# Development of an On-line Ride Comfort Evaluation Tool

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# Abstract

To produce competitive vehicles, their comfort is one important issue to take into account during the development process. The aim of this Master Thesis is to develop an on-line comfort evaluation tool in order to improve research and education in the field of vehicle comfort at the division of Vehicle Dynamics at the Royal Institute of Technology.

Based on ISO standards concerning comfort an on-line evaluation tool has been developed using DASYLab, which is a software that allows creation of acquisition, control, simulation and analysis tasks.

The developed tool has been evaluated by performing measurements of a VOLVO V40 equipped with sensors. Different sorts of surfaces and driving conditions have been investigated, and from this investigation one can conclude that the comfort tool works properly.

# Acknowledgements

First of all, I would like to thank my parents, José and Mari Luz, for giving me the opportunity to study abroad during this time in order to continue growing as a person and as an engineer.

I want to express my gratitude to the Division of Vehicle Dynamics at the Royal Institute of Technology in Stockholm for accepting me to carry out my Master's Thesis with them. I am especially very grateful to Adam Rehnberg and Jenny Jerrelind, the supervisor and examiner of my project, to be able to learn more about vehicles thanks to their knowledge in this field.

I also want to thank to John Rys and Glenn Abrahamsson, from IOTech and Saven Hitech AB respectively, to help me with the troubles I had regarding the connection between the car and the laptop.

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As stated before, carrying out this Master Thesis at the division of Vehicle Dynamics at the Royal Institute of Technology in Stockholm has allowed me not only discovering a new culture and improving my English but also growing as a person and as an engineer.

Stockholm, Sweden June 2007

José Manuel Sala

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# 1. Introduction

## 1.1. Background

Cars today are getting more and more technologically advanced, customers and passengers are becoming more exigent with their purchase and the demand for a more comfortable travelling environment is constantly increasing. Therefore, to produce competitive vehicles, the ride comfort for the passengers is one important issue to take into account during the development process. Today, standardized evaluation criteria exist in order to get a measure of the comfort level, i.e. the ISO Standards.

## 1.2. Objective of the thesis

The aim with this Master Thesis is to create an on-line comfort evaluation tool for a passenger car in order to improve research and education in the field of vehicle comfort at the division of Vehicle Dynamics at the Royal Institute of Technology.

The tool should follow the ISO standards and calculate and visualize the comfort level on-line during measurements.

When the tool is developed the functionality of the tool should be verified by a comfort evaluation of a Volvo V40 which is owned by the division of Vehicle Dynamics.

This project will also be able to help vehicle dynamic students to learn more about comfort and allow them to practice with the program tool during laboratory exercises.

# 2. Vibrations and comfort in vehicles

## 2.1. Vibrations

Vibrations which are transmitted to passengers either by tactile, visual or aural paths appear as a consequence of the high speed during travelling and the presence of bumps along the road. This broad spectrum may be divided according to the frequency and classified as ride (0-25 Hz) and noise (25-25000 Hz). The 25 Hz boundary point is the lower frequency in the threshold of hearing and the 25000 Hz is the upper limit of the vibrations common to all motor vehicles [3].

Normally, from this spectrum, only the tactile and visual vibrations affect the ride comfort of the passenger, whereas aural ones are referred to as noise. For this reason, the vibration environment is one of the more important criteria by which people judge the design and the construction quality of the car.

The multiple excitation sources that cause vibrations in the vehicle could be grouped in two. The ones that are indirect, as for example the road roughness, and the ones that come from the car, such as the engine, the driveline or the tire/wheel assembly. Furthermore, there is another excitation source, the aerodynamics vibrations produced by the air flow around the bodywork of the car, but depending on the situation it could be included in both groups [2].

In figures 2.1 and 2.2, two sketches are represented. The first one tries to summarize the ride dynamics system of a vehicle, showing how the excitation sources have an affect on passenger compartment and determine the passenger’s perception of the vehicle. In figure 2.2 the different ride excitation sources are clearly defined.

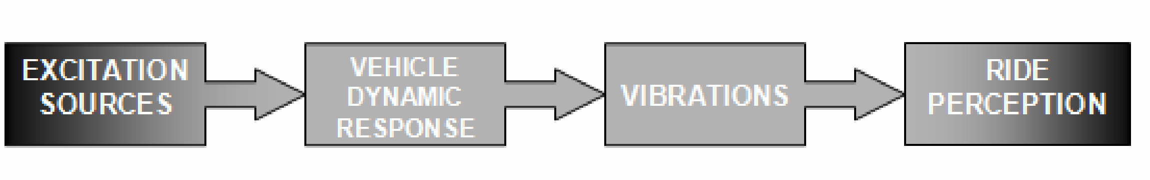


*Fig. 2.1. Ride dynamics system of a vehicle*

| | | |
|---|---|---|
| EXCITATION SOURCES | INDIRECT | GROUND CONDITIONS |
| | | ROAD ROUGHNESS |
| | | SURFACE IRREGULARITIES |
| | DIRECT | ENGINE |
| | | DRIVELINE |
| | | TIRE / WHEEL |
| | OTHERS | AERODYNAMICS |

*Fig. 2.2. Excitation sources [2]*

## 2.2. Human perception and tolerance of vibrations

The vehicle design should be sensitive to the performance of the human body from the mechanical point of view, including the capacity to stand vibrations. In fact, nowadays, the car development is more focused on comfort and safety trying to diminish the tiredness and attention loss of the driver.

As a general rule, the human body, constituted by members with mass and elasticity, behaves like a vibrating system. It is formed by viscous-elastic elements that cushions general vibrations originated by external actions. The equivalent vibrating system is not linear and also depends on the relaxed situation or the muscular tension of the individual. It is also influenced by the posture of him (sitting or standing) and, in general, by the support of the different parts of the body to the structure from where the vibrations are induced [3].

The muscular system continuously reacts to the solicitations generated by vibrations, adapting to them and muscularly compensating the charges, what finally produces physic tiredness.

### 2.2.1. Ride comfort

The vibration level or passenger's ride comfort may be defined as a subjective perception, normally associated with the level of comfort experienced when travelling in a vehicle. Thus, in its broadest sense, the perceived ride is the cumulative product of many factors. Additionally, the general comfort level can be influenced by seat design and its fits to the passenger, temperature, ventilation, interior space, hand holds, and many other factors. In summary, there are many factors that may all contribute to the ride quality of a vehicle as it is showed in Figure 2.3 [3].

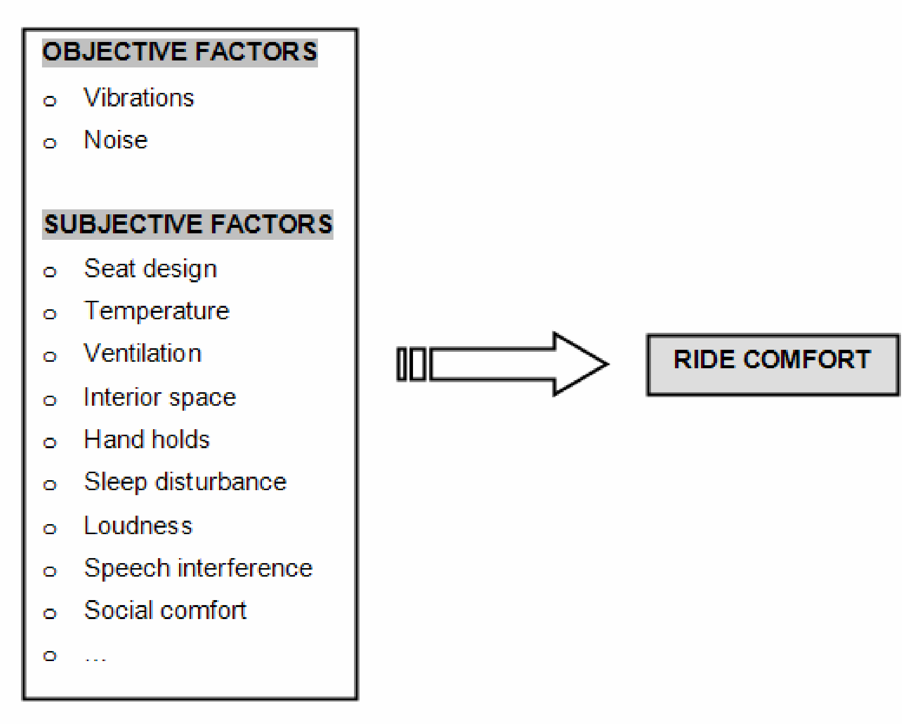


*Fig. 2.3. Factors that contribute to the ride comfort [3]*

The comfort or discomfort levels experienced during travelling are evaluation subjective elements of the ride comfort quality of the vehicle. Disturbances, vibrations, noise levels and high frequency vibrations can be measured objectively, but the interaction of all of these readings and the sensation perceived by vehicle occupants is never perfectly exact or universal.

Basically, it can be said that it does not exist a comfort absolute standard or human discomfort expressed in physical terms such as amplitudes or accelerations in a fixed frequency. However, there is certainly a sufficient concordance between the data obtained in experiments by different researches to be able to define a zone above which the vibration is intolerable or below which is insignificant.

As stated before, considerable researches have been conducted by a great number of investigators to define ride comfort limits. Various methods for assessing human response to vibration have been developed. They include subjective ride assessment, shake table tests, ride simulator experiments and ride measurements in vehicles. In general, these methods attempt to correlate the response of test subjects in qualitative terms, such as uncomfortable and extremely uncomfortable, with vibrational parameters such as displacement, velocity, acceleration, and jerk over the frequency range of interest.

The assessment of human response to vibration is complex in that the results are influenced by the variations in individual sensitivity, and the diversity of test methods and sensation levels used by different investigators. Over the years, numerous ride comfort criteria have been proposed, and almost all of them are summarized in the International Standard ISO 2631 updated in 1997 [4]. This guide, explained with more details in the appendix A, is recommended for the evaluation of vibrational environments in transport vehicles as well as in industry, and defines distinct limits for whole-body vibration in the frequency range 1-80 Hz regarding comfort.

### 2.2.2. Vibrations from the ergonomic point of view

The vibration importance, from the ergonomic point of view, is given by two magnitudes, intensity and frequency. Any physical structure, including the different parts of the human body, can amplify the intensity of a vibration received from another body. This happens if the vibration appears in certain frequencies which are characteristics of the recipient structure (resonance frequency).

It is important to know that the different parts of the human body possess specific resonance frequencies, and vibrations received at those frequencies can be amplified in intensity and, therefore, damaging to health.

One of the latest methods used to measure the human sensibility to vibrations is the introduction of specialized dummies, where this sensibility is measured on 12 different axes. Three linear accelerations (in the X, Y and Z planes) are registered in chest, bottom and feet, besides of pitch, roll and yaw accelerations in the seat cushion. On the other hand, dynamic finite-element-models of the human body for seating and vibrations simulations on passenger car seats are also used.

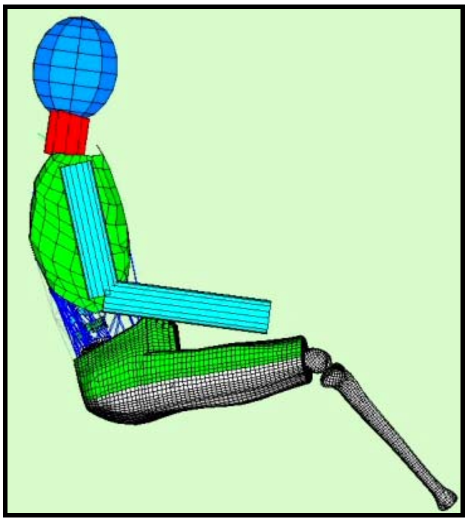

*Fig. 2.4. Dummy for computer vibrations simulations on passenger car seats [16]*

As general conclusions to the multitude of studies carried out about the influence of vibrations in the whole human body while travelling with a vehicle, it is important to remark again the risk that some part of the body gets in resonance with the excitation frequency. The human body reacts to vibrations in a different way, according to their senses.

Table 2.1 summarizes the resonance frequencies for different parts of the human body. The frequencies always depend on the individual and on the vibration amplitude, but in general it is true that bigger amplitudes increase the frequency which the individual becomes sensory.

*Table 2.1. Summary of the resonance frequencies of the human body [3]*

| RESONANCE FREQUENCIES IN THE HUMAN BODY | | |
|---|---|---|
| **ZONE** | **FREQUENCY (Hz)** | **EFFECT** |
| Ear | 0,5 – 0,75 or 1 | Dizziness and sickness |
| Flexed leg | 2 | General fatigue |
| Shoulders | 4 – 5 | General fatigue |
| Diaphragm | 4 – 8 | Respiratory difficulties |
| Muscles | 5 – 6 | General fatigue |
| Visceral region | 5 – 7 | Dizziness and sickness |
| Forearm | 5 – 10 | General fatigue |
| Spinal column (axial) | 10 – 12 | General fatigue |
| Thorax | 10 – 50 | Respiratory difficulties |
| Arm | 16 – 30 | General fatigue |
| Head and neck | 18 – 20 | General fatigue |
| Cervical vertebras | 20 | General fatigue |
| Rigid leg | 20 | General fatigue |
| Eyeball | 20 – 90 | Loss of keenness of sight |
| Hand | 30 – 50 | General fatigue |

It is also known that pitch accelerations produce feeling of nauseas and vertical frequencies, which turn out to be more uncomfortable for humans, are between 20 and 200 Hz. Furthermore, the fatigue appears quickly between 4 and 8 Hz or under 0.75 Hz, and then the dizziness and sickness appear as well.

Lateral and longitudinal accelerations in the same frequency range are also unpleasant as they alter the balance mechanism of the inner ear.

To sum up, it is concluded that the field in which vibrations are acceptable is restricted to frequencies between 1 and 2 Hz. So then, vibrations, both permanent and transient, induce on the vehicle occupant oscillations that can be kept in acceptable limits with an appropriate suspension and cushion in the devices where the passenger is seated.

# 3. Development of a comfort evaluation tool

To create a comfort evaluation tool many factors have to be taken into account. Both the ISO Standards (Appendix A) and the type of test that is going to be carried out by the engineer should be studied in advance. Other important factors such as the sensors, the data acquisition unit and the software that are going to be used should be known to avoid possible incompatibilities while connecting the whole measurement system. For this reason, before starting to explain how the comfort evaluation tool works, all of these factors are presented as follows.

## 3.1. The car

For research and educational purpose the division of Vehicle Dynamics at the Royal Institute of Technology have a VOLVO V40 1.8 equipped with a measurement system fit for many applications, see Figure 3.1.


*Fig. 3.1. VOLVO V40 1.8 used in the department of Vehicle Engineering*

This car has a typical dynamic behaviour of a standard touring or sport wagon car. In others words, it has a docile driving with an optimum engine concerning weight-power relationship, ideal for people or families that want to travel around with the car full of baggage. Some others characteristic parameters of that car are presented in Table 3.1

*Table 3.1. Parameters of the VOLVO V40*

| | | | | |
|---|---|---|---|---|
| **CAR'S PARAMETERS** | **CUBIC CAPACITY** | 1730 cc (4 cylinders) | **Ixx** | 490 $kgm^2$ |
| | **TIMING** | 750 $min^{-1}$ | **Iyy** | 2250 $kgm^2$ |
| | **POWER** | 85 kW at 5500 $min^{-1}$ | **Izz** | 2380 $kgm^2$ |
| | **TORQUE** | 165 Nm at 4100 $min^{-1}$ | **Λ** | 0,41 |
| | **MASS** | 1435 kg | **K** | 0,20 |
| | **FRONT AREA** | 2,05 $m^2$ | **Wheelbase** | 2,55 m |

In Table 3.1 the parameters are defined as follows:

- Ixx: moment of inertia around x direction
- Iyy: moment of inertia around y direction
- Izz: moment of inertia around z direction
- λ: distance between front axle and centre of mass / wheelbase
- κ: height between ground and centre of mass / wheelbase

## 3.2. The sensors and the data acquisition unit

As stated before, the investigated car has many sensors that allow engineers to measure different parameters of its dynamic. It is possible to find sensors as for example to measure angular rotation rates (yaw, pitch and roll), one position transducer to measure the steering wheel angle and also a steering wheel torque sensor. But concerning comfort, the only sensors that are going to be used are a one three-axis Entran EGCS3-A accelerometer for measuring in X, Y and Z directions and also a sensor to obtain the longitudinal speed of the car.

The three-axis accelerometer is mounted together with the angular rotation sensors into a block of aluminium placed as close to the car's centre of gravity as possible. The sensor unit box is situated on a platform firmly fixed to the floor plate, adjustable in height and inclination.

Concerning the data acquisition unit, a DaqBook 200 is used. It is an A/D converter with 16 channels of high-speed digital inputs which offers 100 kHz data acquisition and can support up to 800 Kbytes/s data transfer to a PC via a standard or enhanced parallel port interface. There are also a DBK15 channel expansion card connected on channel 0 and a DBK16 strain gauge card connected on channel 1 and 2. The other channels can be used for future sensors. Finally, a low pass filter card is also mounted together with the others cards to filter the signals from the sensors prior to connection with the DBK15 in order to avoid aliasing. All of these devices, together with the laptop, are placed on an aluminium table in front of the passenger's seat.

In figure 3.2 it is showed where the sensor unit box and the data acquisition unit are placed.


*Fig. 3.2. Location of the sensor unit box and data acquisition unit.*

## 3.3. The software

One of the aims of this project was to create a tool that measures and visualizes vibrations from the car in real time in order to calculate the comfort level during the time of the test. After many discussions, the division of Vehicle Dynamics decided that the best option to create this on-line comfort evaluation tool was to use DASYLab [9]. A strong argument was that this software had been used for other measurements made on the divisions test vehicle to collect and visualizes data.

DASYLab is a powerful program that allows creation of acquisition, control, simulation or analysis tasks. Furthermore, it is also possible to design layouts to display data interactively and to document the measurement task.

It is also important to say that, before starting with the tool's design, a new version of DASYLab had to be installed on a new laptop. There after one needed to update, step by step, all the measuring and acquisition devices so the measurements from the sensors of the car where transferred correctly to the laptop and DASYLab.

### 3.3.1. Designing the comfort evaluation tool

Once the whole measurement chain was defined, it was time to design the comfort evaluation tool. The goal was to transfer to DASYLab what ISO 2631 (Appendix A) says about comfort. So the way to measure vibrations, the way to obtain the frequency-weighted r.m.s. accelerations depending on the vibration's acceleration, the crest factor and the way to display some others parameters had to be taken into account to obtain a real and serious tool that shows the on-line comfort level while driving over different surfaces.

DASYLab is a program that uses many boxes grouped in modules that the engineer can link to create a mathematical net depending on the application needed. In the current project, the inputs will be the three accelerations in the three main directions of the car and the longitudinal speed. On the other hand, the outputs will be several. It will show some digital displays showing the instantaneous accelerations, the frequency-weighted r.m.s accelerations values, the crest factor for each direction and also the total r.m.s acceleration value that determine the comfort level. Furthermore, some other analog displays will show both the speed of the car and the total r.m.s acceleration value again, but in this case, pointing out the maximum values reached thanks to peak hold maximum pointers. Finally, two charts will also appear, one recording the four inputs coming from the car and the other one showing the amplitude spectrum in real time of the three instantaneous accelerations.

Figure 3.3 shows the on-line comfort evaluation tool developed by the author of the present thesis using DASYLab and displays how all the boxes are linked to obtain the desired results.

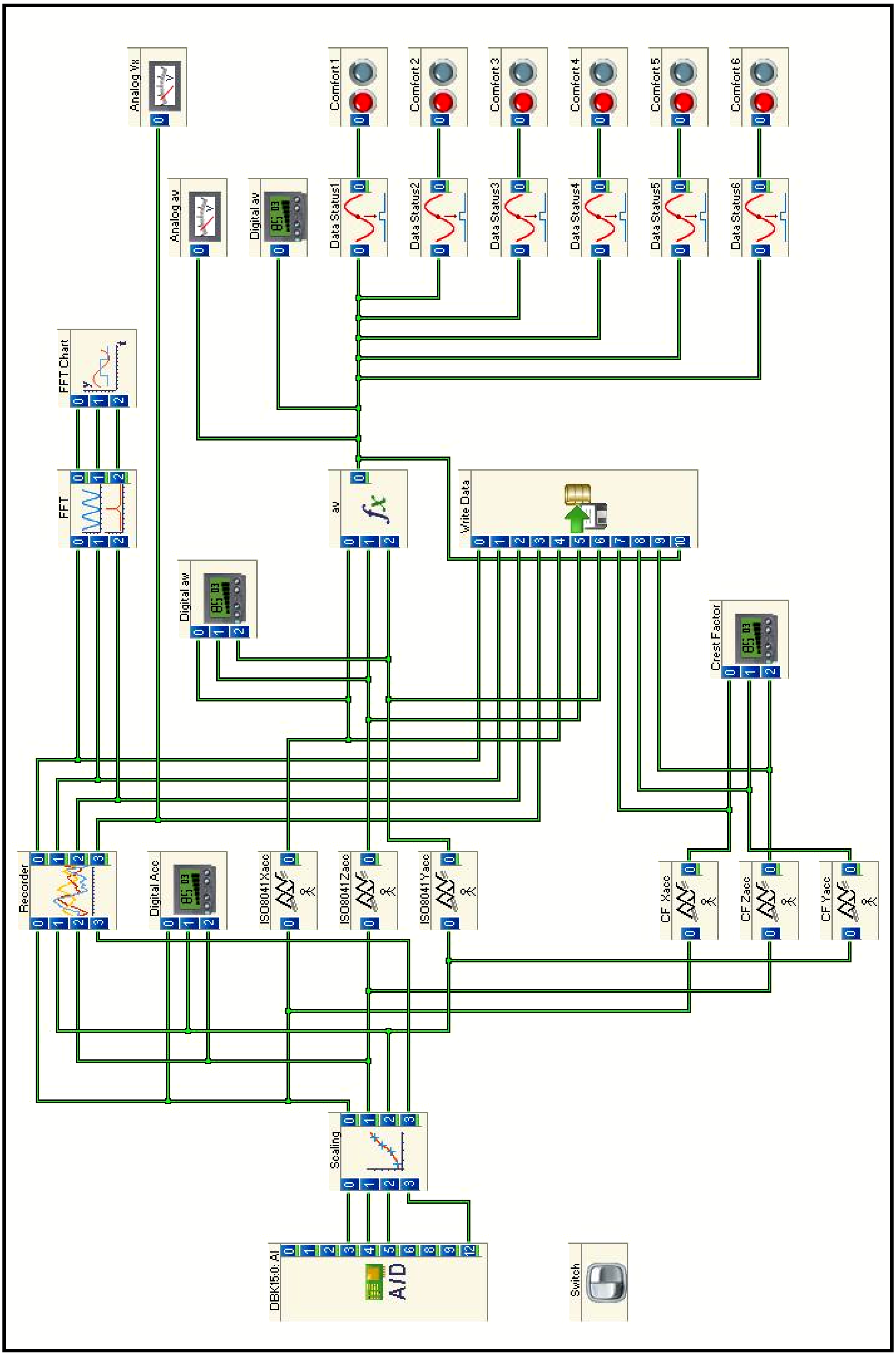


*Fig. 3.3. On-line comfort evaluation tool created with DASYLab*

### 3.3.2. Explanation of the tool's operation

In this chapter, Figure 3.3 is going to be explained in detail trying to make clear to the reader the operation of the tool created. Furthermore, some other settings as for example the hardware setup and the sampling rate are also going to be showed.

The first two boxes on the left side in Figure 3.3 refer to the four signals coming from the car. The first box just collects the signals required for this application from the DBK15 channel extension card, and the other is the scaling. Here, the signals are converted from electric units (V) to the ones that are desired ($m/s^2$ or km/h). For the scaling, the settings from another old tool of the Division of Vehicle Dynamics were taken into account even though they were checked with the sensor's manual and recalibrated to obtain more precision. The new calibrations are presented in Table 3.2 where de 'x' is the electric input in volts.

*Table 3.2. Calibration of the sensors*

| | Linear interpolation f(x) = a·x+b | |
|---|---|---|
| | a | b |
| $X_{acc}$ | 4,0074 | - 1,4484 |
| $Y_{acc}$ | - 4,0404 | 5,0789 |
| $Z_{acc}$ | 3,9993 | 14,0914 |
| $V_x$ | 40,0000 | 0,4500 |

Next, in Figure 3.3, there are some ramifications. On the top, the three instantaneous accelerations together with the speed of the car are displayed in real time with a chart recorder module. There is also another module that displays the FFT of vibrations.

In the middle and in the bottom of Figure 3.3, the most important modules of the tool are placed. They are the human response to vibration modules. The first three calculate the time-average weighted acceleration value since the beginning of the measurement for each direction taking into account the frequency weighting and equation 1 explained in Appendix A. It is also possible to choose the multiplying factors to calculate, later on, the total r.m.s. acceleration value, but they remain 1 for seated people concerning comfort. The last three human response to vibration modules are used for measuring the crest factor in X, Y and Z direction respectively. All of these values are then showed thanks to some digital displays connected to them.

To calculate the total r.m.s. acceleration value equation 3, in Appendix A, is used together with a formula interpreter module. Then, after displaying this r.m.s. value in an analog and digital way, there are six modules to generate a trigger signal at its output depending on the input signal conditions. So for each interval of acceleration that involves a different comfort level according the ISO Standards, there is an alarm which goes on.

A write data module is placed to save all the values while testing. The saved values are the instantaneous accelerations values, the weighted r.m.s. acceleration values, the crest factors and the total r.m.s. acceleration value. Finally, there is also a switch module that helps the engineer who do the test to start and stop the recording.

Concerning the sampling rate and the driver buffer used in this application, they are 500 Hz and 128 Kbytes respectively as it was configured in other old tools using the same acquisition unit.

### 3.3.3. Visualizations of the tool while driving

After creating the comfort evaluation tool, two visualizations were designed to make possible for the test engineer to have a dynamic view of the most important results concerning comfort and vibrations in the car. The first layout, see Figure 3.4, displays for each direction the instantaneous vibration acceleration, the weighted r.m.s. acceleration and the crest factors. The vibration total value of weighted r.m.s. acceleration also appears together with the on-line comfort level according ISO Standards. Furthermore, a speedometer shows at what speed the test is taking place. Finally, the switch, on the left side in the bottom, allows starting or stopping the recording time as stated before.

In the second layout, shown in Figure 3.5, the speed and the comfort level are also displayed in real time, but in this case they are not values in the shape of a number. There is a chart recorder displaying the four analog inputs coming from the car and another chart showing the instantaneous FFT of the instantaneous vibration acceleration. As before, a switch allows control of the recording time.

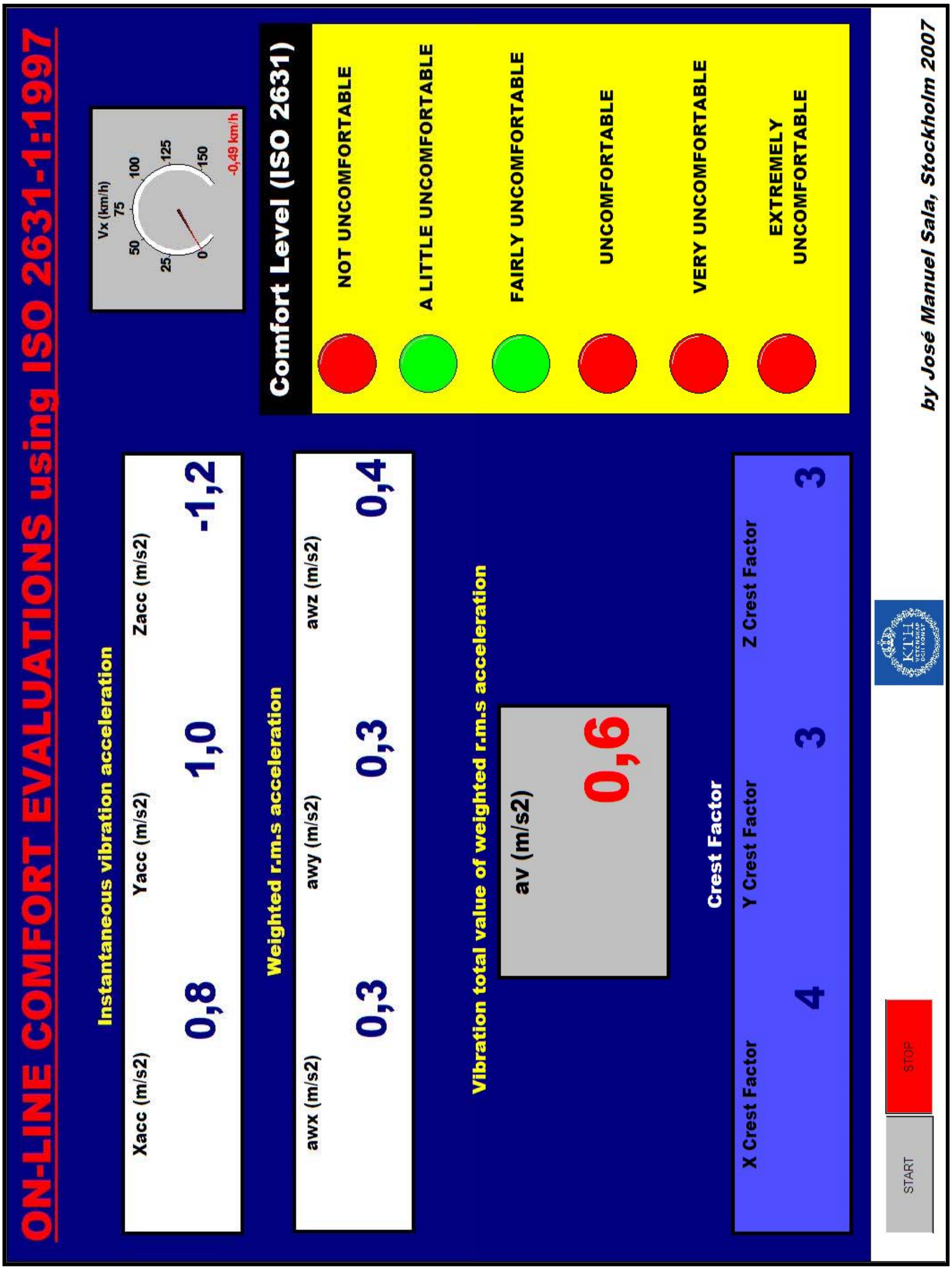


Fig. 3.4. Layout 1 created with DASYLab

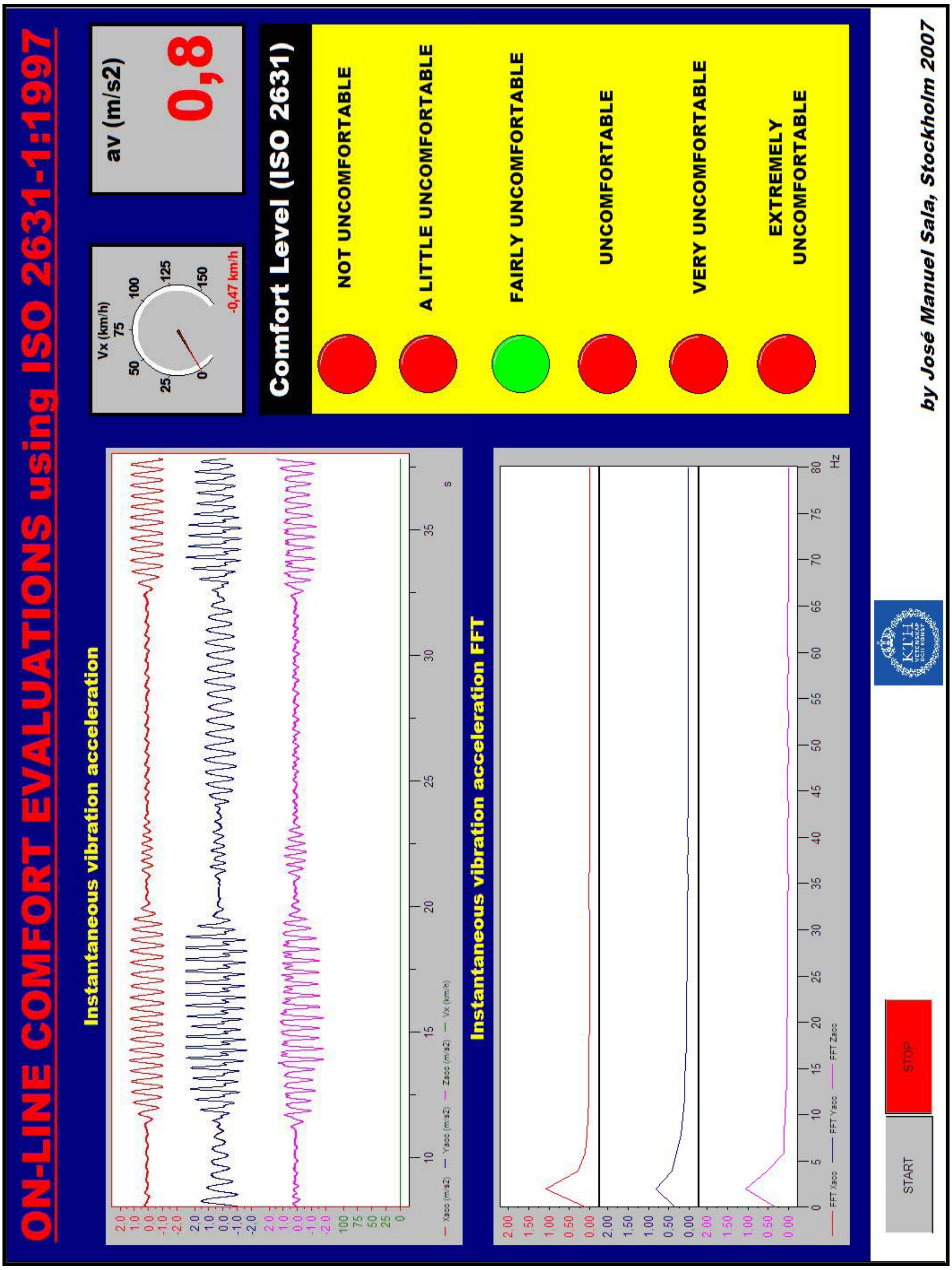


*Fig. 3.5. Layout 2 created with DASYLab*

# 4. Comfort evaluation of the VOLVO V40

After having talked about the car and the whole measurement chain in the last chapter, now it is time to put into practice the comfort evaluation tool in order to evaluate the comfort level in a VOLVO V40 driving over several sorts of surfaces. These surfaces were chosen according the different pavements where a car can drive and all of them were found in Stockholm or in its surroundings. As it is possible to see in the following pages, the tests are ordered by the smoothness of the surface. So, the first evaluations are over asphalt concrete and then it is continued by the Belgian block paving, the cobblestones and the gravel. At last, the car was tested driving over bumps to analyze their importance with regard to possible damages to passengers or just to the suspension of the vehicles.

Conditions under which every test was carried out were varying depending on the place where they were. Normally, the main trouble was to reach high speeds in places very crowed or just because of the length of the surface, as for example it happened testing over the Belgian block paving or over the cobblestone. Besides evaluating how different speed levels affect the comfort level changes in weight and driver have also been made. However, as shown in Table 4.6, it was found that change in weight and driver do not given any large influence on the final result.

Something very important to take into account while testing or recording data is the duration of measurements. They should be as long as possible to ensure statistical precision as long as the car drives on the same surface and do not pass over potholes or bumps. In this last case, the duration of measurements should be kept within the range of what ones wants to analyse; just the acceleration produced by the bump or the effect that this bump combined with driving over a specific surface for a while.

Another aspect that must be presented is that measurements were made at a point near the car's centre of gravity and not in the seat as the ISO Standards recommends. So the accelerations measured are not exactly the same as a passenger could feel because of the absorber effect of the seat and also the different location of the sensors in the y-axis.

Regarding the speed readings, they were taken from the car's speedometer because the sensor that should display them in the visualizations seemed to be broken. Furthermore, no cruise control was available, so the driver had to act as the cruise control and try to keep the speed constant during each specific test.

The comfort level reached in every test is defined according ISO Standards. So for every interval of accelerations there is a different comfort reaction. Table 4.1 shows the different comfort levels depending on vibration total values in public transport. This table can be also found in Appendix A (Table A3).

*Table 4.1. Comfort Level depending on vibration total value [4]*

| FREQUENCY-WEIGHTED ACCELERATION (r.m.s. value) ($m/s^2$) | COMFORT LEVEL |
|---|---|
| Less than 0,315 | Not uncomfortable |
| 0,315 to 0,63 | A little uncomfortable |
| 0,5 to 1 | Fairly uncomfortable |
| 0,8 to 1,6 | Uncomfortable |
| 1,25 to 2,5 | Very uncomfortable |
| Greater than 2 | Extremely uncomfortable |

In the following chapters descriptions, results and conclusions of the different comfort evaluation tests will be presented. During the tests three different drivers where involved: Adam Rehnberg (Test person 1), Simon Decaye (Test person 2) and of course the author of this thesis (Test person 3).

## 4.1. Test #1: Asphalt concrete – City

This test was done to evaluate the total r.m.s. acceleration that someone could be exposed to driving along the streets of a city made of asphalt concrete. This is the typical surface that it is possible to find everywhere, in every city, commonly used for construction of pavements. So this is the main reason to take into account this test and because it also could be interesting to analyse in which conditions people, such as taxi or bus drivers and messengers, are working in the street concerning accelerations levels or frequency vibrations during the whole day.

*Fig. 4.1 and 4.2. Test conditions and zoom of the asphalt*

- Address: Valhallavägen, close to KTH
- Weather conditions: cloudy and warm
- Weight of the car: 1435 kg (standard weight) + test weight conditions
- Level of petrol: 7/10
- Tyre pressures: 2.2 bar (front), 2.0 bar (rear)

### 4.1.2. Development and results of the test

The conditions in which this evaluation was done are quite simple. Test person 1 drove the car while test person 3 recorded the data. So the additional load is two people inside the car, called normal load along the whole tests. Concerning the speed, the driver tried to keep it about 40 km/h during the 48 seconds that were recorded and no acceleration or braking took place since this would give high x-accelerations. The result of the evaluation is showed in Table 4.2 below.

*Table 4.2. Weighted r.m.s. acceleration when driving over asphalt concrete at 40 km/h for 48 seconds*

| | Vibration total value of weighted r.m.s. acceleration ($m/s^2$) |
|---|---|
| | 40 km/h |
| Driver 1 | 0,28 |

### 4.1.3. Conclusions of the test

According to ISO Standards, the comfort level obtained is ‘not uncomfortable’ which means that driving over the asphalt concrete surface does not involve discomfort for the driver as long as it does not appear some potholes or undulations.

During measurements it was observed that the crest factors were quite large. They were between 5 and 6 during the test. It is believed that the reason for this is small bumps that produce a peak of acceleration over the r.m.s. acceleration value. So to avoid effects of small bumps, the duration of measurement should be bigger to ensure reasonable statistical precision. The different crest factors can be found in the CD enclosed with the thesis.

## 4.2. Test #2: Asphalt concrete – Motorway

Besides obtaining the comfort level along the city, why not obtain it while driving at high speed in motorways? The place chosen to recorder data was the motorway E18 leaving Stockholm and driving to the north towards Norrtälje. There, as in the majority of high-speed roads, the asphalt uses to be asphalt concrete. Nevertheless, it is also possible to find another kind of brown or orange asphalt made of some components to improve the grip during the winter season. However, any test was recorded over this different asphalt.

*Fig. 4.3 and 4.4. Different stretches of the motorway E18*

- Address: motorway E18, driving to the North towards Norrtälje
- Weather conditions: cloudy and warm
- Weight of the car: 1435 kg (standard weight) + test weight conditions
- Level of petrol: 7/10
- Tyre pressures: 2.2 bar (front), 2.0 bar (rear)

### 4.2.2. Development and results of the test

This test was carried out as the first one i.e. the test person 1 drove and test person 3 recorded the data so the additional weight was the two people. However, the difference with the preceding evaluation is that in this one the duration of the measurement was around 1 minute. Many tests were done at different speeds and in different lanes trying to find out some different responses.

Table 4.3 presents the results from these tests.

*Table 4.3. Weighted r.m.s. acceleration when driving over asphalt concrete at different speeds for 1 minute*

| | Vibration total value of weighted r.m.s. acceleration (m/s$^2$) | | | | |
|---|---|---|---|---|---|
| | 50 km/h | 70 km/h | 90 km/h | 110 km/h (left lane) | 110 km/h (right lane) |
| Driver 1 | 0,14 | 0,19 | 0,25 | 0,22 | 0,18 |

## 4.2.3. Conclusions of the test

From the tests, when driving on a motorway with asphalt concrete paving, it can be concluded that with a VOLVO V40 one have a maximum comfort level according to ISO Standards i.e. a 'not uncomfortable' level. However, the author of the project felt a continuous high frequency vibration on account of the bigger roughness of the asphalt in comparison to the Spanish high speed roads, where the surface is smoother because of better weather conditions. It should also be pointed out that the evaluations done at 110 km/h do not show as large difference between the two lanes as was expected. It was believed that the difference would be larger due the fact that there are much more cars and trucks driving on the right lane which tend to increase the wear and thereby reduce the quality of the surface. This point should be analysed with more details testing along many motorways. Another possible reason regarding the small differences in the results is that the measurements were done at different places, at different stretches.

As in the first test, considerable high crest factors between 6 and 7 are reached especially at low speeds. The reason is the same as before, so longer duration of measurement time should be used as well as trying to avoid some small potholes or undulations in the road, even though it is also true that this would not be the real driving.

## 4.3. Test #3: Belgian block paving

Nowadays, the Belgian block paving is quite difficult to find in developed cities. However, there are still some places where this surface is present trying to give an old or pretty touch. In the case of Stockholm, this ancient paving was quickly found at the entrance of KTH where cars are allowed to drive, see Figures 4.5 and 4.6.

*Fig. 4.5 and 4.6. Entrance of KTH and zoom of the paving*

- Address: entrance of KTH
- Weather conditions: sunny and warm
- Weight of the car: 1435 kg (standard weight) + test weight conditions
- Level of petrol: 7/10
- Tyre pressures : 2.2 bar (front), 2.0 bar (rear)

### 4.3.1. Development and results of the test

The main trouble in carrying out this test was the impossibility to evaluate the comfort level at high speeds and long distances because of the place was very crowded with students. The test was performed with two different drivers, first test person 2 and then test person 3. The car was driven at different speeds of 20 and 30 km/h and with full load conditions, in others words, three people and three sand bags of 25 kg each, were inside the car. The results of the tests on the Belgian block paving are showed in Table 4.4 below.

*Table 4.4. Tests results from measurements on Belgian block paving. The duration of the tests was around 6 seconds*

| | Vibration total value of weighted r.m.s. acceleration ($m/s^2$) | |
|---|---|---|
| | **20 km/h** | **30 km/h** |
| **Driver 1** | 0,48 | 0,50 |
| **Driver 2** | 0,40 | 0,59 |

### 4.3.2. Conclusions of the test

As stated before, it was impossible to drive over 30 km/h and the available distance for the test was very short, around 50 meters. According to the results, the standard comfort level obtained is '*a little uncomfortable*' but the real feeling could be more uncomfortable. It feels like driving with winter tyres because high frequency vibrations appear and the grip is not very good.

It is also remarkable the difference among the values reached, but in fact, it is easy to think that probably the two drivers did not drive just along the same line and kept exactly the desired speed.

## 4.4. Test #4: Cobblestone

This surface is even more difficult to find than the last one. Once again, it only remains in old or medieval villages or just to decorate the pavements in some parts of a city. Around the Royal Palace in Stockholm, this kind of surface is treaded by thousands of people and tourists who let themselves get carried away by the spell of the city. Many tourist buses drive over that surface, so this is a reason to evaluate the comfort level there.

*Fig. 4.7 and 4.8. Surroundings of the Royal Palace and zoom of the paving*

- Address: South surroundings of the Royal Palace
- Weather conditions: sunny and warm
- Weight of the car: 1435 kg (standard weight) + test weight conditions
- Level of petrol: 7/10
- Tyre pressures: 2.2 bar (front), 2.0 bar (rear)

### 4.4.1. Development and results of the test

Because of the security rules bearing in mind the importance of the place and also the fact that there were a lot of tourist people, it was impossible to drive so much with the car. Actually, only one test was recorded whose results were compared with two more tours. Test person 1 drove while test person 3 recorded the data.

The speed and weight conditions of that evaluation were at 20 km/h and with normal load, only two people inside the car. The result of the test is showed in Table 4.5.

*Table 4.5. Weighted r.m.s. acceleration when driving over cobblestone at 20 km/h for 11 seconds*

| | **Vibration total value of weighted r.m.s. acceleration ($m/s^2$)** |
|---|---|
| | **20 km/h** |
| **Driver 1** | 0,65 |

### 4.4.2. Conclusions of the test

Viewing Figures 4.7 and 4.8, it is easy to think that driving over that surface with a car similar to the VOLVO V40, with regard to dimensions, should be quite uncomfortable. The rocks are fairly big and the distance between them is important, so those characteristics produce high accelerations and also high frequency vibrations. The way how the passengers receive these vibrations is quite random because of the non-uniformity of the surface.

Regarding the results, 0.65 $m/s^2$ represents a standard comfort level of '*fairly uncomfortable*'. This value could seem not very high but keep in mind that neither was the speed reached.

## 4.5. Test #5: Gravel Road

Test number five was carried out in a construction site close to KTH. There, it was possible to find several surfaces made of gravel, but the one which was chosen for the present test was quite uniform and in perfect condition, see Figures 4.9 and 4.10.

*Fig. 4.9 and 4.10. Gravel surface of the test and zoom of the gravel*

- Address: Albano area
- Weather conditions: sunny and warm
- Weight of the car: 1435 kg (standard weight) + test weight conditions
- Level of petrol: 7/10
- Tyre pressures: 2.2 bar (front), 2.0 bar (rear)

### 4.5.1. Development and results of the test

The test was done taking into account three parameters: the weight, the speed and the driving style. The weight had two different levels, normal load (car plus two people) and full load (car, three people and three sand bags of 25 kg each to represent a fourth person). The tests where made for two speeds, 20 km/h and 30 km/h and drivers where test person 1, test person 2 and test person 3.

After analyzing the results from when test person 1 was driving, the test was continued with only the full load and only speed was changed when test person 1 and 2 were driving. The results of the test are summarized in the Table 4.6 below.

*Table 4.6. Weighted r.m.s. acceleration when driving over gravel road at different speeds and loads for 5 or 6 seconds. Driver 1, 2, 3 refers to that person 1, 2, 3 is driving*

| | Vibration total value of weighted r.m.s. acceleration (m/s$^2$) | | | |
|---|---|---|---|---|
| | Normal load | | Full load | |
| | 20 km/h | 30 km/h | 20 km/h | 30 km/h |
| **Driver 1** | 0,60 | 0,89 | 0,50 | 0,85 |
| **Driver 2** | - | - | 0,59 | 0,78 |
| **Driver 3** | - | - | 0,54 | 0,69 |

## 4.5.2. Conclusions of the test

In this test the standard discomfort level was between '*fairly uncomfortable*' and '*uncomfortable*' depending on the speed reached and also on the driver. It is believed that the differences in the results mainly appeared because every time that someone drove along the gravel surface it changed the surface. In others words, after every test was done, the surface was smoother and without so many small rocks. Some others reasons in the variability of the values could be the difficulty to keep low speeds or the fact that everyone had driven along different lines even if it was the same road and place.

The personal point of view of the author i.e. driver 3, is that driving over this kind of surface was a feeling of completely lack of grip especially when the test speed conditions increased. When the car goes over a gravel surface, the rock in the surface are continuously moving and thereby produce instabilities while driving. Furthermore, as in the tests before, a high frequency vibration appears together with high acceleration values.

## 4.5b. Test #5b: Irregular gravel road

In the same place as the previous test, it was possible to find a neglected area. The surface was also made of gravel, but here in an irregular way. There were different sizes of small rocks and also some holes and undulations along the test area, see Figures 4.11 and 4.12. Thus, it was another interesting evaluation to carry out to analyze the comfort level experienced by someone who would drive in these conditions.

*Fig. 4.11 and 4.12. Irregular gravel surface of the test and zoom of the gravel*

- Address: Albano area
- Weather conditions: sunny and warm
- Weight of the car: 1435 kg (standard weight) + test weight conditions
- Level of petrol: 7/10
- Tyre pressures: 2.2 bar (front), 2.0 bar (rear)

### 4.5b.1. Development and results of the test

Although this test was done the same day as the last one, only two drivers, test person 1 and test person 3, did the evaluation. One of the reasons was the lack of time and the little difference between results of the drivers. The comfort level was measured at full load of weight and also changing the speed, at 20 and 40 km/h. Here, it was easy to reach a higher speed thanks to the extent of the place. The final values of that new test are presented in Table 4.7.

*Table 4.7. Weighted r.m.s. acceleration when driving over irregular gravel road at different speeds for 7 or 9 seconds. Driver 1 and 2 refers to test person 1 and 2, respectively*

| | Vibration total value of weighted r.m.s. acceleration ($m/s^2$) | |
|---|---|---|
| | **20 km/h** | **40 km/h** |
| **Driver 1** | 0,98 | 1,06 |
| **Driver 2** | 0,94 | 1,13 |

## 4.5b.2. Conclusions of the test

This test was a clear example of the discomfort that someone can experience driving along an irregular gravel road. The values reached are quite high and the maximum standard comfort level was ‘*uncomfortable*’. Because of the presence of big holes, it was impossible to reach higher speeds because of risk to damage the suspension and the lowest parts of the VOLVO V40.

Compared to the test #5, here it was not experienced very high frequency vibrations because the small rocks were more separated from each other. However, the holes produced a continuous pitching of the car manifested in wide movements of the passengers’ heads.

## 4.6. Test #6: Bumps

Often bumps are placed in the city trying to avoid high speeds of the vehicles because of the presence of a transient area. However, these bumps could be dangerous both for the car and for its passengers if ever someone misses its presence in the street. Furthermore, it can also be annoying for people who frequent run over them, such as taxi and bus drivers and people living in the surroundings. The bump studied was in the middle of a street in Kungshamra, a suburb of Stockholm, see Figures 4.13 and 4.14.

*Fig. 4.13 and 4.14. Bump in the middle of the street and photo detail of the bump*

- o Address: Kungshamra (Solna)
- o Weather conditions: cloudy and warm
- o Weight of the car: 1435 kg (standard weight) + test weight conditions
- o Level of petrol: 7/10
- o Tyre pressures: 2.2 bar (front), 2.0 bar (rear)

### 4.6.1. Development and results of the test

This test did not aim to evaluate the comfort level driving a long a surface. Due to lack of traffic and the available time, many evaluations were done during this test.

As in the majority of tests, test person 1, drove while the test person 3 recorded the data. Hence, the weight conditions were always normal load. Several speeds were tested passing over the bump in the two directions to analyze possible differences between those two sides. In the first tests the duration of the measurement was limited to only include the time from when the car entered the bump until it left it. The results from these measurements are showed in Table 4.8.

*Table 4.8. Weighted r.m.s. acceleration when driving over a bump at different speeds for 1.5 or 2 seconds*

| | Vibration total value of weighted r.m.s. acceleration (m/s²) | | | | | |
|---|---|---|---|---|---|---|
| | West direction | | | East direction | | |
| | 20 km/h | 30 km/h | 40 km/h | 20 km/h | 30 km/h | 40 km/h |
| Driver 1 | 0,69 | 1,06 | 1,20 | 0,84 | 1,42 | 1,78 |

Another kind of test was also done. It was also interesting to see the influence that a bump could have in the total r.m.s. acceleration value after driving along a normal street like in the test #1. The same driver, the same weight, the east direction and evaluating at 30 km/h were the conditions in that second test. It was done two times, with the only difference that the speed over the bump was not the same. The sequence of them were as follows:

- Test #6b.1: around 100 m of straight line (30 km/h) – bump (30 km/h) – around 100 m of straight line (30 km/h)
- Test #6b.2: around 100 m of straight line (30 km/h) – bump (10 km/h) – around 100 m of straight line (30 km/h)

The results from these tests are presented in Table 4.9 below.

*Table 4.9. Weighted r.m.s. acceleration when driving over a bump in accordance to Test #6b.1 and Test #6b.2 for 30 seconds*

| | Vibration total value of weighted r.m.s. acceleration (m/s²) | |
|---|---|---|
| | Test #6b.1 | Test #6b.2 |
| Driver 1 | 0,42 | 0,34 |

## 4.6.2. Conclusions of the test

The first evaluation makes clear the importance to reduce the speed before passing over a bump to avoid high accelerations and prevent future damages to the suspension of the car. Concerning the values, it is possible to see that the maximum discomfort reached is logically at 40 km/h. However driving a long the east direction was clearly more violent that the west one. This worse case resulted in the value 1.78 $m/s^2$, which corresponds to a '*very uncomfortable*' standard comfort level.

The second test shows how a bump can influence the total r.m.s. acceleration value. In test #1 (asphalt concrete in the city) the value reached at 40 km/h was 0.28 $m/s^2$ and here, with the presence of a bump, it increases to 0.42 $m/s^2$ or to 0.34 $m/s^2$ if the car brakes before the bump. This is translated to a standard comfort level of '*a little uncomfortable*'. Comparing now test #6 (1.42 $m/s^2$) with test #6b (0.42 $m/s^2$) driving at 30 km/h and towards the east, it is possible to deduce that the comfort effect from a bump is very much affected by the type of test with regard to the total r.m.s. acceleration value.

However, as stated in the introduction of this chapter, it is important that the duration of the measurements is set with regard to what one want to analyze. So in this case, test #6 measures the comfort level just driving over a bump and test #6b shows the effect that this bump has after driving over a specific surface.

These results should be taken into account by people designing bumps since the bumps can damage the vehicles but also, more importantly, the bumps could produce some future damage to people frequently driving over them. It should also be mentioned that the crest factor reached in z direction in test #6b.1 was 8.49.

## 4.7. Summary of the comfort evaluation

Table 4.10 shows the comfort level that one can experience while driving with a VOLVO V40 along different surfaces according to ISO Standards. The highest comfort level was reached in the streets of the city and at the motorway over asphalt concrete. However, driving over bumps or along an irregular gravel road produces a very high level of discomfort.

After performing these tests, it is possible to deduce that the comfort level depends a lot on the speed, while parameters such as the weight or the driver, which were tested along the gravel road and in the Belgian block paving, do not have such an important effect on the final result.

*Table 4.10. Maximum discomfort level reached in the different tests*

| TESTS vs. COMFORT LEVEL | Not uncomfortable | A little uncomfortable | Fairly uncomfortable | Uncomfortable | Very Uncomfortable | Extremely Uncomfortable |
|---|---|---|---|---|---|---|
| A. concrete – City | | | | | | |
| A. concrete – Motorway | | | | | | |
| Belgian block paving | | | | | | |
| Cobblestone | | | | | | |
| Gravel road | | | | | | |
| Irregular gravel road | | | | | | |
| Bump | | | | | | |
| 200 m a. concrete + bump | | | | | | |

# 5. Conclusions and Future Work

A comfort evaluation tool has been developed, and thanks to this several tests have been performed on a VOLVO V40 to evaluate the comfort level during different types of surfaces and driving conditions. The tests showed that the comfort evaluation tool created works perfectly and also that it is very easy to use and helpful to obtain data concerning comfort levels for passengers in a car. The evaluation tool can be used for much more interesting tests such as evaluating the comfort level when driving over grass, over dirty roads, over repaired asphalt or just in winter conditions with winter tyres. Furthermore, the tool will be very useful for students in order to learn more about ride comfort in vehicles both in a theoretical and in a practical way.

The elaboration of this thesis was not easy due to the troubles that appeared, first with the delay of the new software and later with the connection between the laptop and the car. However, it was a really interesting and practical work and it has given the author an understanding of the importance of ride comfort in passenger cars.

In order to improve the quality of recorded data some changes in the vehicle is suggested for future work. First of all, the parallel cord that nowadays is used to connect the laptop with the data acquisition unit needs to be changed by a new one to avoid some possible breakdowns. This problem sometimes can appear due to the fact that the attachment screws of the cord are defect.

Furthermore, the three accelerometers should preferably be placed at the interface between the human body and the source of its vibration; in other words, in the seat. Otherwise, the measurements recorded from the sensor unit box should be corrected for the transmissibility of the cushion material.

Finally, with the objective to complement the recorded data, a roughness sensor could be installed in the car to register the road surface profiles.

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# Appendix A – Summary of the ISO 2631-1:1997

This appendix summarizes the contents of the International Standard ISO 2631-1:1997 in order to increase the readers understanding of the work carried out in this project and the importance and consequences of vibrations in the whole-body during driving.

## A1. Introduction and scope

Depending on the activities people carry out, their whole-body can be exposed to complex mechanical vibrations which can influence comfort, perception or health. Hence that vibrations should be specially taken into account because they can cause sensations of discomfort, influence human performance capability or present a pathological or physiological risk concerning safety.

This part of ISO 2631 defines methods for measurement of periodic, random and transient whole body vibration and is applicable to motions transmitted to human body as a whole through the supporting surfaces. The frequency range considered is:

- 0,1 Hz to 0,5 Hz for motion sickness
- 0,5 Hz to 80 Hz for health, comfort and perception

## A2. Symbols

The primary quantity of vibration magnitude shall be acceleration 'a' ($m/s^2$), which is quoted as root-mean-square (r.m.s.). The frequency weighted factor is represented by the letter 'W'.

The evaluation will be made by means of the weighted r.m.s acceleration:

$$a_W = \left[ \frac{1}{T} \int_0^T a_W^2(t)dt \right]^{1/2} \tag{1}$$

In Equation 1 the parameters are defined as follows:

- $a_{W(t)}$: weighted acceleration as function of time
- T: duration of the measurement, in seconds

## A3. Frequency weightings

Human response to vibrations depends both on the incidence (health, comfort, perception or motion sickness) and on the part of the body in contact and direction to vibration. Thus, different weightings are used. Guides for the application of frequency-weighting curves for principal and additional weightings are showed in Tables A1 and A2.

*Table A1. Table of frequency curves for principal weightings factors*

| FREQUENCY CURVES FOR PRINCIPAL WEIGHTINGS FACTORS | | | | |
|---|---|---|---|---|
| F. WEIGHTING | HEALTH | COMFORT | PERCEPTION | M. SICKNESS |
| **$W_k$** | z-axis, seat surface | z-axis, seat surface<br>z-axis standing<br>vertical recumbent<br>x-y-z-axes, feet (sitting) | z-axis, seat surface<br>z-axis, standing<br>vertical recumbent | - |
| **$W_d$** | x-axis, seat surface<br>y-axis, seat surface | x-axis, seat surface<br>y-axis, seat surface<br>x-y-axes, standing<br>horizontal recumbent<br>y-z-axes, seat-back | x-axis, seat surface<br>y-axis, seat surface<br>x-y-axes, standing<br>horizontal recumbent | - |
| **$W_f$** | - | - | - | Vertical |

*Table A2. Table of frequency curves for additional weightings factors*

| FREQUENCY CURVES FOR ADDITIONAL WEIGHTINGS FACTORS | | | | |
|---|---|---|---|---|
| F. WEIGHTING | HEALTH | COMFORT | PERCEPTION | M. SICKNESS |
| **$W_c$** | x-axis, seat-back | x-axis, seat-back | x-axis, seat-back | - |
| **$W_e$** | - | rx-ry-rz-axes, seat surface | rx-ry-rz-axes, seat surface | - |
| **$W_j$** | - | vertical recumbent | vertical recumbent | - |

The frequency curves used in this project, regarding comfort in vehicles and the position of accelerometers in the car, are $W_d$ for x-y axes and $W_k$ for z axis in the seat surface.

Figure A1 shows how axes are positioned for a seated person just as a driver could be placed in a car.

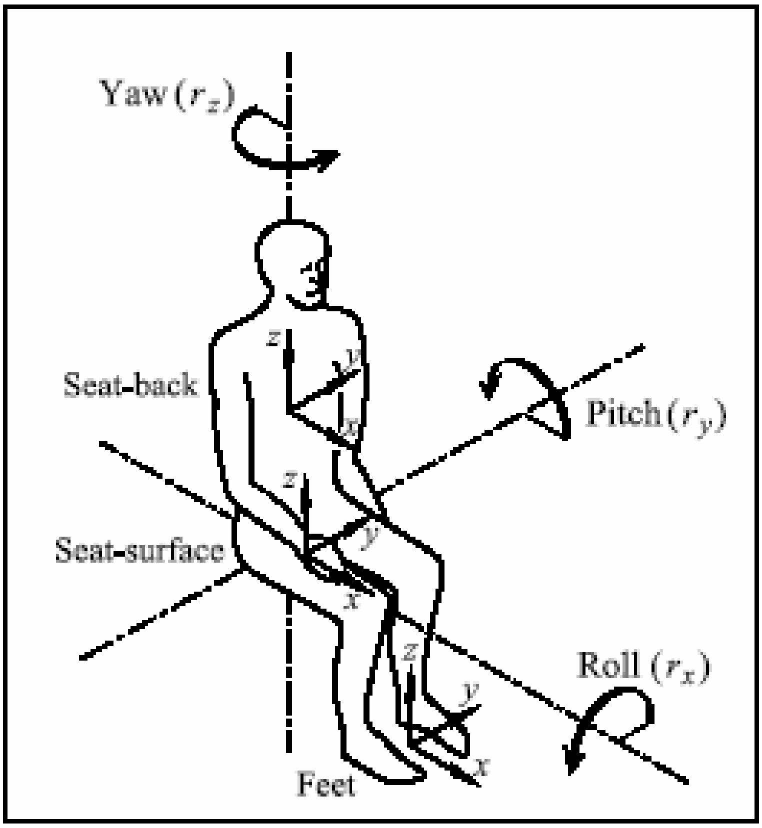

*Fig. A1. Basicentric axes of the human body [4]*

The frequency-weighted curves are presented in Figures A2 and A3. Here, it is possible to see, depending on the frequency, the value for each frequency weighting factor.

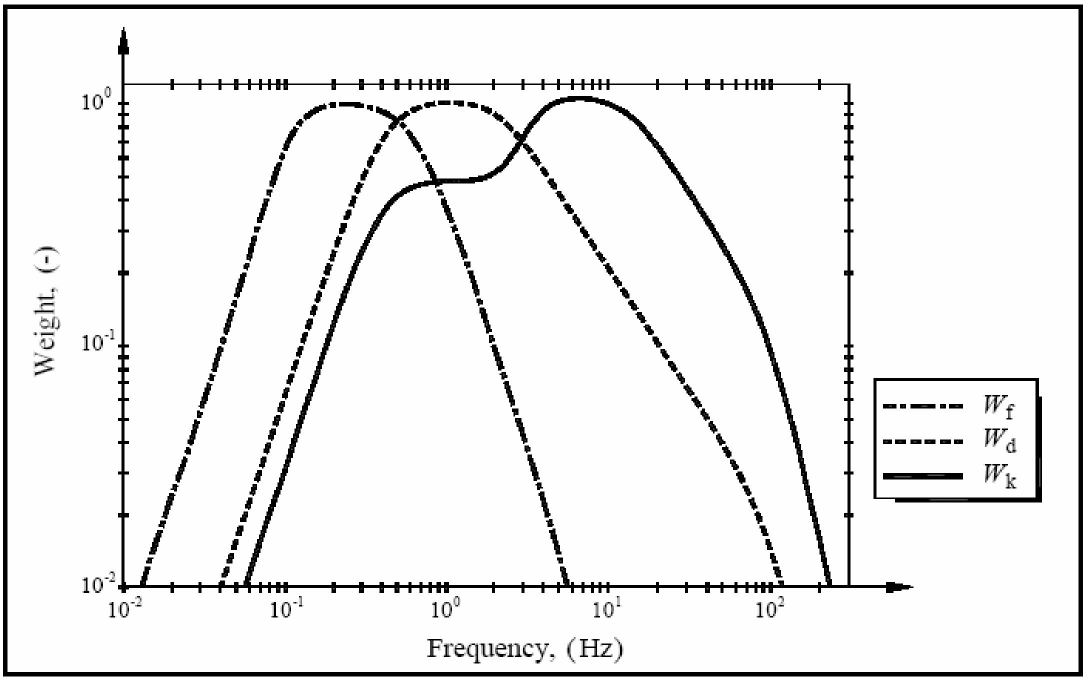

*Fig. A2. Frequency curves for principal weightings factors [8]*

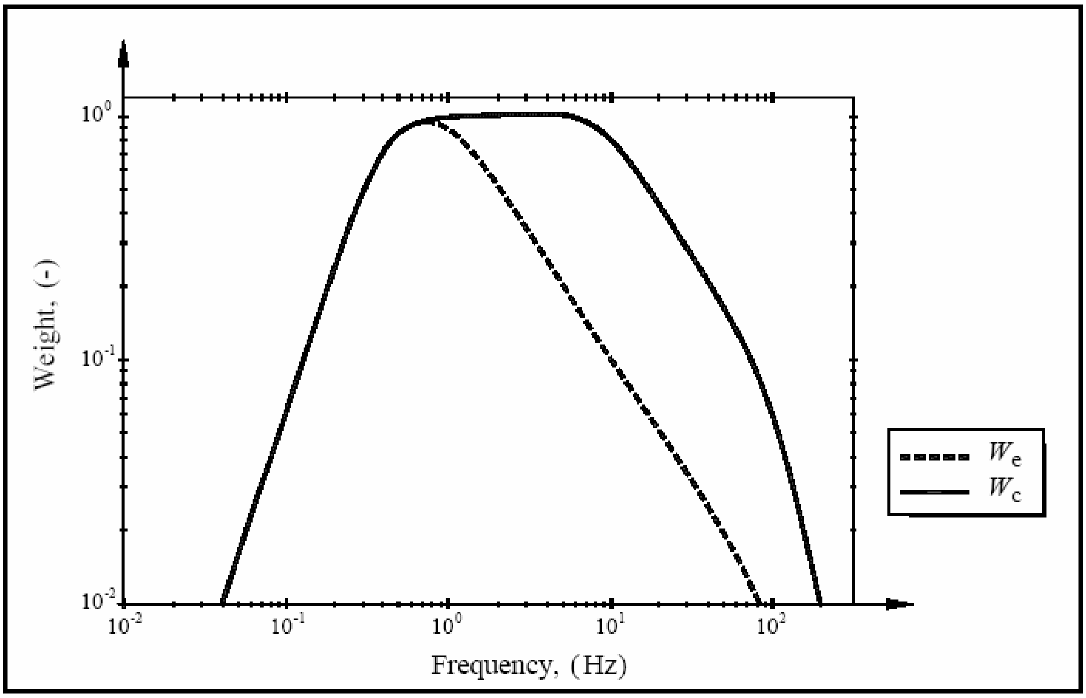

*Fig. A3. Frequency curves for additional weightings factors [8]*

## A4. Vibration measurement

Before starting to take measurements, some aspects must be clear:

- As stated before, the primary quantity of vibration magnitude shall be acceleration.
- Vibration which is transmitted to the body shall be measured on the surface between the body and that surface.
- The duration of measurement shall be sufficient to ensure reasonable statistical precision and to ensure that the vibration is typical of the exposures which are being assessed.
- Reports should include both the magnitude and duration of vibration, information on the frequency content, vibration axes, how conditions change over time, and any other factors which may influence the effect.

## A5. Vibration evaluation

The final result of an evaluation is the frequency-weighted r.m.s. acceleration which is determined by weighting an appropriate addition of narrow band or one-third octave band data using the following expression:

$$a_W = \left[ \sum_i (W_i \cdot a_i)^2 \right]^{1/2} \tag{2}$$

In Equation 2 the parameters are defined as follows:

- $a_W$: frequency-weighted acceleration
- $a_i$: r.m.s. acceleration for the *i* th one third-octave band
- $W_i$: weighted factor for the *i* th one third-octave band

The Equation 2 is expressed in the frequency domain and the equivalent one in the time is the Equation 1.

## A5.1. Combining vibrations in more than one direction

In case there are vibrations in more than one direction, the vibration total value of weighted r.m.s. acceleration, determined from vibration in orthogonal coordinates is calculated as follows:

$$a_v = (k_x{}^2 \cdot a_{wx}^2 + k_y{}^2 \cdot a_{wy}^2 + k_z{}^2 \cdot a_{wz}^2)^{1/2} \quad (3)$$

In Equation 3 the parameters are defined as follows:

- $a_{Wx}$, $a_{Wy}$, $a_{Wz}$: weighted r.m.s. accelerations with respect to the axes x, y, z
- $k_x$, $k_y$, $k_z$: multiplying factors

## A5.2. Applicability of the basic evaluation method. Crest factor

For vibration with crest factors (modulus of the ratio of the maximum instantaneous peak value of the frequency-weighted acceleration signal to its r.m.s. value) below or equal to 9, the basic evaluation method stated before is normally sufficient. In cases where it is not (high crest factors, occasional shocks, transient vibration), the running r.m.s. or the fourth power vibration dose value should also be determined.

However, in the present project, only the basic evaluation method will be used to obtain the comfort levels. Short times of measurement will be taken to avoid that discomfort can be influenced by peak values and underestimated by methods using r.m.s. averaging.

# A6. Vibration evaluation method concerning comfort

ISO 2631 presents some evaluation methods depending on the application needed. For this reason, this paragraph is only focusing on comfort. Health and motion sickness, which are also explained in the ISO Standards, are not considered in this work.

The vibration evaluation method concerning comfort will follow the one explained in paragraph A5. The multiplying factors for seated people will be as follows:

- x-axis (supporting seat surface vibration): $W_d$, k=1
- y-axis (supporting seat surface vibration): $W_d$, k=1
- z-axis (supporting seat surface vibration): $W_k$, k=1

## A6.1. Comfort reactions to vibration environments

As stated in the introduction of the report, ride comfort depends on many factors. However, ISO 2631 gives some approximate indications of likely reactions concerning vibration total values in public transport. Table A3 shows the different comfort levels that can appear.

*Table A3. Comfort level depending on the frequency weighted acceleration*

| FREQUENCY-WEIGHTED ACCELERATION (r.m.s. value) ($m/s^2$) | COMFORT LEVEL |
|---|---|
| Less than 0,315 | Not uncomfortable |
| 0,315 to 0,63 | A little uncomfortable |
| 0,5 to 1 | Fairly uncomfortable |
| 0,8 to 1,6 | Uncomfortable |
| 1,25 to 2,5 | Very uncomfortable |
| Greater than 2 | Extremely uncomfortable |

# Appendix B – Instructions to install DASYLab

If ever there is a problem with the laptop and DASYLab 9.0 must be installed again, find here the instructions to install it correctly to be able to continue with the comfort evaluations tests.

1. Install 'DaqView' which can be found in the 'DASYLab Files' folder in the CD enclosed with the report.

2. Install 'DASYLab 9.0' with the correct serial number that belongs to the Division of Vehicle Dynamics.

3. Install the 'Human Response to Vibration' module with the correct serial number that also belongs to the division.

4. Install the 'DASYLab_drivers' file which can be also found with the CD enclosed.

5. To be able to use data logging (Appendix C), open DASYLab and from the Experiment menu select 'DaqBook/DaqBoard/Daq/WaveBook/tTemp' driver, see Figure B1.

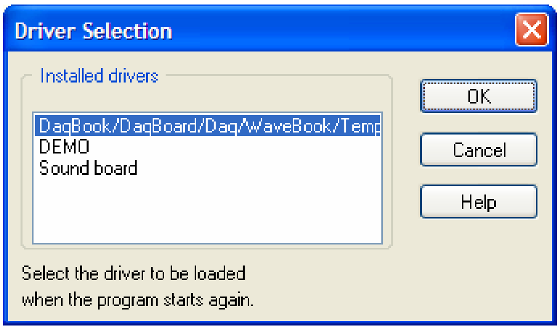


*Fig. B1. Driver Selection*

6. Using again Experiment menu go to Measurement Boards Settings (Hardware Setup) and select a DaqBook/200/260. If it is not the default device, then highlight the default device and select it from the list, see Figure B2

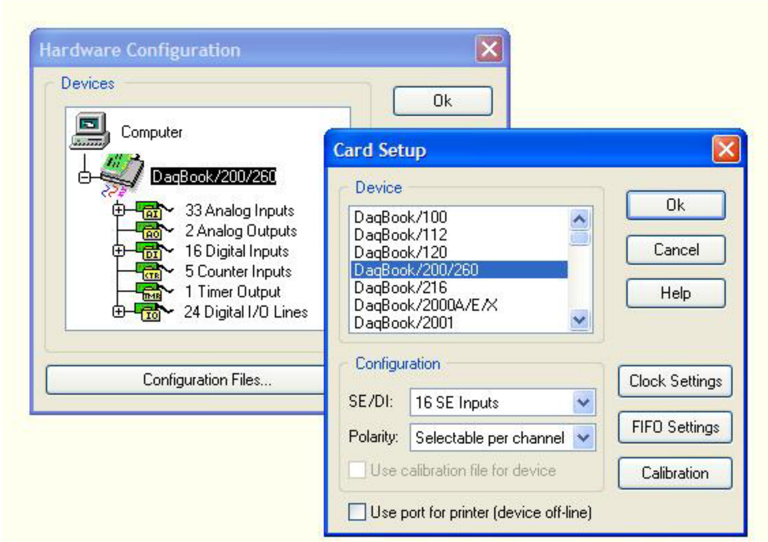


*Fig. B2. Hardware Configuration*

7. Finally, add a DBK15 expansion card to the channel 0 and a DBK16 to the channel 1 and 2 in the Analog Inputs, see Figure B3.

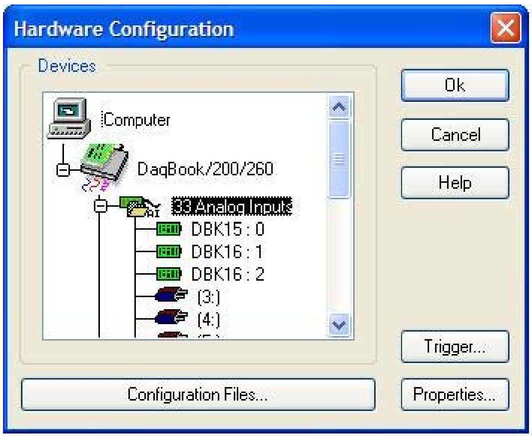


*Fig. B3. Configuration of DBK expansion cards*

# Appendix C – Instructions for data logging

Here are the instructions to connect the laptop (HP Compaq nc6320) to the car (VOLVO V40) which has installed both several sensors and an A/D converter DaqBook 200. Furthermore, the steps that should be followed to carry out comfort evaluations aided by DASYLab are also presented.

1. Connect the parallel cord to the laptop (rear) and place it on the aluminium table in front of the passenger's seat.

2. Connect the two black data collection unit cords to the matching 15 V and 12 V outlets which are under the radio unit in the car.

3. Verify that the data collection unit is switched on.

4. Start the laptop and the car if it is not.

5. Press the Start button in the Windows' Desktop, select Run and enter 'DaqX.Cpl'.

6. Choose 'DaqBook0' and click on Properties, see Figure C1.

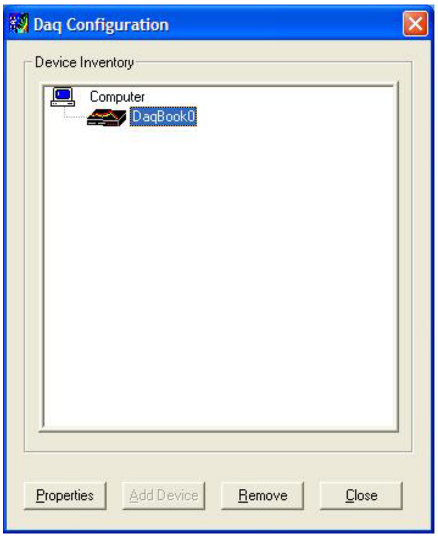


*Fig. C1. Selecting DaqBook0*

7. Verify that the DaqBook/200/260 is selected as device type and then go to Test Hardware and press Resource Test, see Figure C2.

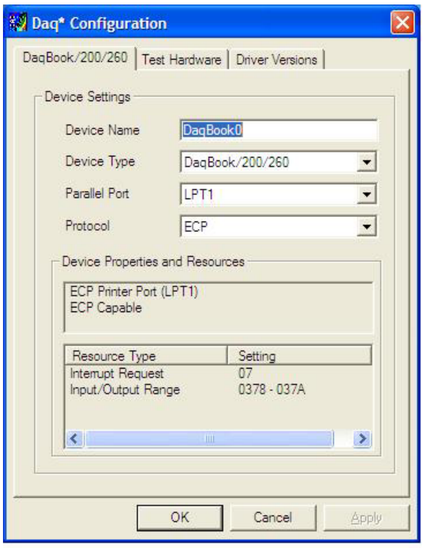


*Fig. C2. Selecting DaqBook/200/260 and testing hardware*

8. After selecting OK to the warning 'please make sure the device is properly configured, connected and powered on', verify that the test has succeeded and if similar result as in Figure C3 appears. If the test fails, try to re-run the test after switching the data collection unit off and on again. If still unsuccessful, do everything from the beginning.

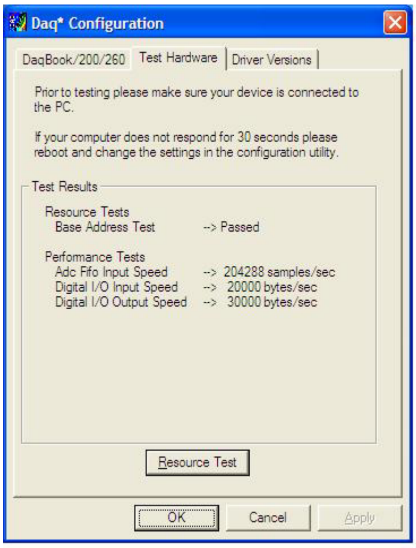


*Fig. C3. Test results after testing hardware*

9. Start DASYLab 9.0 and open the file 'Comfort Evaluation (Write Data).DSB' placed in Desktop\Comfort Evaluation. In case it is only needed do the test without recording data, select then the file 'Comfort Evaluation (No Write Data).DSB' placed in the same folder.

10. If the option chosen is 'Write Data', go to the Write Data module in the worksheet and change the filename clicking on File.

11. Once it is done, click on window\Layout 1 – 1 or Layout 2 – 2 depending on what one want to be visualized while testing with the car. Press CTRL+F to obtain full screen and ESC to exit.

12. The comfort evaluation tool can be controlled pressing the Start/Stop button.

13. If more data must be recorded, start over with '10' above.