Figure 3.15: Process flow diagram for determining the DT.

3.4.1 Participant briefing

Participants were asked to book two time slots of 1 hour 45 minutes over a 5 day period. On arrival of the participant at the 4-poster test rig, the informed consent form, supplied in Appendix A, was discussed. As an additional measure of safety the informed consent form mentions conditions that might deem people unfit to partake in the study. These conditions were established in BS 7085 (British Standards Institution, 1989) and were obtained from Table 1.4 in Griffin (1990). Thereafter the participant was presented with a questionnaire which is supplied in Appendix B. The participant was asked to complete sections 1 and 2 which relates to personal information and exposure to off-road terrain. The participant was then informed about the test procedure that was to follow and what to expect by making use of a Participant Preparation Document. The Participant Preparation Document was predefined and read to each participant to ensure that each participant receives exactly the same information.

The Participant Preparation Document reads as follow: "While seated in the front driver seat a signal of 20 seconds will be played to you followed by a 2 second pause before another 20 second signal will be played. You should then indicate during which of the two signals you experienced the most discomfort. To indicate the first, signal left, to indicate the second, signal right using the vehicle's indicators. There after the same process will be repeated between 30 and 50 times. This will take between 40 min. and 1 hour 40 min. At any point you may indicate if you would like to stop the test. You will also be asked to wear earplugs."

The participant then climbs in to the vehicle. Thereafter the seating position and the use of the earplugs are explained. "Please put on your seatbelt. Hold the steering wheel with both hands in a comfortable manner as you would usually do as a driver. Try to keep a comfortable, but good upright posture with your lower back against the back rest. Please put your right foot clear from the throttle pedal. Please insert earplugs by rolling them between your fingers and then placing them in your ears." After the briefing the DT experimental procedure commenced with the participant seated in the driver seat of the vehicle and one of the researchers seated in the passenger seat. There were therefore two occupants in the vehicle during testing. Another researcher operated the 4-poster from outside the vehicle.

3.4.2 Difference threshold experimental procedure

In order to control the 4-poster and record data inside the vehicle using the Prosig, one researcher was seated in the front passenger seat to trigger the Prosig and the other was outside the vehicle controlling the 4-poster. The UDTR method was used with a three-down-one-up rule as described in Section 2.9. Each signal played to the participant was 45 s long consisting of a 20 s reference road, followed by a 2 s pause and then a 20 s alternative road. The order of the reference and alternative road was alternated randomly. The procedure started with the vertical r.m.s. of the alternative signal at the seat rail being 3 % higher than that of the reference signal. The participant then answers the question: “Did you feel more discomfort during the first or the second stimuli?” If the answers is “the first” the participant would indicate left and if the answer is “the second” he will indicate right using the vehicles indicators. The participant should always feel more discomfort during the alternative stimuli. In order to remind the participant of the question and how to indicate the answer, a board with the question and answer method was placed out side the vehicle in front of the driver as shown in Figure 3.16. After an incorrect response the alternative signal will increase by a single step and after three correct responses the alternative signal will decrease by a step size. The test continued until eight reversal was reached. After approximately 1 hour of testing the test was paused to provide the participant with a break. The breaks lasted between 5 and 15 minutes.

Figure 3.16: View of participant seated in the vehicle showing the sign placed in front of the vehicle reminding participants about the question that is asked and how to respond.

A Microsoft Excel spreadsheet, shown in Figure 3.17, was used in order to keep track of the test procedure for every test. The spreadsheet contains all the necessary information to perform the UDTR procedure. In the “Random indicator” block a “1” or a “2” is generated by the *rand* function. A “1” means that the reference signal is played before the alternative signal and a “2” means that the reference signal is played after the alternative signal. The “Random number definition” block is used to judge if the participant’s response from the left or right indicator is correct or incorrect. The “Visual display of UDTR” table was used to keep track of procedure. The number in each block indicates the order of the reference and alternative signals. A red block denotes and incorrect response and a green block denotes a correct response. The symbols $P11$, $P12$, $P13$, $T1$ etc. indicates Peaks and Troughs. The row titled “Reversals” indicates each time a reversal is completed.

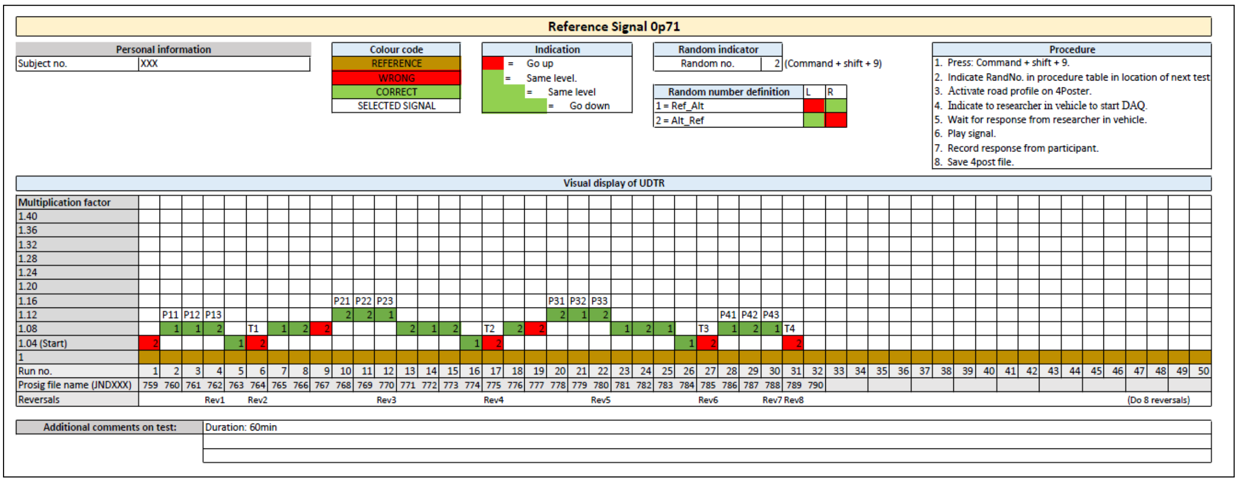

Figure 3.17: Microsoft Excel sheet used by the researcher operating the 4-poster to govern the test procedure.

3.4.3 Participant debrief

After completing the test procedure participants were asked to provide feedback. On the questionnaire, presented in Appendix B, participants were asked if there were any specific indicators which they used to determine which of the two stimuli were the most uncomfortable such as head movement or upper body movement.

3.4.4 Calculating the difference threshold

The ADT and RDT were calculated per set (peak and trough) so that the effect of each set on the result can be observed during the analysis. Variables used in this subsection are also indicated in Figure 2.5. The acceleration data was weighted with the W_b weighting function from BS 6841 as discussed in Subsection 3.2.3. The r.m.s. was used to represent the magnitude of acceleration signals as the crest factor was below six as specified in BS 6841 for all acceleration signals. The crest factor did not exceeded 4 for accelerations recorded during DT testing using reference Road 0p30 and did not exceed 5 for DT testing using reference Road 0p30. The ADT for a set ΔI_i was calculated from Equation 3.1, where i is the number of the set, P_i is the average of the alternative signals at a peak where there is three consecutive correct responses, P_{ref_i} is the average of the three reference magnitudes at a peak, T_i is the magnitude of the alternative signal at a trough and T_{ref_i} is the magnitude of the reference signal at a trough. The RDT for a set C_i was calculated from Equation 3.2. The variables $P_{ref_{i1}}$, $P_{ref_{i2}}$ and $P_{ref_{i3}}$ are the r.m.s. magnitude of the three alternative signals that forms a peak, m is the number of sets, k is the number of the first set used in the calculation, and n is the number of consecutive correct responses. (Therefore $P_i = (P_{ref_{i1}} + P_{ref_{i2}} + P_{ref_{i3}})/3$.) The numerator of Equation 3.2 calculates the average across all reference signals which forms part of the peaks and troughs used in the DT calculation.

The ADT across all sets was calculated from Equation 3.3 by taking the average of the RDTs for each set. The RDT across all sets was calculated from Equation 3.4 by taking the average across all sets.

$$\Delta I_i = \frac{(P_i - P_{ref_i}) + (T_i - T_{ref_i})}{2} \tag{3.1}$$

$$C_i = \frac{\Delta I_i}{\sum_{i=k}^{m}(P_{ref_{i1}} + P_{ref_{i2}} + P_{ref_{i3}} + T_{ref_i}) \div m \times (n+1)} \tag{3.2}$$

$$\Delta I = \frac{\sum_{i=k}^{m} \Delta I_i}{m-k} \tag{3.3}$$

$$C = \frac{\sum_{i=k}^{m} C_i}{m-k} \tag{3.4}$$

3.5 Summary

At this point all details and decisions regarding the experimental setup and test procedure have been discussed. This includes the UDTR procedure and all parameters relating to it, the use of vertical seat rail acceleration to govern the UDTR procedure and the decision to make use of the BS 6841 standard to interpret results. Regarding the experimental setup, the 4-poster, vehicle, data acquisition, participants and the relationship between the road input and seat rail output have been discussed. The testing procedure has been documented in detail including the participation briefing, debrief and how the DT was calculated for every participant. The results obtained while testing each participant will be presented and discussed in the next chapter.

Chapter 4

Results and Discussion

4.1 Introduction

The two research questions at hand are 1) "What is the DT for drivers seated in a vehicle, on a 4-poster test rig, if exposed to all six components of acceleration" and 2) "Does Weber's law hold for a RDT calculated from vertical acceleration when a driver is exposed to all six components of acceleration while seated in a vehicle?". Results and observations from the experimental work are presented in order to answer these two questions. The chapter is divided in to three sections as shown in Figure 4.1. The first section presents the experimentally determined ADTs and RDTs, compares the results to that in literature and discusses the validity of Weber's law. Section two presents subjective feedback obtained from participants after every test and section three provides information on the duration and characteristics of the UDTR procedure followed by each participant.

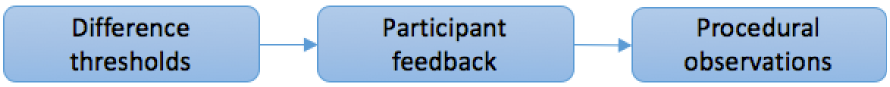

Figure 4.1: Flow diagram of the sections within Chapter 4.

4.2 Difference thresholds

DTs were determined for participants seated in a vehicle while exposed to all six components of acceleration. Up to this point acceleration data from only the vertical FL seat rail accelerometer was presented. This was due to the fact that the UDTR procedure was governed by the vertical FL seat rail accelerometer.

The RDT was calculated for each participant using the vertical seat pad acceleration and also the vertical FL, FR and RL seat rail accelerations. The acceleration measured by the seat pad was viewed as the true acceleration experienced by a participant. Should the RDT calculated from one or more of the seat rail sensors not differ significantly from the RDT calculated from the seat pad acceleration, it could have certain advantages with regards to implementing the RDT. When measuring acceleration in a vehicle to quantify the reduction in vibration due to certain changes that have been made, it is more repeatable to measure seat rail acceleration than seat pad acceleration. Within the simulation environment it would also be easier to determine seat rail acceleration. The acceleration measured from the vehicle on a test track or from the simulation environment can then be compared to the RDT calculated from a seat rail sensor that does not differ significantly from the seat pad.

The reference magnitude at which the DT was calculated is also of importance and will be the first point of discussion in this section. Thereafter, ADT and RDT data is presented. The RDTs were used to investigate the validity of Weber's law and the RDTs were also compared to results from similar studies in literature.

4.2.1 Reference stimulus magnitude

The magnitude of the reference stimulus is of importance when reporting the ADT and RDT. The ADT and RDT is calculated for the specific reference stimulus that participants were exposed to. The RDT is only applicable to other stimulus magnitudes if Weber's Law holds.

During the UDTR procedure a participant is exposed to various trials consisting of a reference and an alternative stimulus (as shown in Figure 2.5). Figure 4.2 presents the r.m.s. magnitude of the W_b weighted vertical acceleration of the reference stimuli measured for the 12 stimuli used to calculate the ADT and RDT (P_{ref_i} and T_{ref_i} in Figure 2.5). Each box consists of 120 r.m.s. values which comprises of the reference stimuli of the peaks and troughs of 12 trails for each of the 10 participants. The distribution from all four vertical vehicle sensors are displayed with reference Road 0p30 on the left and reference Road 0p71 on the right.

The FR seat rail accelerometer measured lower than the FL or RL accelerometer. This difference was attributed to the FR accelerometer being closer to the point around which the vehicle rolls. It was speculated that the vehicle rolls about a point that is close to the lateral centre of gravity. From the equation for tangential acceleration $\overrightarrow{a_t} = \overrightarrow{\alpha} \times \overrightarrow{r}$, a smaller radius $\overrightarrow{r}$ will result in a smaller tangential acceleration $\overrightarrow{a_t}$, for the same angular acceleration $\overrightarrow{\alpha}$. Appendix E provides an analysis of the magnitudes of the six components of acceleration (lateral, longitudinal, vertical, roll, pitch and yaw) that participants were exposed to.

The spread of the acceleration magnitudes measured across the different participants is larger for the seat pad than for the seat rail accelerometers. Figure 4.3 shows the magnitude of the reference stimuli measured on the seat pad for the first 20 trials of each participant. It shows that the variation in the seat pad, seen in Figure 4.2, is primarily due to inter-participant variability and not intra-participant variability. The inter-participant variation can possibly be reduced by scaling the input stimulus according the weighted acceleration measured on the seat. Reducing inter-participant variation will result in participants experiencing reference and alternative signals that differ less in magnitude. The intra-participant variation seen in Figure 4.3 is possibly due to the movement of the participant's body as well as slight changes in posture and sitting position. The maximum difference between two participants in the mean of their reference magnitudes was 30 % for reference Road 0p30 and 22 % for Road 0p71. It was also reported in literature (see Mansfield and Griffin (2000) and Pielemeier et al. (1997)) that the accelerations measured on the vehicle seat differ significantly between participants due to transmissibility of the seat as well as inter- and intra-participant variability.

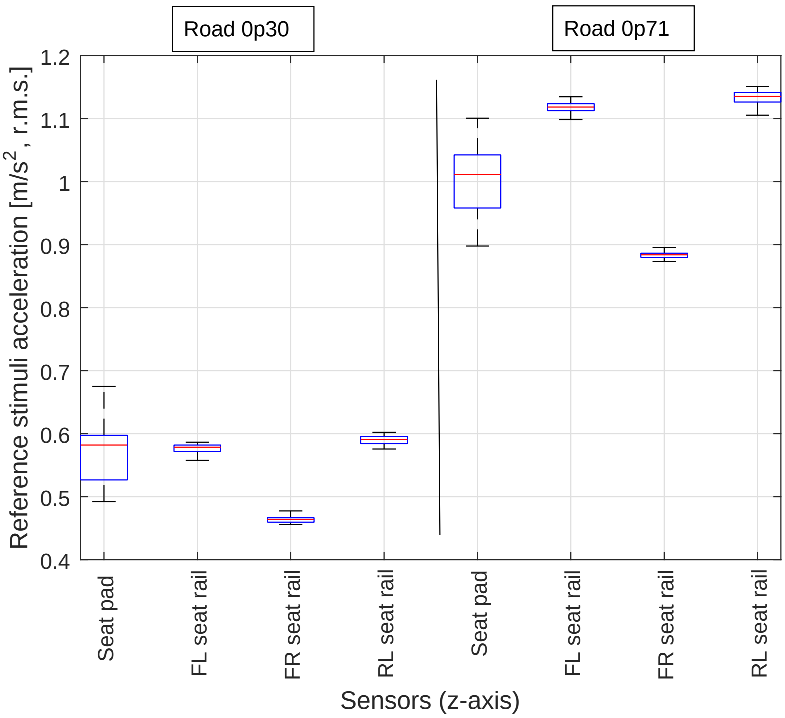

Figure 4.2: Box plot presenting the distribution of the weighted r.m.s. acceleration of the reference signals used to calculate the DTs. Data from all four vertically orientated sensors was presented for each of the two reference roads.

4.2.2 Absolute difference threshold

The distribution of the ADTs calculated for the 10 participants are presented in Figure 4.4 and Table 4.1. (Appendix D provides a comparison between BS6841 and ISO2631-1 for key results.) The inter quartile range (IQR) range between the four sensors for Road 0p30 are similar and the IQR between the four sensors for Road 0p71 are similar. Considering the four sensors, the median ADT for Road 0p30 ranged between 0.05 and 0.07 m/s^2, and for Road 0p71 it ranged between 0.08 and 0.11 m/s^2. Should Weber's law hold it is expected that the ADT for a larger stimulus should be greater than of a smaller stimulus.

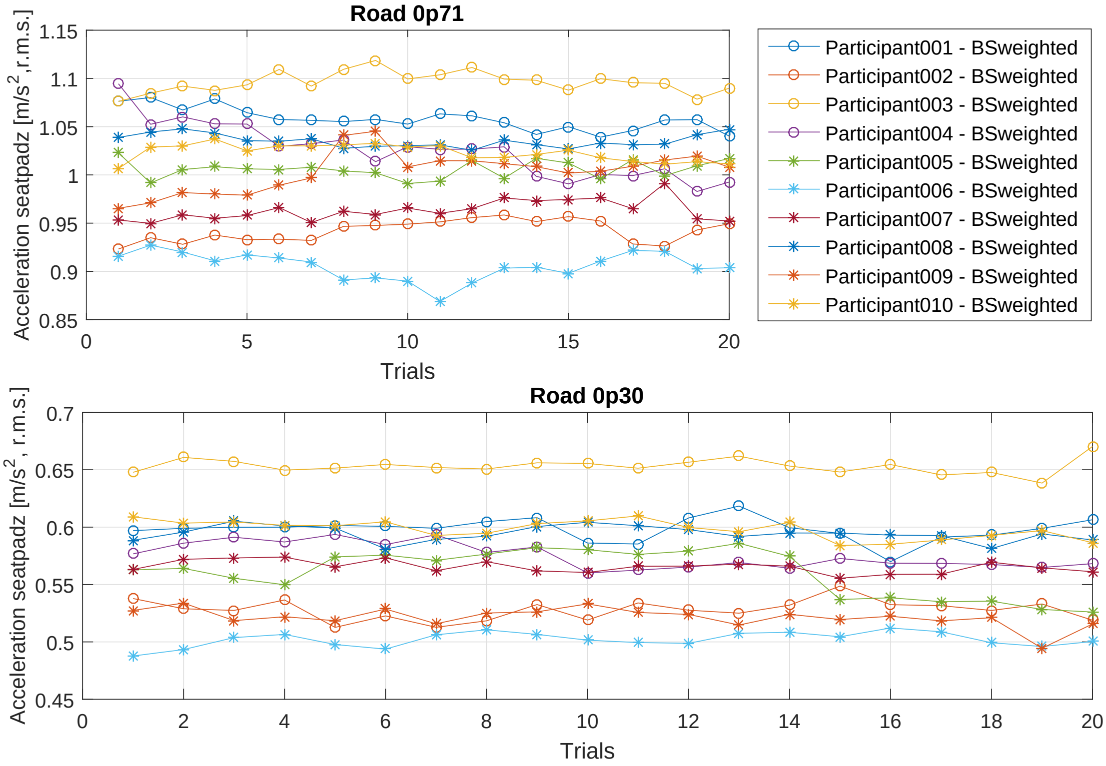

Figure 4.3: Reference stimuli of the first 20 trials for each participant measured by the seat pad accelerometer.

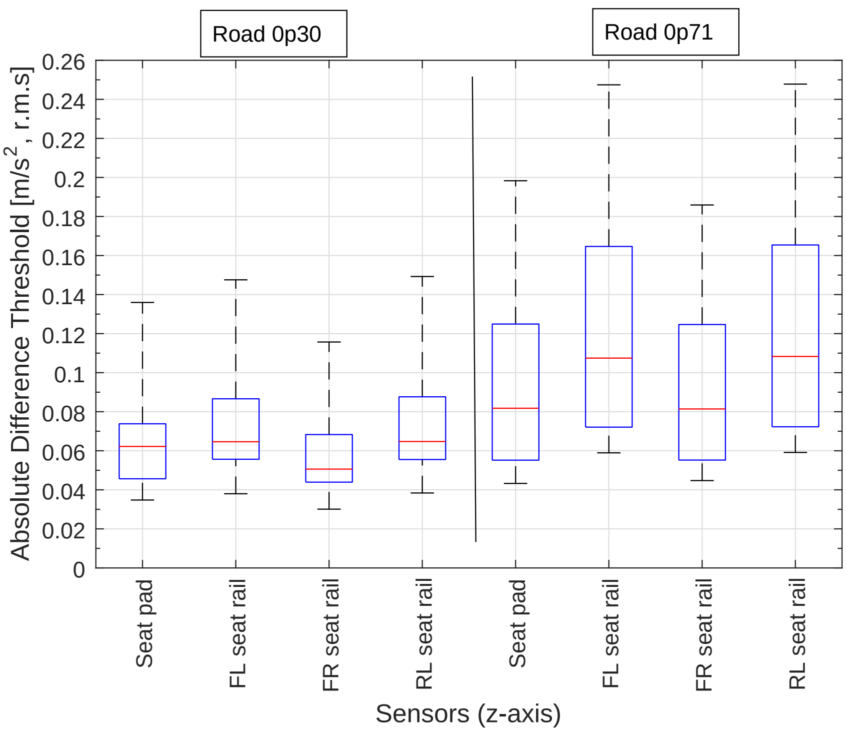

Figure 4.4: Box plot presenting the distribution of the ADTs for the 10 participants as measured by each of the vertical accelerometers.

Table 4.1: ADTs calculated from the vertical seat pad acceleration, vertical FL seat rail, vertical FR seat rail and vertical RL seat rail acceleration.

(a) Vertical FL seat rail acceleration.

Participant	**Road 0p30** [m/s^2]	**Road 0p71** [m/s^2]
Participant001	0.061	0.185
Participant002	0.114	0.114
Participant003	0.056	0.143
Participant004	0.148	0.165
Participant005	0.041	0.059
Participant006	0.038	0.067
Participant007	0.087	0.101
Participant008	0.075	0.247
Participant009	0.057	0.074
Participant010	0.068	0.072
Minimum	0.038	0.059
25$^{\text{th}}$ percentile	0.056	0.072
Median	0.065	0.107
75$^{\text{th}}$ percentile	0.087	0.165
Maximum	0.148	0.247

(b) Vertical FR seat rail acceleration.

Participant	**Road 0p30** [m/s^2]	**Road 0p71** [m/s^2]
Participant001	0.048	0.139
Participant002	0.090	0.086
Participant003	0.044	0.107
Participant004	0.116	0.125
Participant005	0.032	0.045
Participant006	0.030	0.051
Participant007	0.068	0.077
Participant008	0.058	0.186
Participant009	0.044	0.056
Participant010	0.054	0.055
Minimum	0.030	0.045
25$^{\text{th}}$ percentile	0.044	0.055
Median	0.051	0.081
75$^{\text{th}}$ percentile	0.068	0.125
Maximum	0.116	0.186

(c) Vertical RL seat rail acceleration.

Participant	**Road 0p30** [m/s^2]	**Road 0p71** [m/s^2]
Participant001	0.061	0.186
Participant002	0.116	0.115
Participant003	0.056	0.143
Participant004	0.149	0.165
Participant005	0.041	0.059
Participant006	0.038	0.068
Participant007	0.088	0.102
Participant008	0.075	0.248
Participant009	0.057	0.074
Participant010	0.069	0.072
Minimum	0.038	0.059
25$^{\text{th}}$ percentile	0.056	0.072
Median	0.065	0.108
75$^{\text{th}}$ percentile	0.088	0.165
Maximum	0.149	0.248

(d) Vertical seat pad acceleration.

Participant	**Road 0p30** [m/s^2]	**Road 0p71** [m/s^2]
Participant001	0.056	0.153
Participant002	0.095	0.089
Participant003	0.059	0.118
Participant004	0.136	0.125
Participant005	0.037	0.043
Participant006	0.035	0.048
Participant007	0.074	0.075
Participant008	0.068	0.198
Participant009	0.046	0.057
Participant010	0.065	0.055
Minimum	0.035	0.043
25$^{\text{th}}$ percentile	0.046	0.055
Median	0.062	0.082
75$^{\text{th}}$ percentile	0.074	0.125
Maximum	0.136	0.198

4.2.3 Relative difference threshold

The RDT for every participant for the two roads are provided in Table 4.3 with Figure 4.5 comparing the RDT calculated from the four sensors. Figure 4.6 presents the distribution of the RDTs of the 10 participants for each of the four sensors. A statistical analysis was done by Van Staden and Jordaan (2017) to determine if one or more seat rail sensors produce a RDT that is not significantly different from the seat pad RDT. A non-parametric Friedman related samples comparison was done between the medians of the sensors. (A non-parametric test was used since there are only 10 participants in each sample.) A significance level of 0.05 was used. The null hypothesis stated that there is no significant difference between any two or more median readings for the four sensors, while the alternative hypothesis stated that there is a significant difference between at least two of the four sensor readings. In cases where the null hypothesis is rejected in favour of the alternative hypothesis, post hoc multiple comparisons was performed by means of Dunn's multiple comparison. Tests provided adjusted p-values which have been adjusted for multiple comparisons and indicate which two or more median sensor readings differ significantly.

Table 4.2 shows the p-values obtained for the comparison between the seat pad and the three seat rail sensors. A p-value above the significance level of 0.05 indicates that the two sensors are not significantly different. The FR seat rail sensor's median was not significantly different from the seat pad for both roads. Therefore, the RDT calculated from the FR seat rail sensor can also be utilised together with the seat pad RDT.

Table 4.2: P-values from the non-parametric Friendman test with Dunn's multiple comparisons (Van Staden and Jordaan, 2017). (ns, not significantly different; s, significantly different)

	Road 0p30	**Road 0p71**
Seat pad - FR seat rail	0.500 (ns)	0.500 (ns)
Seat pad - RL seat rail	0.226 (ns)	0.003 (s)
Seat pad - FL seat rail	<0.001 (s)	<0.001 (s)

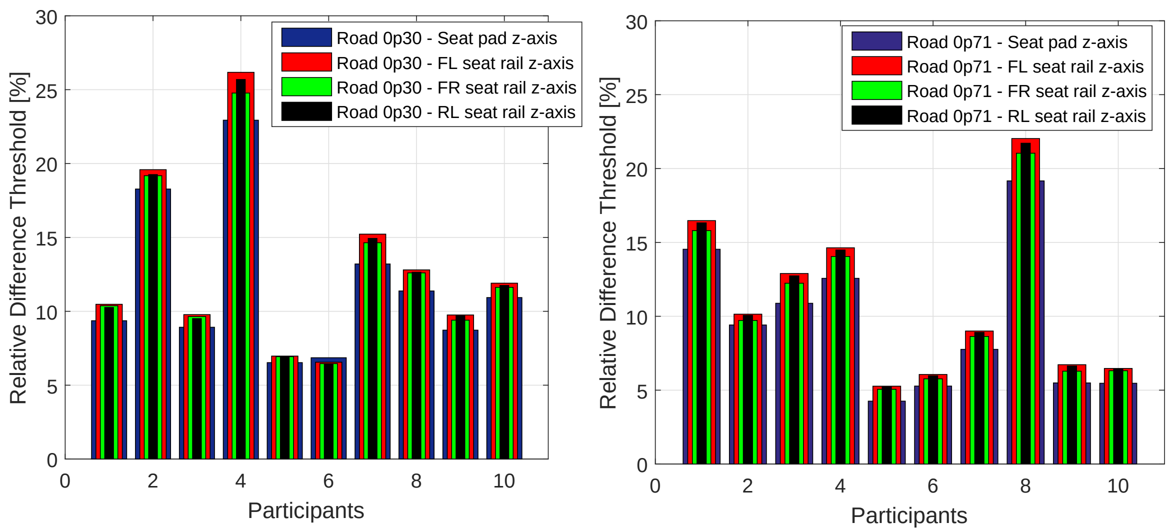

Figure 4.5: Comparison between RDTs calculated using the vertical axis of the seat pad, FL seat rail, FR seat rail and RR seat rail accelerometers for Road 0p30 and Road 0p71.

RDT results fall within the same ranges as that of published results as shown in Figure 4.7. The IQR of results from this overlaps with the IQR of results from Mansfield and Griffin (2000) and Morioka and Griffin (2000). The three participants from Pielemeier et al. (1997) also obtained RDTs similar to that obtained in this study. There are various factors which makes it difficult to draw direct comparison between studies. Some of these factors include different cohorts used, different ages of participants, different psychophysical methods and different stimuli durations.

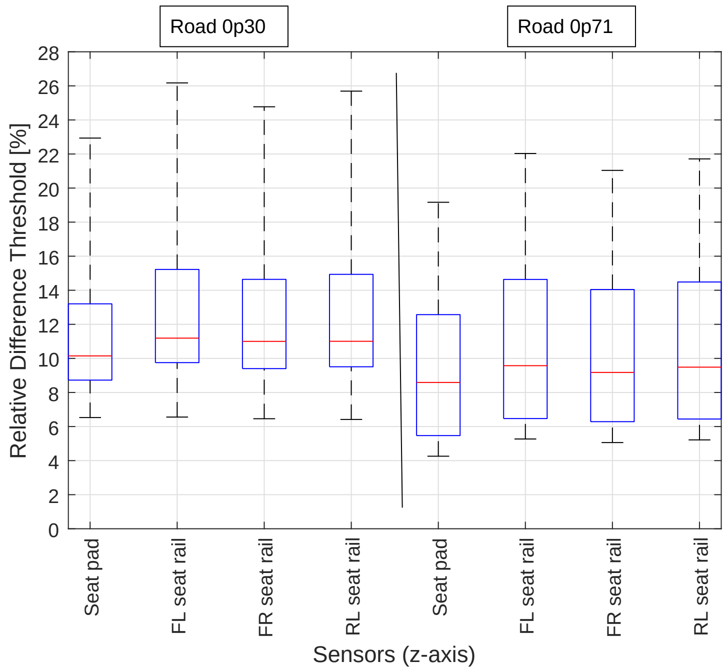

Figure 4.6: Box plot showing the spread of the RDTs for the 10 participants as measured by each of the vertical accelerometers.

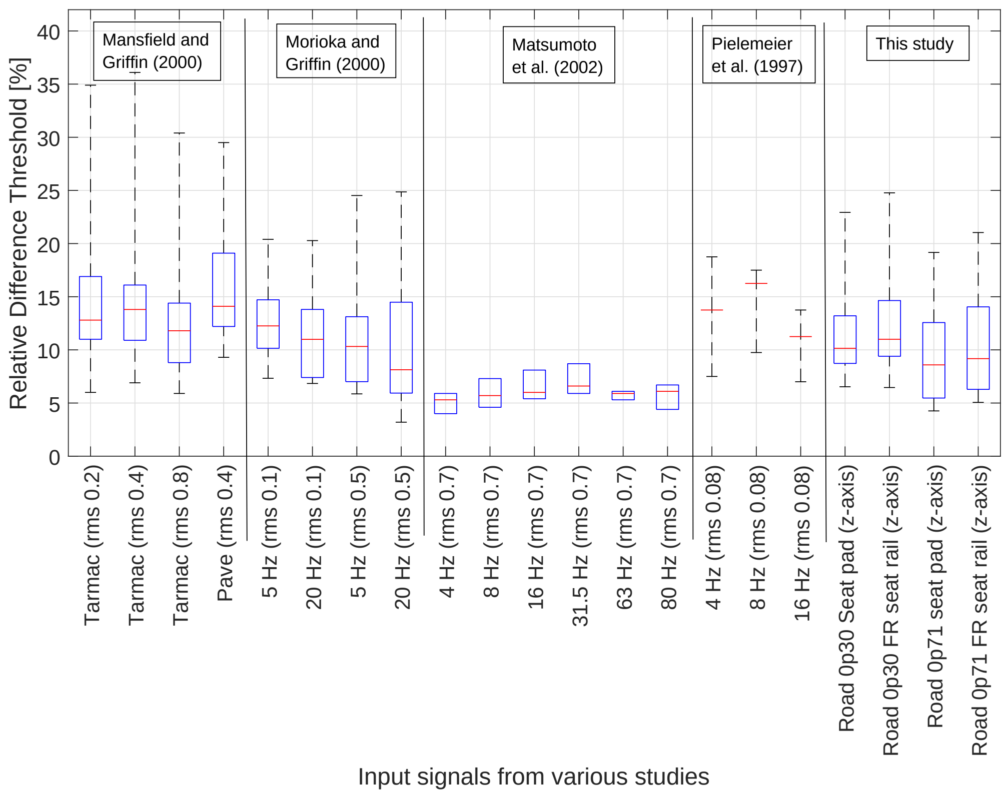

Figure 4.7: Box plot of the RDTs of published data in comparison with data from this study.

Table 4.3: RDTs calculated from the vertical seat pad acceleration, vertical FL seat rail, vertical FR seat rail and vertical RL seat rail acceleration.

(a) Vertical FL seat rail acceleration.

Participants	**Road 0p30** [%]	**Road 0p71** [%]
Participant001	10.475	16.475
Participant002	19.586	10.143
Participant003	9.777	12.895
Participant004	26.174	14.636
Participant005	6.970	5.270
Participant006	6.556	6.062
Participant007	15.223	9.003
Participant008	12.804	22.030
Participant009	9.753	6.724
Participant010	11.904	6.469
Minimum	6.556	5.270
25^{th} percentile	9.753	6.469
Median	11.190	9.573
75^{th} percentile	15.223	14.636
Maximum	26.174	22.030

(b) Vertical FR seat rail acceleration.

Participants	**Road 0p30** [%]	**Road 0p71** [%]
Participant001	10.377	15.798
Participant002	19.178	9.717
Participant003	9.644	12.238
Participant004	24.772	14.045
Participant005	6.932	5.060
Participant006	6.459	5.767
Participant007	14.640	8.636
Participant008	12.601	21.038
Participant009	9.402	6.287
Participant010	11.622	6.316
Minimum	6.459	5.060
25^{th} percentile	9.402	6.287
Median	11.000	9.176
75^{th} percentile	14.640	14.045
Maximum	24.772	21.038

(c) Vertical RL seat rail acceleration.

Participants	**Road 0p30** [%]	**Road 0p71** [%]
Participant001	10.259	16.324
Participant002	19.255	10.061
Participant003	9.509	12.736
Participant004	25.690	14.486
Participant005	6.888	5.217
Participant006	6.417	5.975
Participant007	14.935	8.912
Participant008	12.644	21.713
Participant009	9.691	6.634
Participant010	11.750	6.442
Minimum	6.417	5.217
25^{th} percentile	9.509	6.442
Median	11.005	9.487
75^{th} percentile	14.935	14.486
Maximum	25.690	21.713

(d) Vertical seat pad acceleration.

	Road 0p30 [%]	**Road 0p71** [%]
Participant001	9.364	14.538
Participant002	18.276	9.413
Participant003	8.922	10.881
Participant004	22.934	12.570
Participant005	6.528	4.258
Participant006	6.859	5.278
Participant007	13.204	7.763
Participant008	11.378	19.165
Participant009	8.725	5.491
Participant010	10.931	5.469
Minimum	6.528	4.258
25^{th} percentile	8.725	5.469
Median	10.147	8.588
75^{th} percentile	13.204	12.570
Maximum	22.934	19.165

4.2.4 Validity of Weber's law

There is uncertainty regarding exactly when Weber's Law holds and to which extent it holds. Current literature suggests that Weber's Law holds to some extent in most cases. Mansfield and Griffin (2000) found that Weber's Law holds for reference stimuli with r.m.s. in the range of 0.2 to 0.8 m/s^2 after being weighted (BS 6841) where participants were exposed to an acceleration signal measured in a real vehicle. Morioka and Griffin (2000) found that Weber's Law holds approximately for a 5 and 20 Hz sine wave at r.m.s. magnitudes of 0.1 and 0.5 m/s^2.

A statistical analysis was done by Van Staden and Jordaan (2017) in order to determine if the RDTs calculated from the seat pad and FR seat rail acceleration differ significantly between Road 0p30 and Road 0p71. (Only the FR seat rail sensor was considired as it gave a RDT which is not significantly different from that of the seat pad accelerometer.) The non-parametric related samples Wilcoxon signed rank test was used with a significance level of 0.05. The null hypothesis stated that there is no significant difference in the median of the two sensors across Road 0p30 and Road 0p71, while the alternative hypothesis stated that there is a significant difference in the medians of the two sensors across Road 0p30 and Road 0p71. For the seat pad a p-value of 0.203 was obtained and for the FR seat rail a p-value of 0.285. With both sensors the null hypothesis is retained and therefore there is no significant difference in the RDT from the seat pad for Road 0p30 and Road 0p71 and from the FR seat rail sensor for Road 0p30 and Road 0p71. Therefore it can be concluded that Weber's law holds for a RDT calculated from vertical acceleration when a driver is exposed to all six components of acceleration while seated in a vehicle.

Table 4.4 provides a summary of the RDT values that could be utilised. When the median RDT is implemented it means that 50 % of the sample would have a 79.4 % chance of correctly identifying the largest of two stimuli. (The probability of the rest of the sample would be lower than 79.4 %) If the 75 % percentile RDT is implemented it means that 75 % of the sample would have a 79.4 % chance of correctly identifying the largest of two stimuli. If the maximum value is implemented it means that 100 % of the sample would have a 79.4 % chance of correctly identifying the largest of two stimuli.

Table 4.4: Summary of the RDTs (median, 75^{th} percentile and maximum) from the vertical seat pad and vertical FR seat rail acceleration that can be utilised.

	Vertical seat pad sensor		**Vertical FR seat rail sensor**	
	Road 0p30 [%]	**Road 0p71** [%]	**Road 0p30** [%]	**Road 0p71** [%]
Median	10.147	8.588	11.000	9.176
75^{th} percentile	13.204	12.570	14.640	14.045
Maximum	22.934	19.165	24.772	21.038

4.3 Participant feedback

Subjective feedback plays an important role when performing experimental work with humans. Through subjective feedback from the participants, correlations can be made between objectively measured results and the subjective perception of the participants. As each participant completed a test he was asked if there was any specific indicators which he used to evaluate the roughness of the road, such as head movement or upper body movement (see questionnaire in Appendix B). The responses obtained from participants were analysed and a summary thereof is given here. The approach used here was to present to participants two possible answers as examples in order to guide their response, without guiding and or influencing the participant's response too much. The two movements (i.e head and upper body) was mentioned as it was noted to be the most prominent and obvious during preliminary testing.

4.3.1 Road 0p30

Three participants mentioned that upper body movement was the primary method used to evaluate stimuli. Two participants indicated that they used the feeling in their lower body or lower abdomen. Other participants made use of shaking of hands, arms, abruptness/harshness of the acceleration as well as high frequency content. Two participants mentioned that it was more difficult during Road 0p30 to select the most uncomfortable stimulus. Three reported less body movement. Two made reference to the importance of concentration with one of the two mentioning, during their break, that they struggle to concentrate and that the test was becoming long. One participant mentioned that he kept his eyes closed.

Participant number four ran into the ceiling of the test procedure where the difference, between the reference and the alternative, could not be increased any further. After the test, during the feedback session, he mentioned that “between yesterday and today” he changed his method of evaluation. In an effort to improve his way of evaluating each stimulus, he adopted a more holistic approach where he evaluated by observing the vehicle body movement, seat vibration and his body movement and then asking himself: “Would I accept this level of comfort for this vehicle?”. It was interesting to note his “different” approach. This was not seen as a fault, but emphasizes the complexity of the human. The result from participant four was included in the analysis.

4.3.2 Road 0p71

Seven out of 10 participants mentioned that they used their upper body movement as an indicator. Three out of the seven made specific reference to lateral movement of the upper body. Three participants also mentioned head movement with two specifically referring to lateral movement of the head. Participant’s feedback correlated with the magnitude of the six axes of vibration supplied in Appendix E. The lateral vibration was the axis with the largest magnitude in relation to the vertical vibration. The lateral vibration was 36 % of the vertical vibration for Road 0p30 and 55 % of the vertical vibration for Road 0p71.

Four participants mentioned that the sharpness of the peaks of the acceleration as well as the abruptness/harshness of the stimuli were used. One participant explained what he meant by “harshness” by referring to a triangular wave that would be viewed as being “harsh” and a sine wave that would be less “harsh”. Three participants mentioned that specific events in the stimuli were selected and used for evaluation. Only one participant mentioned that he used the first part of every stimulus for evaluation. The same participant also mentions that he experienced the most “harshness” through the parts of his body that are in contact with the vehicles body, such as knee against the centre console. Two participants reported that they kept their eyes closed during the trials. One participant mentioned that he noted a drop in concentration after 35 min. A participant also mentioned that the acceleration at the hip is less obvious than the head and upper body acceleration.

4.3.3 Comments on the questionnaire used

The purpose of question two in the questionnaire (see Appendix B) was to obtain information on the frequency that participants were exposed to off-road driving conditions. The sample size was too small to relate this information to RDT results obtained. Question three posed in the questionnaire asked: "Were there any specific indicators which you used to evaluate the roughness of the road?" The question was intentionally an open ended question in order to allow participants to describe indicators that they used in their own words and in the way they perceived it as it was unknown how they would react. From this a broad range of answers were obtained with a multitude of terms used to describe what were perceived. This gave good insight. The drawback is that it can be difficult to note trends and make correlations as different participants would use different wording to describe the same feeling. In future, based on results obtained here, it might be valuable to make use of methods that would make it easier to identify trends and draw correlations.

4.4 Procedural observations

Certain observations were made with reference to the UDTR method that was used. The UDTR routine that was followed for each participant is supplied in Appendix C indicating the actual BS 6841 weighted r.m.s. acceleration and the participant's responses. Six out of the 10 participants were first exposed to the more rough Road 0p71. During 7 out of 10 tests for both Roads 0p30 and 0p71 (thus 14 out of 20 tests) participants reach the floor of the test procedure. This happened when participants got three consecutive correct responses with the alternative being only 1 step size larger than the reference. In such a case the difference between the reference and alternative stimuli had to be reduced, but it was already at the smallest difference of approximately 3 %. This implied that the step size was too big and that participants could detect a change of +- 3 %. This was unexpected as other studies (see 3.1) made use of step sizes ranging between 2.9 and 4 % without experiencing such a problem. During testing, trials continued when a participant reached the floor of the procedure until an incorrect response was obtained and 8 reversals were completed. An implication of these events could be that the DT reported could possibly have been lower if smaller step sizes were used. It happened only in one case that the participant (participant four) reached the ceiling of the procedure, not being able to detect a 27 % change between the reference and alternative stimuli. The results from participants that reach the floor or the ceiling were included in the analysis.

The mean time that it took to test 1 participant for 1 reference road was 56 min. with the minimum being 35 min., the maximum 89 min. and the standard deviation 18 min. A short break, not exceeding 15 min., was taken after approximately 60 min. of testing. During one test, a break was required after 36 min. when the participant indicated that he was becoming tired. The mean number of trials for a single test was 37, with a minimum of 25, a maximum of 54 and a standard deviation of 9 trials. Across both reference roads, the number of trials having a reference-alternative order (reference stimulus was played before alternative stimulus) were the same as the number of trials having an alternative-reference order. Within the incorrect responses, a bias was observed towards selecting the second stimulus as being the most uncomfortable when in fact the first stimulus was the most uncomfortable. With 85 % of incorrect responses participants selected the second stimulus to be the most uncomfortable when in fact it was the first stimulus. In only 15 % of incorrect responses the first stimulus was selected as being the most uncomfortable when in fact is was the second. Matsumoto et al. (2002) comments on such a trend by stating that it is generally known that when the magnitudes of two stimuli, of any type, in a series are compared the magnitude of the second stimulus tends to be judged relatively greater than the magnitude of the first stimulus.

4.5 Summary

The FR seat rail sensor was the only seat rail sensor of which the RDT was not statistically significantly different from that of the vertical seat pad acceleration for both Road 0p30 and Road 0p71. Therefore, the FR seat rail sensor can be used to implement the RDT as it is more repeatable than the acceleration measured on the seat pad. There was no statistically significant difference when comparing the RDT for vertical seat pad acceleration and FR seat rail acceleration across Road 0p30 and Road 0p71. Therefore it can be concluded that Weber's law holds for a RDT calculated from vertical acceleration when a driver is exposed to all six components of acceleration while seated in a vehicle. Selecting the most conservative (largest) RDT from the seat pad for the two roads would result in a median RDT of 10 % and the 75$^{\text{th}}$ percentile RDT of 13 %. Selecting the most conservative RDT from the FR seat rail for the two roads would result in a median RDT of 11 % and the 75$^{\text{th}}$ percentile RDT of 15 %.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

The aim of this study was to answer two research questions 1) "What is the DT for drivers seated in a vehicle, on a 4-poster test rig, if exposed to all six components of acceleration" and 2) "Does Weber's law hold for a RDT calculated from vertical acceleration when a driver is exposed to all six components of acceleration while seated in a vehicle?".

DTs were determined for 10 participants for two reference road inputs. Participants were seated in a Range Rover Evoque on a 4-poster test rig. Selecting the most conservative (largest) RDT from the seat pad for the two roads would result in a median RDT of 10 % and the 75$^{\text{th}}$ percentile RDT of 13 %. Selecting the most conservative RDT from the FR seat rail for the two roads would result in a median RDT of 11 % and the 75$^{\text{th}}$ percentile RDT of 15 %. There was no statistically significant difference when comparing the RDT for vertical seat pad acceleration and FR seat rail acceleration across Road 0p30 and Road 0p71. Therefore it can be concluded that Weber's law holds for a RDT calculated from vertical acceleration when a driver is exposed to all six components of acceleration while seated in a vehicle. The implementation of the DT is wide. In the vehicle design environment simulations are done with full vehicle models. Vehicle models can predict the effect of design changes to the acceleration measured on the seat rail. DTs could be used to provide an indication if participants would be able to perceive a change in comfort due to the design change. Objective and subjective evaluations are also performed by driving vehicles over test tracks. Here DTs can be used to interpret changes between design iterations to determine if customers would be able to perceive a difference between old and new or sport and comfort suspension modes.

5.2 Limitations of study

The following are limitations and points to consider when using the results presented.

- The cohort used consisted of male engineers with a technical background to vehicle engineering. The DT results obtained may therefore not be representative of the broader population.

- Seven participants reached the floor of the UDTR procedure where they were able to detect the most uncomfortable stimulus three times in a row at the lowest level of alternative stimulus. One participant reached the ceiling where he was not able to identify the most uncomfortable stimulus at the largest alternative stimulus. It is therefore a possibility that the true RDT was not measured, because of these constraints.

5.3 Future work

The following are proposals for future work regarding questions that came to light during this study.

Applicability of weighting functions to difference thresholds. Mansfield and Griffin (2000) makes the following comment: "Additional experimental work is required to investigate the applicability of frequency weightings to the prediction of difference thresholds." Based on published literature presented in this study it seems as if RDT results does not correlate to what is expected in light of the BS 6841. The W_b weighting curve for vertical vibration has a magnitude of roughly 0.4 from 0.5 to 2 Hz where it peaks at 5 Hz and then drops to 0.2 at 80 Hz. Therefore it implies that people are 5 times more sensitive to vibrations at 5 Hz than at 80 Hz. Such a trend is not observed in published DT data. It is known, as stated in Section 2.7, that frequency weighting curves might not be applicable for small accelerations near the perception limit as well as very large accelerations. Published data presented in the literature study does not fit into one of these two categories. It could be valuable to investigate the data and methods used to determine frequency weighting curves, with the aim to understand why difference threshold data does not indicate the same frequency sensitivity as weighting functions. It is not known if and when frequency weightings should be applied when determining and implementing difference thresholds. Reference could also be made to Els (2005) that found that due to the suspension transfer function of a vehicle good correlation was obtained between objective and subjective results, for weighted as well as unweighted vertical vibration.

Driver sensitivity to various components of acceleration. Investigate a driver's sensitivity to various components of acceleration (e.g.vertical, roll, pitch etc.) in order to determine what motions people are the most sensitive to. For example, lateral movement of the torso or head toss caused by roll. It might be possible to determine a DT for various motions. This could give an indication of what most attention should be paid to when improving suspension.

Sensitivity to frequency band magnitude change. Investigate the effect of magnitude changes within certain frequency bands by determining DTs for a magnitude increase per frequency band. This could provide valuable information in terms of suspension design and comfort. Note that such an analysis could possibly be very time consuming. Analysing four frequency bands at two magnitudes would result in eight tests per participant. If the same method is used as for the experimental study in this dissertation, with 10 participants, it would amount to approximately 20 days of continuous testing. It could be considered to use a two-down-one-up rule to shorten tests.

Psychophysical methods. The effect of various psychophysical methods on the DTs obtained are not known. Matsumoto et al. (2002) mentions that the low RDTs obtained could be as a result of the psychophysical testing method used. Published literature makes use of various psychophysical methods with different test parameters making it very difficult to investigate the effect thereof. Investigating the effect of psychophysical testing methods could yield valuable results for future JND testing.

Repeatability of RDT results. The repeatability of the RDT results obtained in this study was not investigated, although it is an important aspect of reporting results. The repeatability can possibly be investigated over short periods of time (days) or longer periods of time (months). Knowing what the variability of the results are over a duration of time would assist with the implementation of results.

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Appendix A

Informed consent form

Informed consent form

Title of research project: Ride comfort analysis of off-read vehicles by using objective subjective correlation and the just noticeable difference threshold.

Introduction:

You are invited to partake in a research study. The information provided in this document will assist you to decide if you would like to participate. Before you decide to partake in the study it is important that you understand how the tests will be conducted and what will be expected of you. If you have any questions or feel that anything has not been fully explained, do not hesitate to ask the investigator. Your health is important. Please do not participate in this study should you have any medical condition that deems you unfit for such activities.

Purpose of the study:

The purpose of this study is twofold: a) to improve the correlation between the measured comfort of a vehicle and the actual comfort that a person perceives; and b) to determine the smallest change in magnitudes or frequency of vibration that a person can perceive.

Health conditions that will deem you unfit:

Should you identify any one of the following conditions that are applicable to you, please inform the investigator before continuing.

- <u>Active disease of the respiratory system</u> including recent history of couching-up blood or chest pain.
- <u>Active disease of the gastro-intestinal tract</u> including internal or external hernia, peptic ulcer, recent gall-bladder disease, rectal prolapse, anal fissure, haemorrhoids or pilonidal sinus.
- <u>Active disease of the cardiovascular system</u> including hypertension required treatment, angina of effort, valvular disease of the heart, or haemophilia.
- <u>Active disease or defect of the muscular-skeletal system</u> including degenerative or inflammatory disease of the spine, long bones, or major joints, or a history of repeated injury with minor trauma.
- <u>Active or chronic disease or disorder of the nervous system</u> including eye and ear disorders and any disorder involving motor control, wasting of the muscle, epilepsy or retinal detachment.
- <u>Pregnancy</u>
- <u>Mental health</u> subjects must be of sound mind and understanding and not suffering from any mental disorder that would raise doubt as to whether their consent to participate in the experiment was true and informed.
- <u>Recent trauma and surgical procedures</u> this include any persons under medical supervision following surgery or traumatic lesions (e.g. fractures).
- <u>Prosthesis</u> including persons with internal or external prosthetics devices.

Explanation of the procedure to be followed:

You will be required to sit in a vehicle on a 4 post test rig in the vehicle testing laboratory of Tenneco, Sint-Truiden. Different inputs will be given to the vehicle. You will then be required to respond to one or more questions base on what you perceived. At any point you may indicate that the test should be stopped should you wish to terminate your participation.

Risks involved:

There are no significant risks involved. The vibration experienced will be well below levels that could have health implications.

Benefits of the study:

You will be making a contribution to the development of more comfortable vehicles, as well as to the understanding of the human body and its perception to vibration.

Has this study received ethical approval?

Yes, this study has been approved by the Ethics Committee of the Faculty of Engineering, Build Environment and IT of the University of Pretoria.

Confidentiality:

All information submitted on the questionnaires or verbally will be regarded as confidential. The results obtained from the questionnaires as well as the measurements taken on the vehicle will be published in such a fashion that participants remain unidentifiable.

Contact details:

If any further questions comes to mind or if there are any concerns after you have partaken in the study please contact:

- Mr Roland Gräbe on +27 83 288 9587 or roland.grabe@gmail.com.
- Dr Cor-Jacques Kat on +27 314 7774 or cor-jacques.kat@up.ac.za

Consent to participate in this study:

1 I …………………………………………… hereby voluntarily grant my permission for participation in the project as explained to me by ………………………………………

2 The nature, objective, possible safety and health implications have been explained to me and I understand them.

3 I understand my right to choose whether to participate in the project and that the information furnished will be handled confidentially. I am aware that the results of the investigation may be used for the purposes of publication.

4 Upon signature of this form, you will be provided with a copy.

Signed: ____________________ Date: ____________

Witness: ____________________ Date: ____________

Researcher: ____________________ Date: ____________

Appendix B

Questionnaire

Questionnaire

Subject number: ______

1. Personal information

Age: ________________________________

Sex: ________________________________

Length: ________________________________

Weight: ________________________________

Occupation: ________________________________

Fitness level – hours of exercise per week/month: ________________________________

2. General information

Frequency of exposure to off-road terrain and driving conditions:

Frequently		More than once in 6 months		Less than once in 6 months		No exposure to off-road terrain.	

Terrain roughness exposure:

4x4 only routes (off-road)		Rough gravel roads (off-road)		Good gravel roads (off-road)		Only tar roads	

3. Feedback

Was there any specific indicator which you used to evaluate the roughness of the road? E.g. head movement, upper body movement?

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Appendix C

Record of UDTR routine

The two sets of graphs are presented indicating the FR vertical seat rail accelerometer and seat pad weighted r.m.s. acceleration of the reference and alternative stimuli at each trail throughout the UDTR procedure. The weighted r.m.s from the FR vertical seat rail accelerometer was shown as sensor gave RDTs that are not significantly different from that of the vertical seat pad acceleration. The seat pad provides the closest acceleration that participants experienced.

Note on UDTR procedure for participant 001: For reversal number 5 or peak number 3 for participant 001 on Road 0p71, it might seem as if the peak only consists of 2 correct responses and not 3. Because of a technical fault the acceleration of the first of the 3 correct responses was not recorded and can not be plotted.

Note on UDTR procedure for participant 004: During the testing of participant 004 on Road 0p30 an error was made by the test operator at trial 28 by lowering the test magnitude although 3 consecutive correct responses have not yet been obtained. Therefore trial 45 to 47 was used as peak number 3 and 50 to 52 as peak number 4.

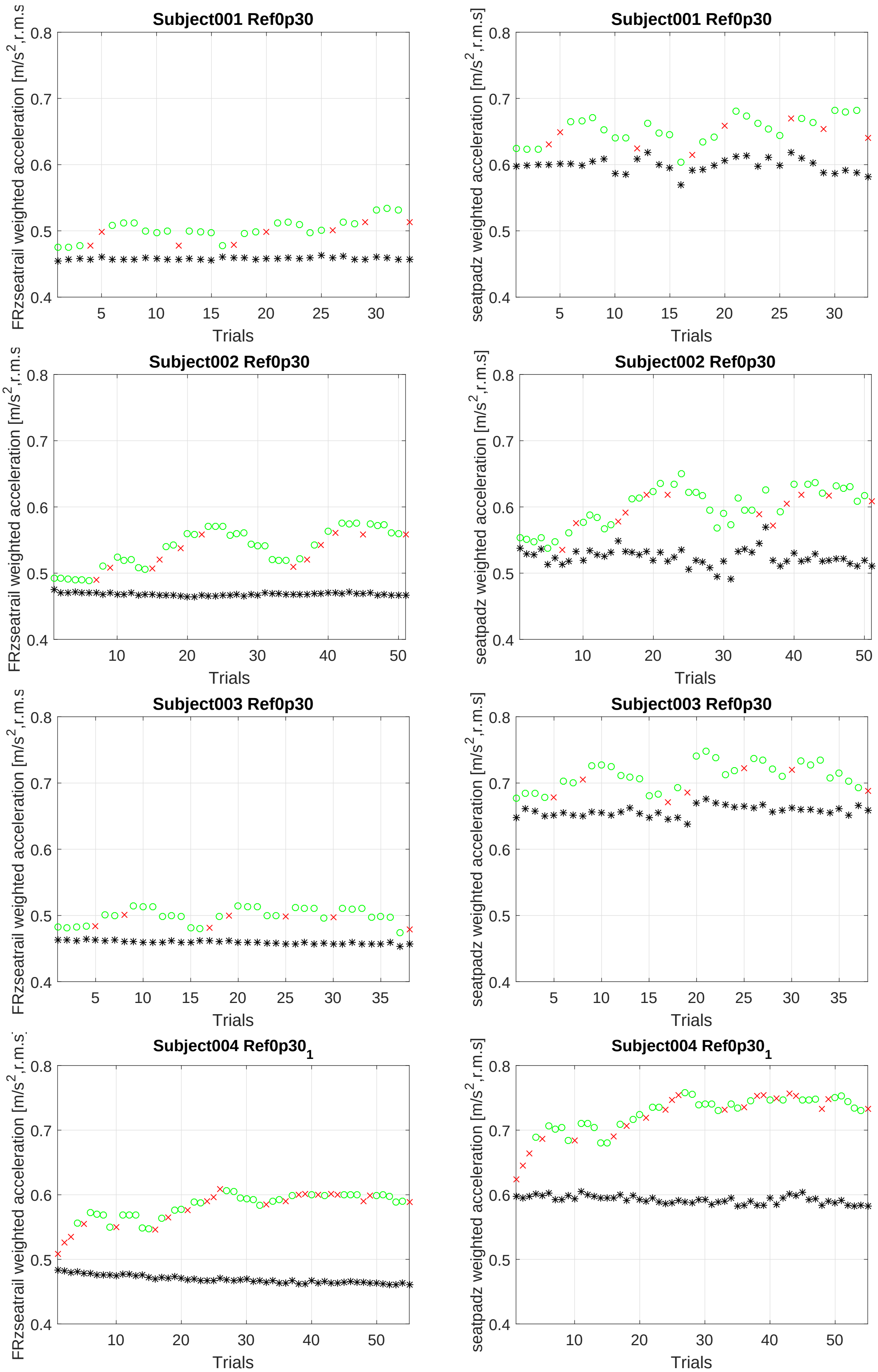


Figure C.1: Graphical representation of vertical seat rail and seat pad data in the UDTR routine on Road 0p30 for participants 001 to 004.

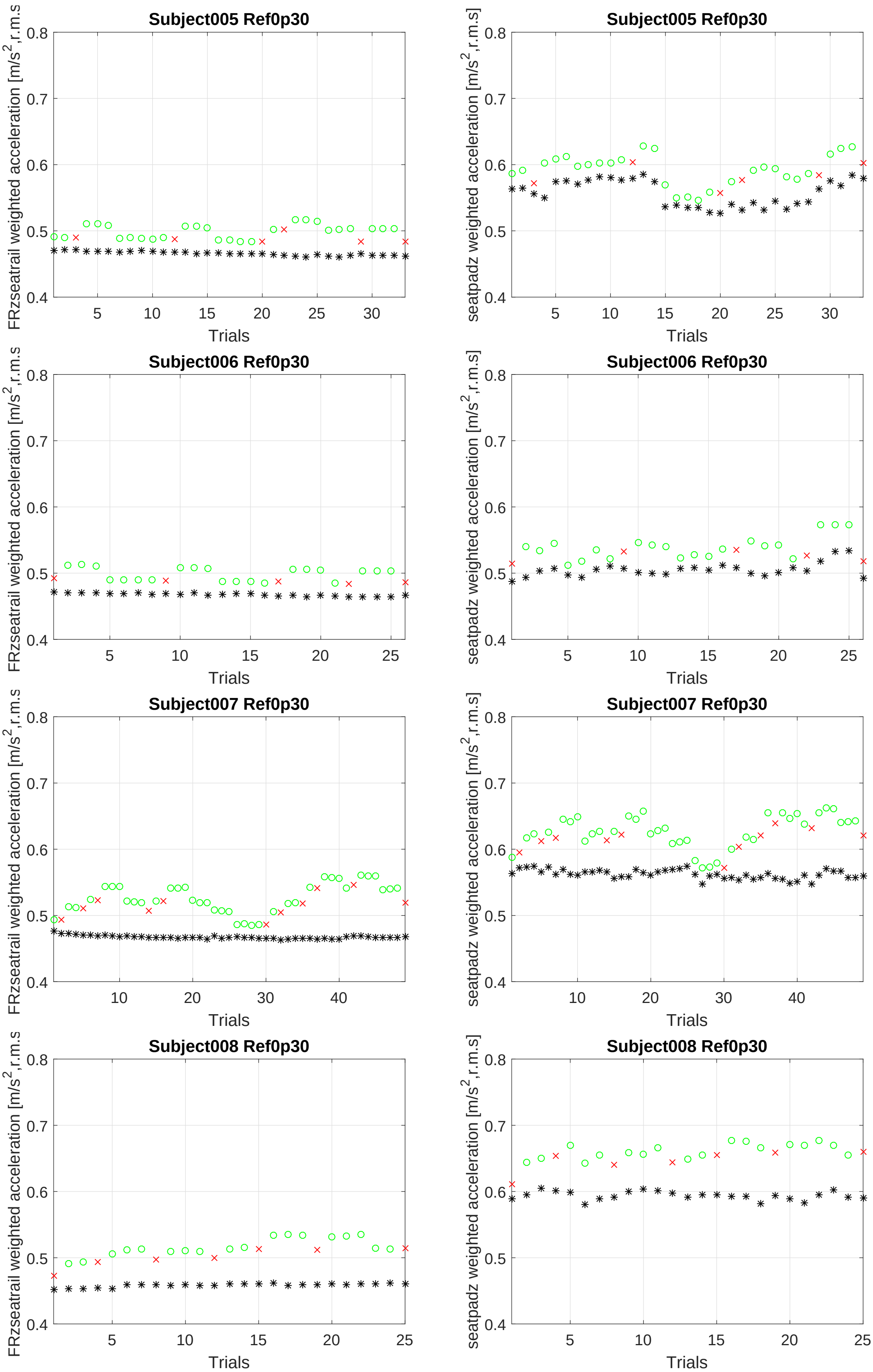


Figure C.2: Graphical representation of vertical seat rail and seat pad data in the UDTR routine on Road 0p30 for participants 005 to 008.

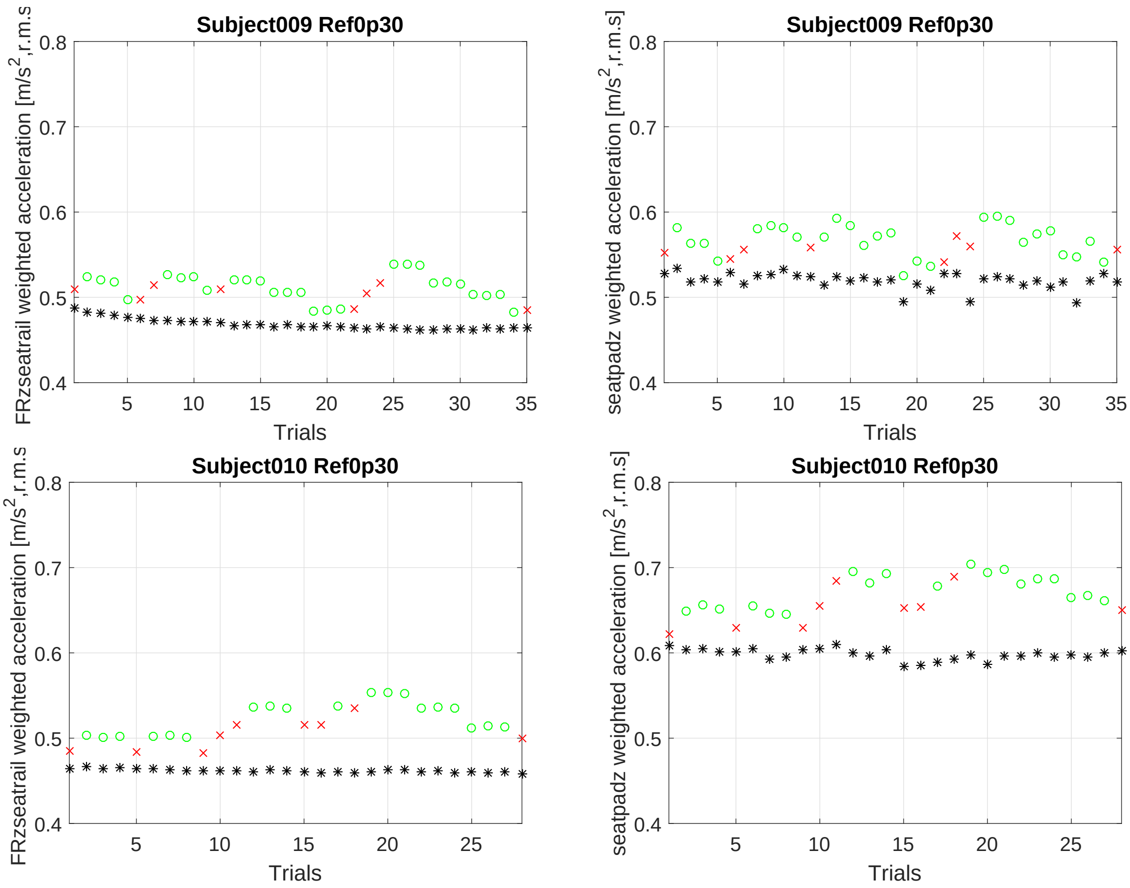


Figure C.3: Graphical representation of vertical seat rail and seat pad data in the UDTR routine on Road 0p30 for participants 009 to 010.

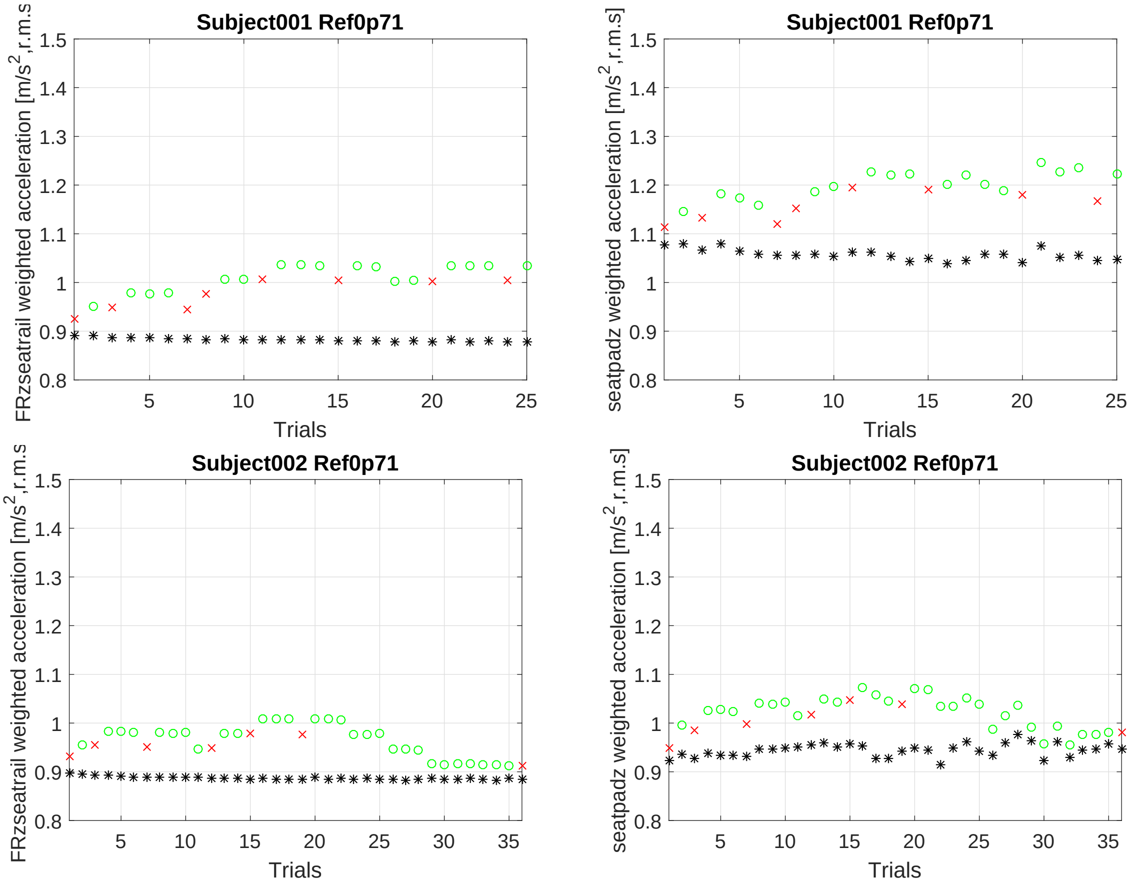


Figure C.4: Graphical representation of vertical seat rail and seat pad data in the UDTR routine on Road 0p71 for participants 001 to 002.

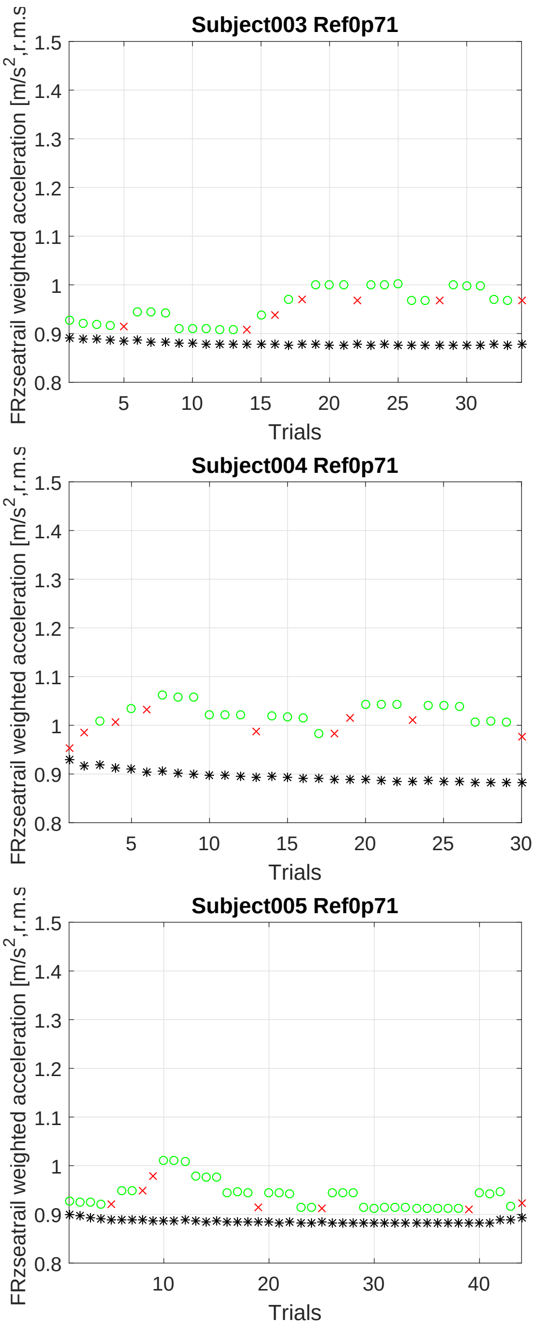


Figure C.5: Graphical representation of vertical seat rail and seat pad data in the UDTR routine on Road 0p71 for participants 003 to 005.

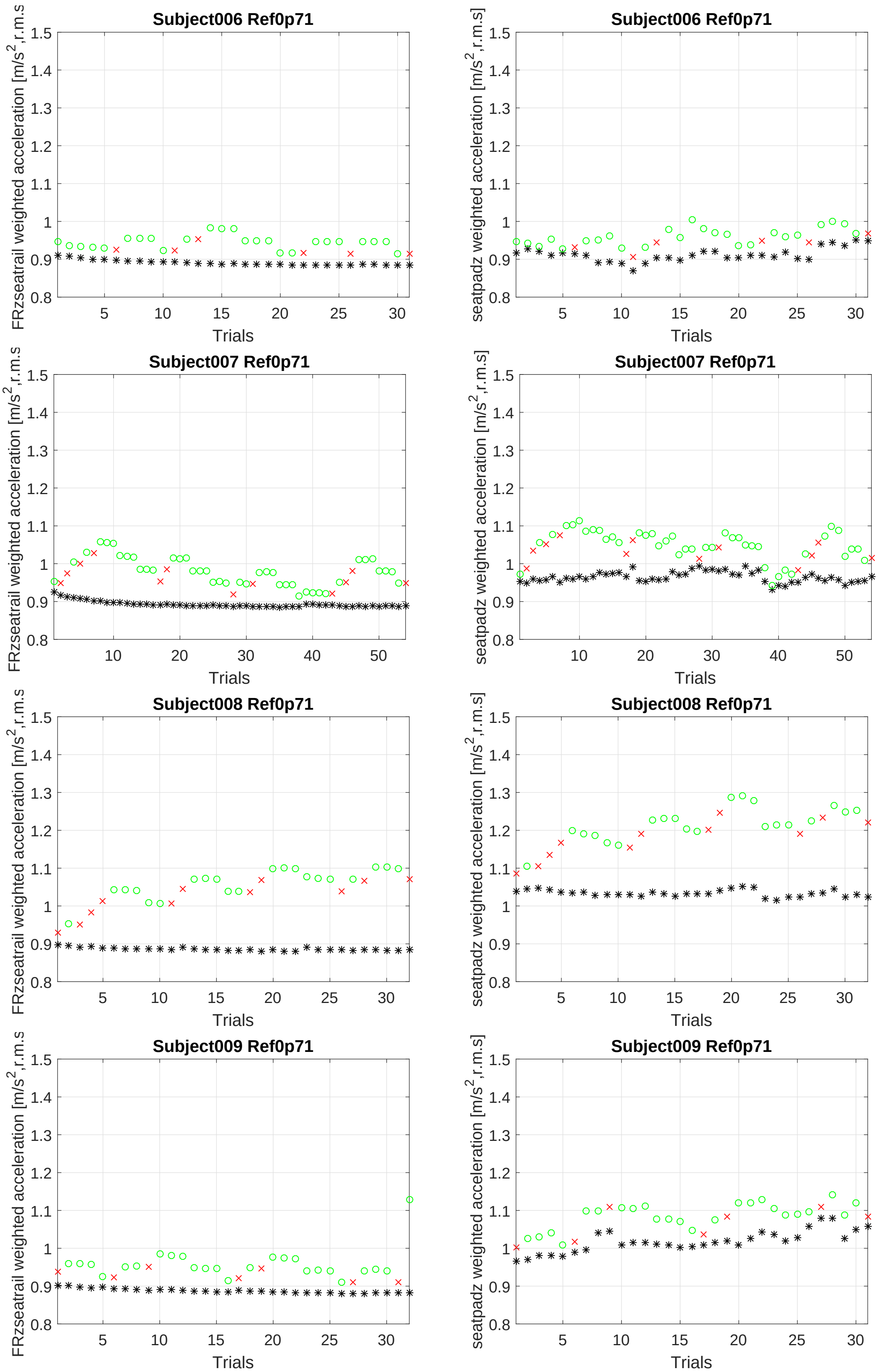
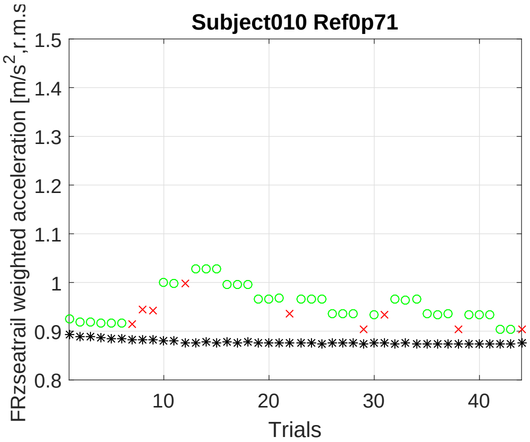


Figure C.6: Graphical representation of vertical seat rail and seat pad data in the UDTR routine on Road 0p71 for participants 006 to 009.



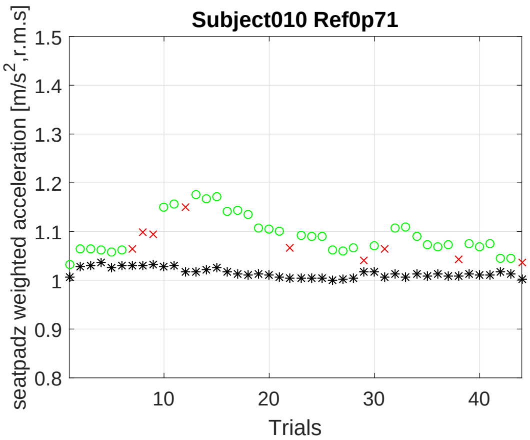


Figure C.7: Graphical representation of vertical seat rail and seat pad data in the UDTR routine on Road 0p71 for participants 010.

Appendix D

RDT results comparison: BS 6841 vs ISO 2631-1

As stated in Subsection 3.2.3 the W_b weighting from BS 6841 was used to interpret the vertical acceleration data used to calculate ADTs and RDTs. As ISO 2631-1 is regarded as the current norm, Table D.1 provides a comparison of RDTs interpreted using BS 6841 and the W_k weighting from ISO 2631-1. The W_k weighting was applied to acceleration data in the frequency domain using MATLAB. The frequency domain response of the Laplace domain transfer functions given in Annex A of ISO 2631-1 was used. All frequency content below 0.5 Hz and above 80 Hz was discarded as it falls outside the range of interest as well as to discard content that falls outside of the sensors' specifications. Figure D.1 displays the frequency response (weighting) of both BS 6841 and ISO 2631. For Road 0p30 the median RDT from ISO 2631-1 differed by 0.152 % from the median RDT from BS 6841, with the median RDT from BS 6841 being bigger. For Road 0p71 the median RDT from ISO 2631-1 differed by 0.103 % from the median RDT from BS 6841, with the median RDT from BS 6841 being bigger. These differences are small in comparison to the median RDT for Road 0p30 and Road 0p71 which are between 8 and 10 %.

Table D.1: Difference between RDT results interpreted using the BS6841 weighting and the ISO2631-1 weighting for Road 0p30 and Road 0p71. The RDT data supplied here were calculated using the vertical seat pad acceleration.

	Road 0p30 - RDT			Road 0p71 - RDT		
Participant	**BS Approx** [%]	**ISO TF** [%]	**Difference** [%]	**BS Approx** [%]	**ISO TF** [%]	**Difference** [%]
1	9.364	9.352	0.133	14.538	14.530	0.051
2	18.276	18.253	0.124	9.413	9.407	0.055
3	8.922	8.914	0.092	10.881	10.874	0.063
4	22.934	22.893	0.179	12.570	12.553	0.135
5	6.528	6.521	0.106	4.258	4.251	0.156
6	6.859	6.846	0.191	5.278	5.274	0.077
7	13.204	13.184	0.157	7.763	7.751	0.163
8	11.378	11.365	0.114	19.165	19.147	0.093
9	8.725	8.713	0.143	5.491	5.485	0.099
10	10.931	10.913	0.168	5.469	5.464	0.097
25^{th} percentile	8.725	8.713	**0.143**	5.469	5.464	**0.097**
Median	10.147	10.132	**0.152**	8.588	8.579	**0.103**
75^{th} percentile	13.204	13.184	**0.157**	12.570	12.553	**0.135**

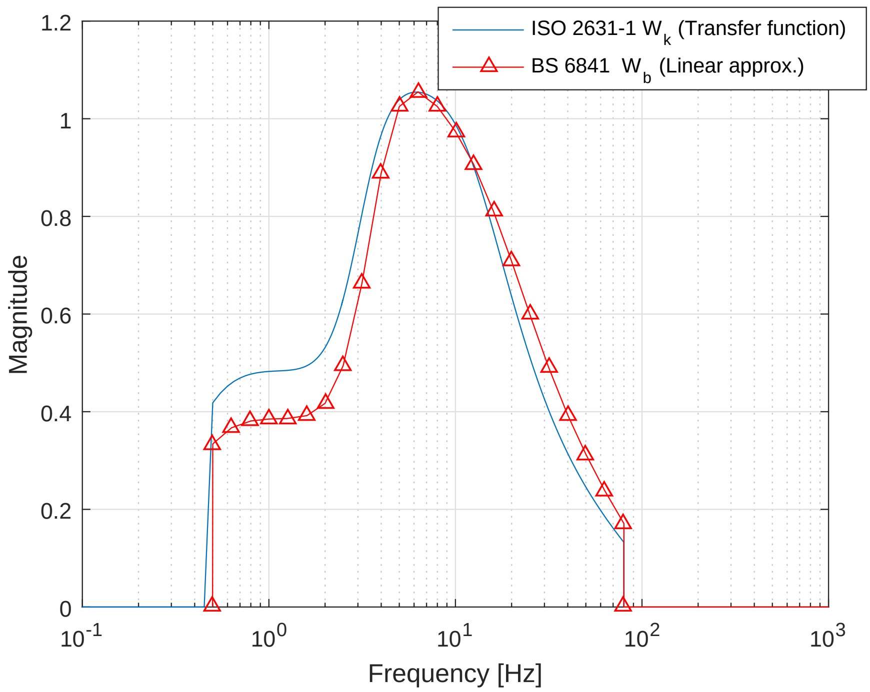


Figure D.1: Frequency response of BS 6814 and ISO 2631-1 filters (weightings) used.

Appendix E

Six axes of vibration magnitude

Participants were exposed to longitudinal, lateral, vertical, roll, pitch and yaw acceleration while seated in the vehicle. Accelerations were recorded during each individual trial. The first 20 reference stimuli recorded from each participant were used to quantify the six components of acceleration. Twenty stimuli from 10 participants provides 200 data points. Figure E.1 and Figure E.2 displays the distribution of the r.m.s. magnitudes for the six components of acceleration for Road 0p30 and Road 0p71 respectively. The lateral (x), longitudinal (y) and vertical (z) accelerations were record from the seat pad accelerometer. The roll, pitch and yaw were calculated from the accelerometers mounted on the seat rail by assuming ridged body motion. The roll, pitch and yaw is an approximation of what the participants experienced as the accelerations measured on the seat rail does not take the effect of the seat cushioning in to account.

Weighted acceleration magnitudes in Figure E.1 and Figure E.2 were weighted using BS 6841. The Laplace domain filters (weightings) defined in Table 2 of BS 6841 were used instead of the approximations in Table 3 of BS 6841. Multiplication factors (k) specified under Section 6.2.1 of BS 6841 for seated persons were also applied to roll ($k = 0.63$), pitch ($k = 0.4$) and yaw ($k = 0.2$). The frequency weighting functions and multiplication factors (k) defined in BS 6841 provides the same results as those in ISO 2631-1 (using filters defined in Annex A with multiplication factors from Section 8.2.2.1 of ISO 2631-1) for lateral, longitudinal, roll, pitch and yaw except for the vertical vertical vibration. Table E.1 shows the differences in the magnitudes of the median vertical accelerations between BS 6841 and ISO 2631-1. The differences are small.

Table E.2 provides a summary of the medians of the six axes of vibration for Road 0p30 and Road 0p71 for unweighted as well as BS 6841 weighted results. BS 6841 states that in calculating a point vibration total value the weighted value for an axis can be excluded if it is 25 % smaller than the largest axis of vibration. For Road 0p30 the lateral and longitudinal axes are larger than 25 % of the vertical axes (largest axis of vibration). For Road 0p71 the longitudinal, lateral and roll axes are larger than 25 % of the vertical axes. The lateral axes are the largest and most significant being 36 % of the vertical vertical for Road 0p30 and 55 % of the vertical for Road 0p71.

The magnitude of the various axes of vibration are also supplied after being weighted with

ISO 2631-1 for purpose of caparison (see Table E.3). When interpreting data using ISO 2631, only lateral acceleration is larger than 25 % of the vertical acceleration. The longitudinal vibration magnitude for Road 0p30 and Road 0p71 is close to 25 %, so too is the roll magnitude for Road 0p71, and could therefore contribute significantly to the perception of the occupant.

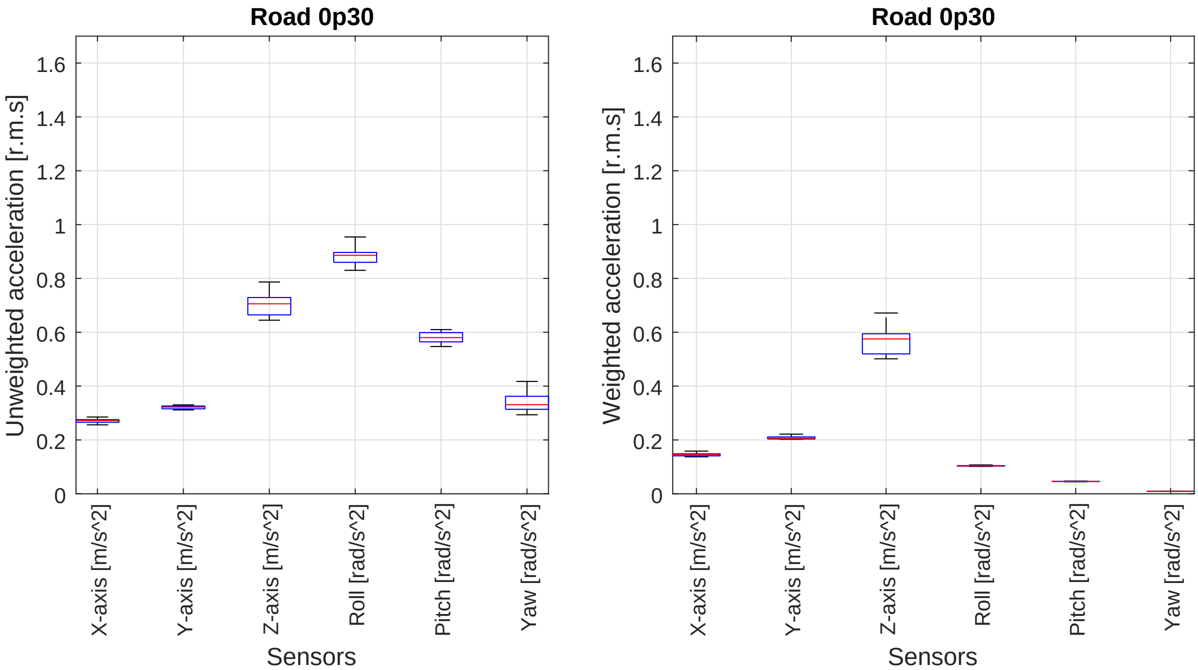


Figure E.1: Boxplot of the unweighted and BS 6841 weighted r.m.s. magnitudes of the six axis of vibration (longitudinal, lateral, vertical, roll, pitch, yaw) that participants were exposed to for Road 0p30.

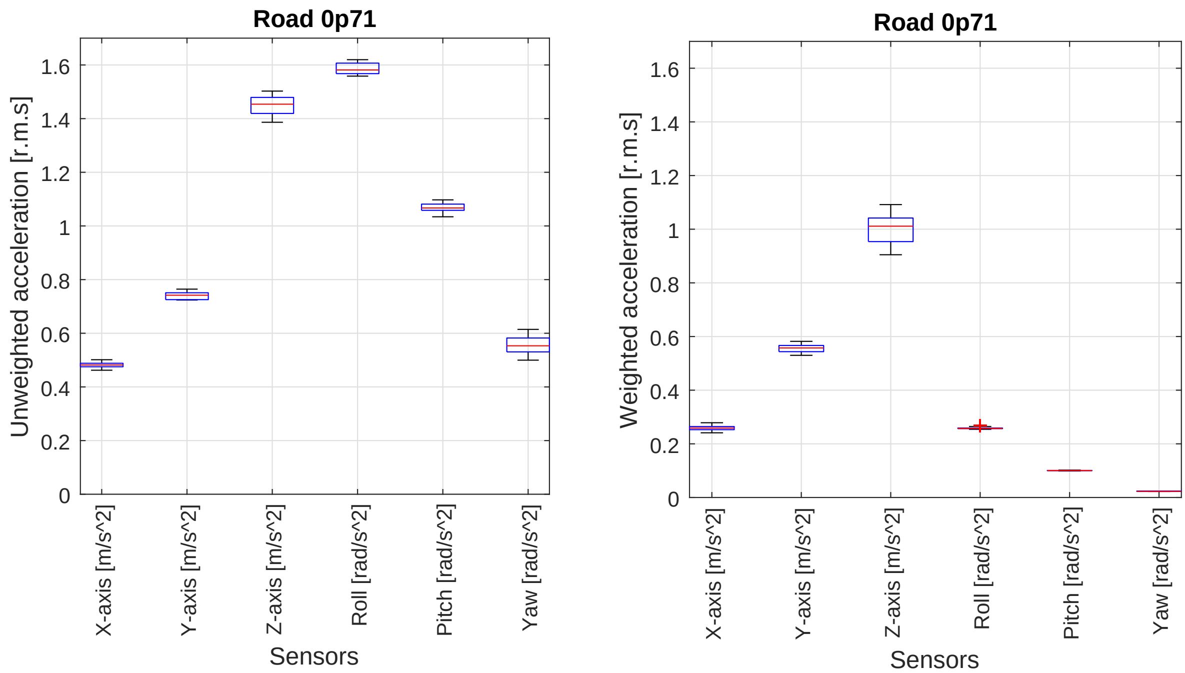


Figure E.2: Boxplot of the unweighted and BS 6841 weighted r.m.s magnitudes of the six axis of vibration (longitudinal, lateral, vertical, roll, pitch, yaw) that participants were exposed to for Road 0p71.

Table E.1: Difference between the r.m.s. magnitude of the median vertical acceleration measured on the seat, when using the ISO 2631-1 weighting in comparison to the BS 6841 weighting.

	Road 0p30 [m/s^2]	**Road 0p71** [m/s^2]
ISO 2631-1	0.596	1.074
BS 6841	0.575	1.011
Difference	0.021	0.063

Table E.2: Unweighted and BS 6841 weighted median r.m.s. magnitudes of the six axes of vibration (longitudinal, lateral, vertical, roll, pitch, yaw) that participants were exposed to.

	Road 0p30			**Road 0p71**		
Vibration (axis)	**Unweighted**	**Weighted**	**% of z-axis (weighted)**	**Unweighted**	**Weighted**	**% of z-axis (weighted)**
Longitudinal	0.272 m/s^2	0.145 m/s^2	**25.266** %	0.482 m/s^2	0.259 m/s^2	**25.585** %
Lateral	0.322 m/s^2	0.206 m/s^2	**35.829** %	0.742 m/s^2	0.557 m/s^2	**55.121** %
Vertical	0.706 m/s^2	0.575 m/s^2	-	1.454 m/s^2	1.011 m/s^2	-
Roll	0.886 rad/s^2	0.104 rad/s^2	18.033 %	1.581 rad/s^2	0.257 rad/s^2	**25.434** %
Pitch	0.580 rad/s^2	0.046 rad/s^2	7.929 %	1.067 rad/s^2	0.100 rad/s^2	9.924 %
Yaw	0.331 rad/s^2	0.009 rad/s^2	1.539 %	0.553 rad/s^2	0.023 rad/s^2	2.282 %

Table E.3: Unweighted and ISO 2631-1 weighted median r.m.s. magnitudes of the six axes of vibration (longitudinal, lateral, vertical, roll, pitch, yaw) that participants were exposed to.

	Road 0p30			Road 0p71		
Vibration (axis)	**Unweighted**	**Weighted**	**% of z-axis (weighted)**	**Unweighted**	**Weighted**	**% of z-axis (weighted)**
Longitudinal	0.272 m/s^2	0.145 m/s^2	24.372 %	0.482 m/s^2	0.259 m/s^2	24.075 %
Lateral	0.322 m/s^2	0.206 m/s^2	**34.559 %**	0.742 m/s^2	0.557 m/s^2	**51.856 %**
Vertical	0.706 m/s^2	0.596 m/s^2	-	1.454 m/s^2	1.074 m/s^2	-
Roll	0.886 rad/s^2	0.104 rad/s^2	17.392 %	1.581 rad/s^2	0.257 rad/s^2	23.928 %
Pitch	0.580 rad/s^2	0.046 rad/s^2	7.648 %	1.067 rad/s^2	0.100 rad/s^2	9.337 %
Yaw	0.331 rad/s^2	0.009 rad/s^2	1.534 %	0.553 rad/s^2	0.023 rad/s^2	2.148 %