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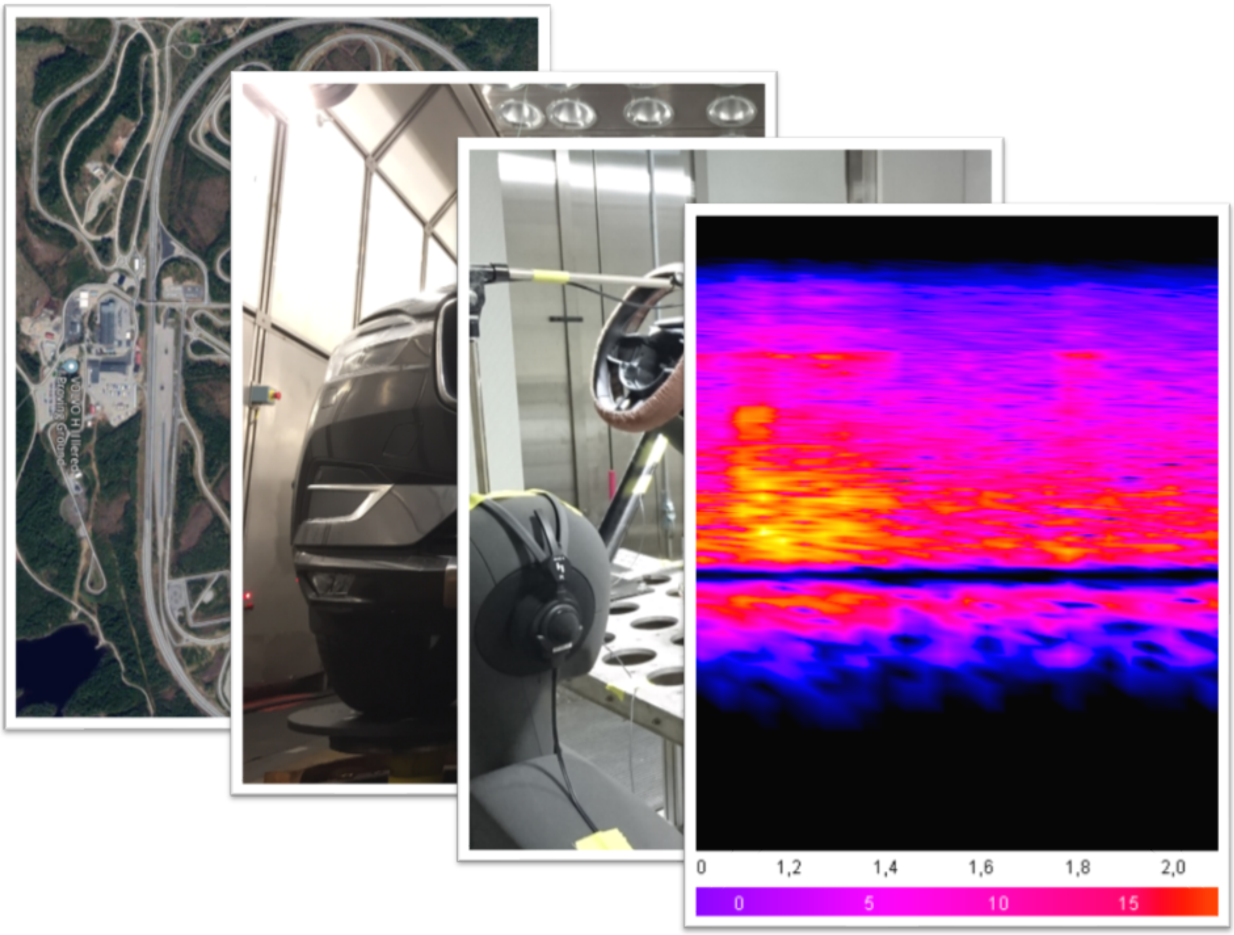

Squeak and Rattle Sound Database and Acoustic Characterisation

Master's Thesis in Product Development

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Department of Industrial and Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2018

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'A report on characteristics of squeak and rattle inside car's cabin'

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Abstract

Squeak and Rattle is one of the growing concerns in the perceived quality, especially in the premium car industry. Each day, cars are emitting less noise due to advancements in dampening of noise and vibration. The S&R directly affects the customers' perception towards the quality of the car and in turn affects the brand value of a company. To understand this issue, there is a need to look into squeak and rattles in automobiles.
Volvo Cars Corporation being one of the leaders in premium car industry would like to eliminate the occurrence of S&R, in their cars, during early design stages. To tackle S&R, the initial step is to create a database of the unanticipated irregular sounds produced by the car, and characterise them based on their acoustical properties. The process involves recording sounds in different test methods and conditions. Each of the collected S&R sounds are then filtered, processed and analysed for their psycho-acoustics properties.
The outcome of the thesis includes a sound database of the S&R sounds and statistical analysis of the properties of the sounds and how the test conditions and the test methods affect the psycho-acoustic properties of the collected sound such as loudness and sharpness.

Keywords: *"squeak, rattle, sound characterisation, psycho-acoustics, loudness, sharpness, test method comparison, automotive"*

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We are thankful to people who helped us along our way to the successful completion of this thesis. We would specially want to thank our supervisor at Volvo Cars Corporation, Mohsen Bayani, for being very supportive and helping us with his insights throughout the thesis and our co-supervisor Anneli Rosell for her continuous support and helpful tips and guidance through the project. We are also grateful for the co-operation from the entire Solidity group at Volvo Cars Corporation for helping us navigate the procedures and routines of the company and carry out our thesis as smoothly as possible. Special thanks to Nenad Hast, Tomas Fernstrom and Edward Gruia from the Durability lab for their inputs and support with the experiments conducted in the test rigs.
A major part of the thesis was testing the vehicles in the test track at Hällered Proving Ground, and we sincerely appreciate the support from all the staff members at the test facility for helping us in the test process.
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Vishal Kulkarni, Sharath Monappa Nairy, Gothenburg, August 2018

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Glossary

FFT — Fast Fourier Transform
HPG — Hällered Proving Ground
KSK 4 — 4 Poster test rig
RAM — Random Access Memory
RPM — Revolutions Per Minute
SDHC — Secure Digital High Capacity
S&R — Squeak and Rattle
SUV — Sport Utility Vehicle

1
Introduction

In today's world, one of the increasingly important attributes of perceived quality in a passenger vehicle is solidity. The major components involved with solidity are squeak and rattle (S&R) sounds. These sounds affect the perception of the customer on the quality of the product, in turn affecting the product line and the brand.

Volvo Cars Corporation – Swedish car manufacturer based at Torslanda, Gothenburg - has an organisational goal to be a leading car brand to produce the next generation of premium cars. To achieve this feat, one of the areas of research under its human centric design, is to address the S&R issues in its cars.

1.1 Background

Squeak and rattle are the sounds which occur when the adjacent parts come in contact by sliding or by impact. These sounds when occurred in the car's cabin, exhibit deficiency in the quality of the car, directly affecting the customer's perception.
The strategy within the Volvo Cars Corporation is to bring this quality aspect early on in the product development phase, where it would be evaluated beforehand, rather than 'find and fix' method. With the advent of electrification in cars - engine noise being silenced further more - Volvo Cars Corporation has invested in research on S&R to tackle this perceived quality problem objectively and address the issue of S&R in their cars.

1.2 Scope

To achieve this upfront engineering tasks of tackling the S&R problem, there is a need for a study on the different S&R occurrences and to create a sound database of S&R sounds. The scope also includes evaluation of different S&R sounds, produced in the car cabin and to objectively categorise and study the psycho-acoustic characteristics of these sounds generated inside the car's cabin.

1.3 Objectives

The objectives of the thesis are as follows:

- **Sound database and categorisation:**
  To create a comprehensive database of S&R sounds inside the car cabin in different driving conditions. These driving conditions and test setups includes driving speed, type of the vehicle, test tracks and ambient conditions. And to categorise them based on their sound characteristics.
- **Comparison of test methods:**
  The intended objective is to compare different S&R test methods and to assess the outcomes from each of the test method. Later, analyse the sounds by comparing their acoustical properties from different test methods.
- **Effect of temperature on S&R:**
  To check if the test subject when exposed to extreme temperatures produce S&R sound with varied acoustical properties, or if the temperature has any impact on the S&R sounds.
- **Comparison of electric engine and combustion engine:**
  To assess if the engine noise and vibration of a petrol powered car affects the S&R sound properties in comparison to a electrically driven car, or if it is independent of the type of engine in the car.

1.4 Deliverables

The following milestones were expected to be met during the course of this thesis study:

- Initial planning report (appendix A)
- S&R sound database and test data: The measured sound data collected from all the tests and the results from the analysis of the sounds. The data collected tagged along with the respective test data-sheets.
- Presentation of results to Volvo Cars Corporation and Chalmers University of Technology.
- Thesis Report: A detailed report of the complete thesis project.

1.5 Stakeholders

The thesis work was carried out at Volvo Cars Corporation by Vishal Kulkarni and Sharath Monappa Nairy, Master's students from Product Development, Department of Industrial and Materials Science, Chalmers University of Technology, Gothenburg. The work was supervised by Mohsen Bayani and co-supervised by Anneli Rosell, both from Solidity group at Volvo Car Corporation. Prof Rikard Söderberg, Professor at Department of Industrial and Materials Science, was the supervisor and examiner from Chalmers University of Technology along with Casper Wickman, co-supervisor from Chalmers University of Technology. The results will mainly be used and analysed by Volvo Cars Corporation, which makes them the significant stakeholder in this project.

1.6 Delimitation

The thesis study was to be completed within limited time which was calculable to accommodate only certain number of experiments to collect the sounds, and to process them to achieve the objectives set.
Availability of the test rig, equipment and assisting personnel was limited for repetitive testing.
The data collected depends on the car tested, therefore if the car used for all kinds of planned experiments has any assembly or production error it could skew the results slightly, which might not be the case in other cars of that model.

2

Literature Study

Based on the objective and scope of the thesis study the initial literature study could broadly be categorised into three sections.

2.1 Fundamentals of S&R

The section here gives more insight on squeak and rattle, the causes and their effect on the customer. S&R is not restricted to just automotive, but can be witnessed in many application where there is relative motion between the parts of a system. The scope of this thesis is limited to automotive application, passenger cars in specific. These noises can be regularly occurring from a certain component system or in random occurrences. Some duly noticeable and come strongly evident. But these noises impact the quality perception on the customer.
Squeak and rattle noises are a result of relative motion between two parts or surfaces. Both are generated in a different form, but together they would be one of the major concern for automotive warranty according to a study by JD Power and Associates (J.D. Power & Associates, 2007).

Squeak is a type of noise caused when two surfaces which are in contact move oppositely with respect to one another causing a sliding action. This action generates a intermittent stick and slip motion between the two surfaces which generates the squeaking noise. There are many factors responsible for the generation of squeak including temperature and humidity between the contact surfaces. The frequency of such said noise could be from 200 Hz to 8 kHz (Martin Trapp, Fang Chen, 2012b).
Rattle occurs as a result of impact between two contact points. This can be due to the vibration between the close-by components, a quick loss of contact between mating parts, inadequate tolerances or due to excitation of a loose element in a component. The number of rattles mainly depends on the road excitation and thus induced vibrations in the automobiles. The frequency of rattles could be from 50 Hz to 8 kHz (Martin Trapp, Fang Chen, 2012b).

The scope of this thesis being restricted to passenger cars, a study (S.A. Nolan, Y.X. Yao, V. Tran, W.F. Weber, G.S. Heard, 1996) shows that over 50 percent of the total S&R problems found in an automotive occur in instrument panels, seats and door of vehicle. To quantify and process the data of such sounds, based on literature found, the experience and advice of our supervisors, few of the sound properties were chosen for this study. And the properties are as discussed below.

2.1.1 Fundamental psycho-acoustic parameters

To understand each of the S&R sounds produced, it is important to define properties which define the sound in to calculable quantities. The properties considered in the scope of this thesis are:

2.1.1.1 Loudness

Loudness is a psycho-acoustic property and a perceived measure of sound intensity (sound pressure level) on the ear. It denotes how harsh or soft a sound is as compared to a standard tone. And is measured in 'sone'. According to (Hugo Fastl, Eberhard Zwicker, 2007) one sone is the loudness sensation caused by a 1 kHz tone at 40 dB level. The unit of sone of rather more linear scale of perception in nature than decibel level which is logarithmic. Increasing SPL by 10 dB increases loudness in sone by a factor of 2.

2.1.1.2 Sharpness

Sharpness of a sound is defined by the high frequency portion in the signal. Higher the portion of these high frequencies, higher is the sharpness, The sharpness of a sound is measured in acum. Eventhough it is not a standardised metric,according to (Hugo Fastl, Eberhard Zwicker, 2007) a reference sound of 1 acum is a narrow band noise, one critical-band wide at a centre frequency of 1kHz having a level of 60dB'.

2.1.1.3 SPL

Sound pressure level (SP level) is a logarithmic scale to measure the effective pressure by a sound wave relative to a reference sound of threshold of human hearing is $2\times10^{-}5$ Pa. And it is measured in units of decibels (dB).

2.2 Existing test methods for S&R

The literature survey for this section was to find different types of exciting the complete vehicle or concerned part at a known frequency. After the study, the data gathered could be split into two sections, namely, full vehicle test and component test.

2.2.1 Full vehicle test

The vehicle as a whole must be tested for squeak and rattle, to replicate the perspective of a customer. Multiple factors such as temperature and humidity need to be considered to imitate the accurate driving conditions and also to understand the S&R behaviour with respect to those factors. The full vehicle test can be achieved in two ways, one is by road test and another would be by simulating a car in a test rig (Martin Trapp, Fang Chen, 2012a).

2.2.1.1 Road test

The surface on which the vehicle will be driven on will vary with respect to country and regions. For instance, flat tarmac is most common but a few places in Europe have cobble stones and Belgian blocks as road path. Since it would be hard to travel across the globe to test the cars for different terrain, few OEM's have their proving grounds which would have all the different terrains that the vehicle should be tested on. Different terrain surface would excite the vehicle in different frequency, so it is very important to test the vehicle at all possible terrains to evaluate the types and variation in S&R. While testing on the road, one should always consider a real-life scenario and include those factors while testing. For instance, sunroof open, sun shades moved in various positions and seat positions. This is the best testing case for squeak and rattle, since it gives the opportunity for acceleration and deceleration and also shows the effects of from it (Martin Trapp, Fang Chen, 2012a).

2.2.1.2 Road simulation

Direct body excitation (DBE) method is used to excite or simulate the vehicle for road condition in closed doors. The signals are recorded on the car using tri-axial accelerometers in the proving ground which is later fed to the four hydraulic actuated plates. The vehicle is usually parked on these four actuators during the test. Due to difference found in the suspension and wheels of a car, signal needs to be recorded individually for each of the models. The advantage of this method is that it would give the flexibility to the manufacturer to test at any given point of time. The temperature inside these test rigs can also be controlled, hence multiple tests can be run on the same day. The disadvantages of this method is that there is no movement of the car, hence removing all the squeaks and rattle caused by fore and aft (Martin Trapp, Fang Chen, 2012a).

2.2.2 Component test

Similar to the full vehicle test, each of the sub-assemblies also needs to be checked for squeak and rattle. This will help in localising the source and can also be used as a method to assure production quality. For this test, S&R specific shakers are used to excite the components or sub-assembly. The signals are recorded on the proving ground with the help of tri-axial accelerometers which are placed on these parts. These shakers are generally installed in a noise-controlled rooms which helps in recording or noting the S&R in a better way (Martin Trapp, Fang Chen, 2012a).

2.3 Statistical metrics and analysis methods

2.3.1 Metrics

Given the amount of data collected during experimental researches, it is often hard to understand the results without a scientific way of interpretation of such data. In such situations, the research makes use of statistical tools to navigate the enormous chunk of data. With the help of literature, this study uses few of the most suitable statistical metrics. And the following can be described as follows:

- **Arithmetic Mean:** Arithmetic Mean or Mean is the arithmetic sum of the all values divided by the number of values.

- **Median:** Median is the middle number in a data-set arranged in an ascending order. In other words it is the value which separates higher and lower halves of a data-set equally.

- **Standard deviation (σ):** Standard Deviation (sigma) is a measure of amount of dispersion or variation in a set of values. It denotes how much the values tend to fall close to the mean.A high value of standard deviation means the data values are widely spread out.

- **Variance:** The variance is the square of the standard deviation. It denotes how far a set of values are spread out from their average value.

- **95^{th} percentile:** 95^{th} percentile divides the distribution into top 5 percent values and bottom 95 percent values.

- **Crest Factor:** Crest factor is defined as the ratio between the peak value and root mean square (RMS) value.

- **Skewness:** A distribution said to be symmetric if it can be equally divided into two halves. Often than, data-sets are not symmetrically distributed with respect to the central value. Skewness of a data-set defines in which direction the values cluster. Distributions are either positively skewed (skewed to the right) or negatively skewed (skewed to the left).

2.3.2 Peak properties

Apart from the statistical metrics, the sound signals obtained can be expressed as a signal with aberrations where there are peaks, which imply higher measures of the quantities. A signal can be quantified by using the properties of the peaks found in the signal. These properties of peaks is discussed in section 4.2

3
Methodology

The chapter here deals with the procedure followed during the research period for different test setups, apparatus and equipment used, and the design of the experiments in detail. Each section addresses multiple experimental setups carried out in different test methods. Further, processing of the collected data, methods and tools used, and metrics involving the S&R analysis are described. Also, certain limitations with the study and experiments, issues faced during the process and the designing of the test setups are discussed in the later section of this chapter.

3.1 Test procedure

The test procedure for the research was arrived through an iterative process due to unavailability of a universal approach or standard procedure for collecting S&R data. The following sections explain the devices used and steps involved in the collection of data.

3.1.1 Recording devices

The following products were used to record the signals throughout this research study. These products were chosen based on their availability at Volvo Cars Corporation which were also backed by the literature study.

SQuadriga II

SQuadriga II, seen in the fig. 3.1, is a portable device that was used to record signals captured by sensors such as binaural headphone, accelerometer, microphone, and many more. The recorded signals will be written onto a removable SDHC card which can be used later for analysis of the data. The device contains a touchscreen display and functional physical buttons which helps in navigating through the available options and settings (HEAD acoustics GmbH, 2018c). The device contains 7 input ports where the sensors can be connected to. One of the input ports on the device is dedicated for binaural recording device and the rest can be used for other sensors such as accelerometer and microphone. SQuadriga II was also used to calibrate the sensors as well as to set the recording range for all the input peripherals.

Figure 3.1: SQuadriga II (HEAD acoustics GmbH, 2018c)

Microphones

A set of binaural headphones and two microphones of similar properties were used as sound recording sensors. BHS II by HEAD acoustics GmbH, shown in fig. 3.2, is a headphone capable of recording binaural signals. The adjustable headphone can be calibrated according to the needs of the user and the operating range can be set with the help of SQuadriga II, within it's working limits. The two earpiece in the headphone can be used to playback the recordings and the outer part of the earpiece acts as the recording device (HEAD acoustics GmbH, 2018b). The device can be either worn by a person while recording or can be placed on a fixture to replace the human during recording.
GRAS microphone is a free field recording device capable of recording lower frequencies signal of 0.5 Hz up to 20 kHz. The compact microphone contains a cartridge and a pre-amplifier, which are coupled together to reduce the sensitivity error. The working range and the sensitivity of the microphone is unique to each device, which is informed to the user through data sheets. This sensor can be calibrated within it's working range upon coupling with a compatible recording device (GRAS Sound & Vibration A/S, 2018). One such microphone can be seen in the fig. 3.2. Both, the binaural headphones and the microphones were calibrates for their limits with extreme input signals.

Figure 3.2: BHS II - binaural headphone (HEAD acoustics GmbH, 2018b) & GRAS microphone (GRAS Sound & Vibration A/S, 2018)

Accelerometer
A pair of triaxial accelerometers were used in the test setup to record the motion of the car at two different points. Accelerometers made by Brüel & Kjær were used throughout the research study to maintain data consistency. The sensor gives out three individual output for their respective axis, which is perpendicular to each other. Similar to other sensors, the sensitivity is provided in the data sheets and the recording range can be calibrated from the recording device (Brüel & Kjær, 2018).

Figure 3.3: Triaxial accelerometer (Brüel & Kjær, 2018)

HEAD measurement system-HMS IV
The acoustic head, as seen in fig. 3.4, is an independent operating device, which can record sound signals. But in this research, the acoustic head was used to replicate a human in the seat. As the collected data will be used to have a jury test in the future, the recording from the acoustic head would not be accurate since the sounds will be played back to the jurors through a headphone. Hence the head was used to position and place the headphone for recording as explained in section 3.1.1.

Figure 3.4: HEAD Measurement System - HMS IV - Acoustic Head (HEAD acoustics GmbH, 2018a)

3.1.2 Test data fact sheet

Since there are many factors affecting the outcome of the test, the pre-test data needs to be documented in an organised manner. This created a requirement to have a data sheet to record all the values. This data sheet was kept constant for all the test methods. The fact sheet starts with the basic data related to the time and persons involved in the test. The later part is divided into three sections, namely, vehicle details, ambient conditions, and other details. Under vehicle details, the specifics pertaining to test car is noted down. This is noted for future reference if any of the tests need to be repeated. This is followed by ambient conditions section, which provides details related to the weather and test conditions. The final section is named as other details, which informs about the test setup and all the equipment used for the test. This along with the car map, which will be explained in upcoming sections, collectively provides data related to a particular test.

3.1.3 Data collection

The tests were repeated on different test rigs, hence there was a requirement to come up with a standard setup for all tests. This would help in comparing the test rigs and also reduces the setup error. For all of the tests conducted, 2 triaxial accelerometers were placed in two different locations inside the cabin, one on the instrument panel close to the A-pillar, recording values of "X" and "Z" axis and another placed on the bolt of the front passenger seat rail, recording values of "Y" and "Z" axis. The accelerometers were hooked to SQuadriga II to record and store the data. Only two of the axis was chosen for both the accelerometers due to a limited number of input ports available on SQuadriga II. Along with the accelerometers, a binaural headphone and couple of microphones were set up in three different configurations to capture most of the squeaks and rattles inside the car cabin.

Configuration 1: The acoustic head was fixed to the front passenger seat and two microphones were attached to the left and the right rear door windows using a suction or vacuum stand as shown in fig. 3.5.

Figure 3.5: Configuration 1

Configuration 2: Similar to configuration 1, the acoustic head was fixed to the front passenger seat, one of the microphones was suspended onto the middle of instrument panel using a suction stand which is mounted on the front windshield, and another microphone on the window of the front right door which can be seen in fig. 3.6.

Headphone Microphone 1 Microphone 2

Figure 3.6: Configuration 2

Configuration 3: In this configuration, the acoustic head was fixed on the headrest of the left rear seat in the car. One of the microphones was suspended over the instrument panel, similar to configuration 2 and the second microphone is mounted on the headrest of the front passenger seat as seen in fig. 3.7.

Headphone Microphone 1 Microphone 2

Figure 3.7: Configuration 3

The microphones are mounted onto the door and the instrument panel to record sounds from them respectively and the binaural headphone is used to record the noise from the complete cabin. The positions of the microphone were chosen to capture sound from most of the S&R sources.

A subjective analysis was done in real time during the test wherein the source is recognised and noted along with time. A stop-clock was started simultaneously to the sound recording to note the instance at which the sound occurred. The fig. 3.8 shows the medium used to note the sound, wherein the S&R source will be noted along with the time of occurrence. The sound is also subjectively rated on a scale of 1 to 3 - 1 being mild and 3 being worst - which is in turn linked to the instance and source. A completed set of data for SUV is recorded on the car map which is shown in appendix B along with a list of all recording with subjective rating and time of occurrence.

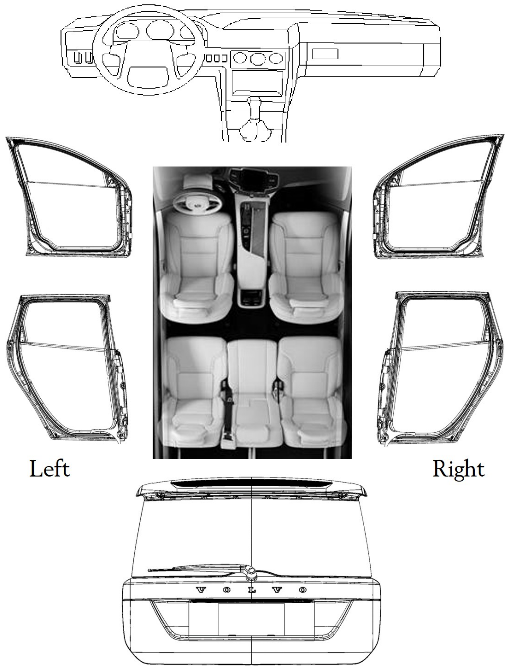


Figure 3.8: Car map used for subjective rating

3.1.4 Data management

A large amount of data was collected from all of the tests and would be hard to refer back if it is not handled in an organised manner. A generic naming system was generated by considering all the factors that could vary between each of the recordings. The naming would first cover the test method and then followed by the name of the car. As there were multiple tests done on the same car, the month and the day were also recorded which was followed by the car's registration number. Each of the cars was run multiple times with different configuration, the configuration number was mentioned after the registration number in the name. Every track was given a number which was registered in the name of the recording along with the speed of the car at which the signal was recorded and a unique recording number, which will help in differentiating between each recording if multiple runs were done on the same test setup. Every recording was cut into clips to capture only the squeak and rattle. For the sound clips, the position of the microphone and the start time of the clip is mentioned. Altogether, this helped in organising the sound database that was created. The fig. 3.9 shows a pictorial representation of the steps followed in saving a file.

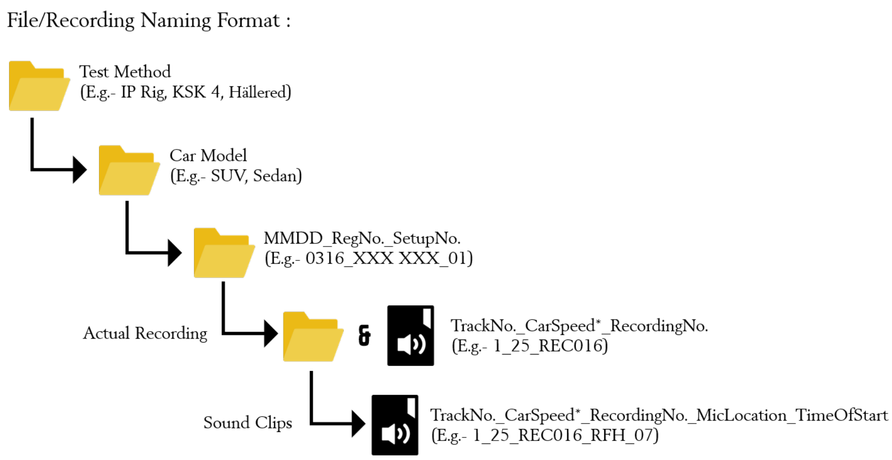


Figure 3.9: Template for naming of files and folder

3.2 Design of experiments

In this research study, three different test methods were chosen, namely, full vehicle test, 4 poster rig test (KSK 4), and component shaker test (IP rig). The test setup, as described in section 3.1.3, was designed in accordance with these test methods. The motivation for choosing so is based on the initial literature study about various experiments and tests conducted in the field of squeak and rattle (Paulo Eduardo França Padilha, Alexandre Nunes, 2002) (R P Senthil Kumar, N Jaya Kumar and Sajith Nair, 2013), and advise from the people experienced in this division at Volvo Cars Corporation. All the tests were carried out in the Volvo Cars Corporation facilities and all the test subjects chosen – cars and components – were produced by Volvo Cars Corporation.
The design of experiments for the research study was such that, the three testing methods were conducted in the order of full vehicle test, 4 poster rig test (KSK 4), and component shaker test (IP rig) and then repeated if the collected data was found inadequate or there was a requirement of more data with different test condition. Below are the details of the first set of tests carried out.

3.2.1 Selection of cars for the tests

The intention behind the car selection was to cover a wide range of platform and form factor of the cars. Thus, on consulting with the mentors at Volvo Cars Corporation, it was finalised to have one SUV, one estate, one sedan and a hybrid SUV. The chosen SUV was powered by a combustion engine. The car weighed in at 1826 kg, with a total of 1360 km on the odometer. Hereafter this car will be referred as SUV in this document. The estate car, hereafter referred as an estate is also powered by a combustion engine. The car weighed at 1896 kg with a total of 2967 km on the odometer. The sedan chosen, will be referred as sedan was powered by a combustion engine. This car had run 25911 km on the odometer and weighed in at 1570kg. The final car chosen was a plug-in hybrid SUV, hereafter referred to as hybrid SUV. The hybrid SUV weighed at 2318 kg and had a reading of 24307km on the odometer. In the latter part of the research study, a different variant of the SUV was added to this fleet of cars. Thus, there were five models in total as test subjects. The cars chosen for the study have been kept the same throughout, to avoid sampling errors and to obtain consistent results. The hybrid SUV would be considered as two subjects during the full vehicle test because it was driven in electric mode and petrol mode individually. Each of the test methods is discussed in the upcoming sections which will give insights into how these cars were tested.

3.2.2 Selection of test tracks

Hällered Proving Ground as seen in fig. 3.10, situated at Hedared, is one of the testing grounds for the vehicles made at Volvo Cars Corporation. Various automobile manufacturers use this facility to test their vehicles for various purposes. The proving ground has a variety of terrains available for the test cars depending on the objective of the test carried out. One such purpose of testing the cars in this facility is to detect and carry out root cause analysis of squeak and rattle, and also the same tracks are used for verification purpose as well.
Amongst the available tracks at Hällered, the tests were designed for four tracks, namely, **Comfort Track, Country Road 1, Country Road 2 and Durability Track**. Each road has its own characteristic quality of texture and unevenness. The purpose of choosing these was to have varied excitation levels, keeping in mind the practicality or day-to-day road conditions that the cars are generally exposed to. Below the fig. 3.11 shows the FFT of the four tracks, which shows the excitation recorded from the accelerometer, i.e. acceleration experienced in the Z direction, as seen in section 3.1.1, which is attached to the instrument panel of the car when driven in each of the tracks. This shows how each track imparts a difference in the excitation level experienced by the car. It can be seen that durability track has the highest amplitude with respect to the acceleration experienced by the accelerometer in the Z direction. The decision was based on the previous experience of testing vehicles by the Solidity group, as these are conventional tracks used for testing for S&R at Volvo Cars Corporation.

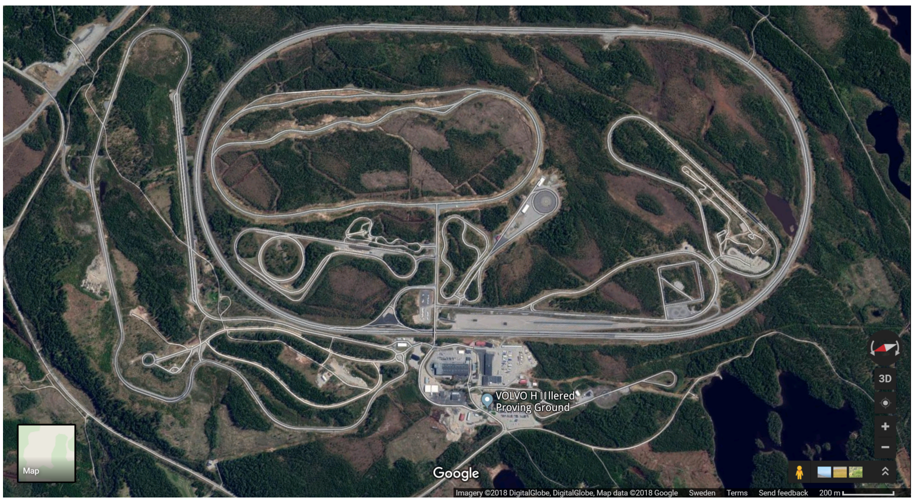


Figure 3.10: Aerial shot of Hällered Proving Ground (Google Maps, 2018)

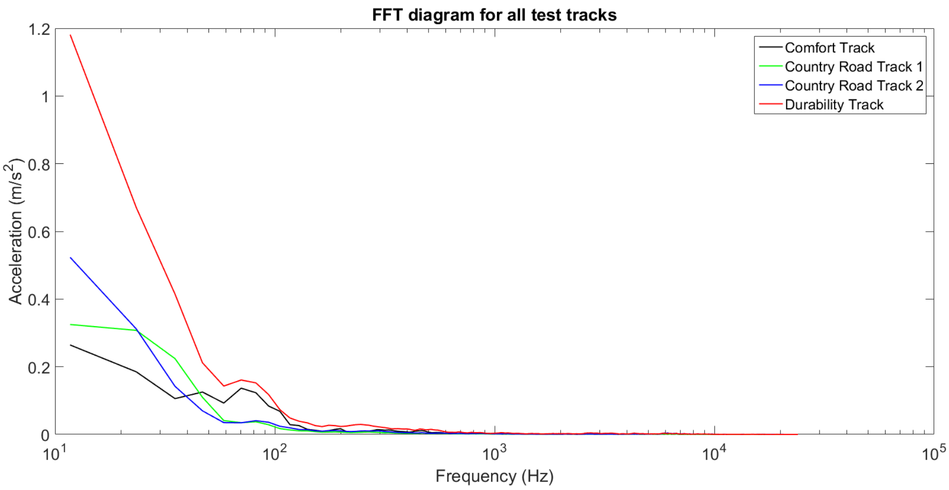


Figure 3.11: FFT Diagram for Comfort Track, Country Road 1, Country Road 2 and Durability Track

3.2.3 Full vehicle test

The method involves testing of the full vehicle at Hällered Proving Ground (HPG) on a varied uneven surface of the tracks which producing excitation level which is unique to each other. As discussed previously in the section 3.1, the test setup consists of SQuadriga II, acoustic head, binaural headphone, microphones, accelerometers and respective cables for data exchange. The car was initially weighed on the weighing scale at HPG, and the humidity and temperatures - both inside the car and outside - were recorded on the day of the test and were documented in the test data sheet.

3.2.3.1 Setting up recording devices

Acoustic head with binaural headphone is tucked to the head-rest of the passenger seat with stiffeners to imitate an actual passenger. The two microphones were placed on each of the rear doors' window using vacuum plugs. The position of the recording sensors was recorded and used in component testing in later stages of the study.

3.2.3.2 Equipment calibration

The sampling rate of all the recordings was set at 48 kHz. As it is standard for all digital audio tapes and the frequency response covers the frequency range that S&R lies in. Also, the intention behind choosing this frequency is that higher resolution of frequency can be downgraded based on applications, but the other way is not possible (Otto, N., Amman, S., Eaton, C., & Lake, S., 1999). Thus, recording at a higher frequency is always recommended. The microphones and the accelerometers were calibrated using sound calibrator and the manuals of the respective sensors. SQuadriga II was auto-ranged to record the excitation and sounds within the specified limits. This was set-up by driving the car, with all the sensors positioned in place, at a track with a high level of excitation frequency at speeds greater than the ones chosen for the test. This setting was maintained constant throughout the test at HPG.

3.2.3.3 Seat positioning

Based on the literature from the design department at Volvo Cars Corporation, the seat was positioned according to ergonomic standards. This included the height of the seat, the angular orientation of back-rest with respect to the seat cushion, and the distance of the seat from the instrument panel of the car (SAE International, Issued 2005-08, Revised 2008-08).
According to SAE Human Accommodation And Design Devices Standards Committee recommendation, the seat height was adjusted to 320 mm from the car floor, a distance of 1040 mm was kept between headrest and instrument panel and an angle of 25° from the seat was added to the backrest. A point on the right post of the headrest was a conventional point of reference for our measurements and was maintained the same for all cars and tests. A pictorial representation of the setup can be seen in fig. 3.12.

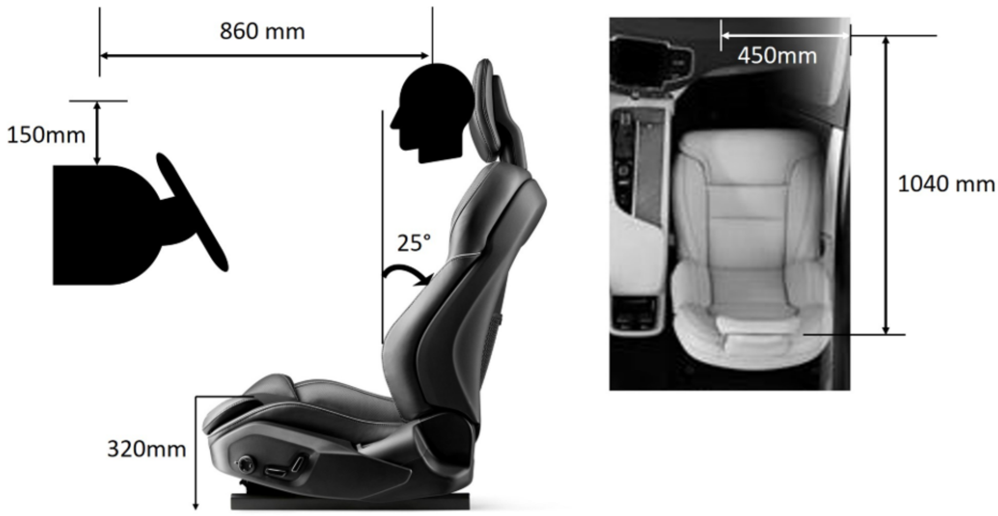


Figure 3.12: Measurements for seat position

3.2.3.4 Car accessories status

The car accessories like air conditioning, windshield wipers, and sunroof if in action will impart unnecessary disturbances in the recordings. To avoid this, all the aforementioned were shut off. And these conditions were maintained throughout all the recordings in HPG and KSK 4. While at HPG, if the tracks were damp or if it was raining, none of the tests was continued since the raindrops falling on the sunroof or windshield and the water splash from underneath the chassis would influence the recording.

3.2.3.5 Accelerometer positioning

Two triaxial accelerometers were used to record the excitation of the car while on tracks and were placed on the rigid components, one on the instrument panel close to the A-pillar and another on the seat rail of the front passenger seat. The purpose of recording the excitation was to compare the signals with other test methods, which will be cover in the later sections. A standard convention was followed while placing the accelerometers in the car and was kept constant through all the tests carried out. As shown in the fig. 3.14 with car cabin in the background, the Z-axis covers the vertical motion of the car from the driver's point of view. The forward and backward motion is measured by the sensor detecting the X-axis and lastly, the sideways motion of the car is measured by the Y-axis sensor on the accelerometer.

Figure 3.13: Accelerometer on the instrument panel and seat rail

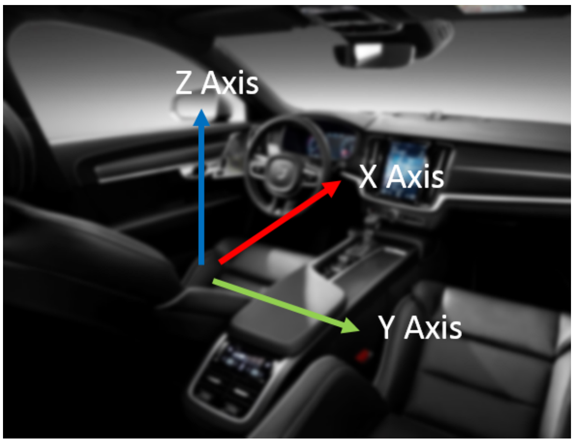


Figure 3.14: Convention followed for the accelerometers

3.2.3.6 Modifications and rearrangements

The first car - SUV - was then driven on the afore-mentioned tracks with speeds of 25, 30, 40, 50 and 60 kph. It was found that the recordings had unwanted sounds and disturbances from the unbalanced front passenger seat. Since the head was attached to the headrest and the seat was empty, which induced vibration and sound from the lower part of the seat. Due to this, the binaural headset could not effectively record the S&R from the instrument panel and sounds produced from the front part of the car cabin. It was observed that squeaks and rattles were also significantly noticeable at lower speeds.
To solve these shortcomings, it was then decided to fix the acoustic head with the binaural headset on the seat with the base of the head firmly planted on the seat instead of hanging on the headrest. This helped in reducing the unnecessary vibrations and disturbances. Recordings were done for various higher and lower speeds. And to keep the consistency and avoid errors, the test was repeated three times for few of the speeds. table 3.1 and table 3.2 shows speeds recorded on tracks and speed used for repetition of the test.

Track	Speed (in kph)
Comfort Track	10, 25, 30, 40
Country Road Track 1	10, 20, 30, 40
Country Road Track 2	10, 20, 30, 60
Durability Track	10, 20, 30, 40

Table 3.1: Speeds for individual tracks at HPG

Track	Speed (in kph)
Comfort Track	10, 25
Country Road Track 1	20, 40
Country Road Track 2	30, 60
Durability Track	20, 40

Table 3.2: Speeds repeated at HPG for data consistency check

3.2.3.7 Final test setup

Improvements with continuous iteration, the final setup was concluded to test all cars on four different tracks of varying road type and excitation levels shown in fig. 3.11 in their respective speeds, as seen in tabletable 3.1, with multiple recordings for a few specific speeds in three different microphone configurations. This resulted in a huge database of track recordings with respect to sounds and excitation frequency.

3.2.4 4 poster rig

4 poster rig, also called as KSK 4, is a test rig wherein four independent hydraulically actuated plates reproduce a track's excitation, based on the pre-recorded signal fed

to each of them. These actuators translate the motion experienced in Z direction on an actual track by individually raising and lowering the plate on which the tyres of the car is resting. This way the movement of the vehicle is intended to have the same effect as in the tracks. The KSK 4 rig is an airtight chamber, capable of simulating multiple weather conditions with respect to humidity and temperature, ranging from -40℃ to 80℃, and a full range of humidity from 10 to 95% RH which can be controlled above 10℃. It can also simulate sunlight with the lamps inside the chamber.

3.2.4.1 Test setup

The car is positioned such that each wheel lands on each of the four actuators and they are held in place at two opposite corners using a fixture. This does not let the car out of the actuators' space when the plates start to move upon excitation. The cars are then prepared with triaxial accelerometers - specifically used for the KSK 4 rig - at six places to record the car's excitation. Two accelerometers are installed on both sides of the instrument panel, two accelerometers on the seat rails of both the front seats and two more on the B-pillar of the car being tested. These recorded signals will be processed further to serve as an input for component testing. The motivation for the positions of the accelerometers will be discussed in the next section under IP rig.
Once the car is prepped, it was left to soak in the desired temperature and humidity for over four hours. This is done so that the temperature can be spread evenly inside and outside of the car. The test was conducted in a similar to the tests at HPG with three configuration of the microphones and the same two accelerometers at their respective positions. The SQuadriga II settings were kept constant including the range of the signal and also the sampling rate of the recordings was kept constant i.e. 48 kHz. The table 3.3 shows the speeds at which the rig was excited for each of the tracks.

Track	Speed (in kph)
Comfort Track	25, 30, 40
Country Road Track 1	40
Country Road Track 2	60
Durability Track	40

Table 3.3: Speeds for individual tracks at KSK 4

3.2.4.2 Testing for room temperature

SUV, estate, sedan and hybrid SUV were all tested for the room temperature of 23℃ and humidity of 23.5% RH in the KSK 4. The hydraulic actuators in contact with the tyres were then fed with pre-recorded signals, kept constant for all test subjects, for the same four tracks as in HPG test and the sounds were recorded from the car cabin.

3.2.5 Component shaker test

Component shaker test is also known as IP rig test. While testing at HPG and in the KSK 4 rig, it was made a point to observe if there were certain parts which made prominent S&R sounds comparative to other components of the car. This was the basis for choosing one component which caused more sounds or happened to be a major contributor to S&R sounds. Each of these components after being selected was tested individually on the shaker table of the IP rig. The IP rig chamber is hemi-anechoic and versatile with regard to ambient temperature conditions. The chamber can maintain the temperatures ranging from -20℃ to +70℃ but does not have the flexibility to change the humidity like in the KSK 4 test rig. The chamber is equipped with the two huge vibration inducers connected to a metal shaker table with mounting capabilities. The components are generally placed with a fixture and the fixture in turn is attached to the shaker table. Each component chosen for testing are detailed in the upcoming sections.
As mentioned in the section 3.2.4.1, the signals recorded by the accelerometers placed at six different places in the car during KSK 4 rig test were used as the input excitation signals for the shaker table depending on the respective car's components being tested. For e.g.: the signals from the accelerometers on the instrument panel of SUV were used as an input signal while testing the instrument panel which is explained under section 3.2.5.2.

3.2.5.1 Left rear door

The SUV's left rear door was chosen for the IP rig test, the door was disassembled from the car and was mounted on the fixture – a fixture made for shaker table to fix the door in the same points as in a car – to reproduce same fixed loads and stress as experienced in the car at the connecting joints between the door and the car body. This fixture was modified to suit the door with some additional supports on top to prevent unnecessary vibrations produced in the upper part, which in general are suppressed by the weather strip and car ceiling in the car but are not present during this test. Once the rig was set up, the microphones were placed in configuration 1 and 2. The placement of the sensors was kept similar to the distances recorded at HPG, with the component that is tested as the reference. The shaker table was fed with the excitation signals of the four tracks which were recorded by the triaxial accelerometers on the B-pillar of the car while testing in the KSK 4 rig. The signals that are fed as input to the IP rig was kept unaltered from the KSK 4 test. Since there is no seat to mount the acoustic head, or availability of space to place the head in its place within this confined space, the recordings are made only from the microphones.

3.2.5.2 Instrument panel

The instrument panel (IP) of SUV was mounted on the shaker table. Due to time limitation and lack of resources, IP from the actual SUV could not be removed, so an IP of the same car but a different variant of SUV, hereafter referred as SUV2, was ready and available testing. The accelerometer was attached to the instrument panel in a similar fashion as in HPG and KSK 4 and the microphones were placed in configuration 2 and 3 including the acoustic head placed at the same position as the previous test methods. The results were recorded for the instrument panel of the SUV. Configuration 1 was omitted in this test since the microphones are at the rear and it does not contribute to any substantial recordings for IP testing.

3.2.5.3 Seats

The front passenger seat of the estate and the hybrid SUV was found to be causing S&R while testing at HPG and KSK 4, hence these were disassembled from the cars and were mounted on the shaker table. The seats were positioned such that the angle of the backrest, the height of the seat from the car floor and distance from the instrument panel or microphone on the instrument panel were kept as it was at HPG and KSK 4. The shaker was fed the signals whichever recorded by the accelerometers on the seat rail while testing at KSK 4. Same tracks and speeds were used for seat testing also and the sounds were recorded.

At the end of these three test methods, the first cycle of testing was concluded.
There are certain advantages and drawbacks to each of these test methods. Especially, when it comes to the degrees of freedom it offers which translates to the motion of the car.
At HPG, it is evident that we have the car moving in all the three directions, meaning, the motion is not restricted. But in KSK 4 and IP rig, the motion is restricted to only z direction since the vehicle is not being driven. Hence this restriction in the x and y-direction could be a major factor to consider when comparing S&R from KSK4 and IP rig to the results from HPG.
Nevertheless, the track testing at HPG is dependent on weather conditions and unavoidable external disturbances. At KSK 4 and IP rig, the ambient conditions can be controlled to a desired level within the rig's operating range and the testing can be carried out at any given time of the year.

3.2.6 Additional experiments

In KSK 4, the second set of recordings were concentrated more on the temperature effect on S&R. Thus, the recordings were made in the following temperatures and humidity. This was done for all the test cars including SUV 2.
Below table 3.4 gives the temperatures and humidity of the chamber conditions. Car soaking time remained the same for all.

Car	Temperature & Humidity
Estate	23℃ & 23.5%RH, 5℃ & 80.5%RH, -10℃ & 76.0%RH
Hybrid SUV	23℃ & 23.5%RH, 5℃ & 83.7%RH, -10℃ & 77.9%RH
Sedan	23℃ & 23.5%RH, 40℃ & 10.0%RH
SUV	23℃ & 23.5%RH, 35℃ & 80.0%RH, 40℃ & 10.0%RH

Table 3.4: Temperature and humidity of different test at KSK 4

In IP rig, it was observed that the instrument panel of SUV 2 was producing more S&R sounds, hence the effect of temperature on it was checked by testing the instrument panel in the IP rig, which was maintained at 45°C. Like in the KSK 4, the rig was maintained in the same status for over 4 hours to soak the panel and the test was carried with the same speeds and tracks as before.

3.2.7 Post processing

Once the data is recorded and collected, the next step is to process the data in accordance with the objectives set for the study. For processing the data, the tools used were ArtemiS Suite - a sound analysis software from HEAD Acoustics GmbH- and MATLAB for analysing the outputs obtained from ArtemiS Suite. In the next chapter, the data processing and analysis of the data collected is discussed in detail.

4

Data analysis

This chapter elaborates the analysis of the collected S&R sound clips. The chapter is divided into three sections, starting with signal processing - discussing signal processing tools and signal filtration - then about statistical analysis - various metrics calculated using mathematical tools and lastly about the issues and limitations encountered during each of these phases.

4.1 Signal processing

After collecting the sounds recorded from the binaural headphone and two microphones, the next step was to find the S&R sounds in the recorded measurements.

Signal processing involves clipping of test data for specific sounds under study. The recordings from all the tracks and the test rigs are longer and contain redundant sounds which are not of importance. To get the sounds in the required manner, it is important to process the signals and apply suitable filters to make them viable for the study. To achieve this, several tools were used. This section discusses the tools and process in detail.

4.1.1 ArtemiS Suite

ArtemiS Suite is the tool used for processing of the collected sound data and it offers a varied number of processing methods to help in visualising the data at hand. The first step in the process was to cut the recordings into S&R clips so that the unwanted or empty and redundancy parts of the recordings are removed and only the required sounds are retained. The interface of ArtemiS Suite can be seen in appendix C.
There are certain conventions followed throughout the signal processing and clipping of sounds:

- Each of the recordings was listened to separately for binaural headphone, and both the microphones. Thus, making sure most of the sounds are captured while clipping.

- S&R clips are cut such that they span five seconds on an average (Otto, N., Amman, S., Eaton, C., & Lake, S., 1999).

- The sound level of the output, i.e., the listening device was kept at the same volume throughout the clipping process.

- Each sound clip will be subjectively rated for the annoyance on a scale of 1 to 3.

4.1.2 Psycho-acoustics standard metrics

In this research study, the objective characteristics of the recordings considered were of loudness, sharpness and sound level. ArtemiS Suite provides values of these characteristics with respect to time. Once the recordings are clipped, these S&R clippings contained a lot of background noises. The background noises were from the engine, tyres, suspension, and the environment in which the test was conducted. It is required to suppress these background noises to focus only on the S&R. And to address this, filters were imposed on these signals before exporting the loudness, sharpness and sound level values from ArtemiS Suite.

4.1.3 Signal filtration

As previously mentioned, the S&R clips consisted of sounds recorded from various channels on the SQuadriga II. The channel 1 & 2 are the sounds which were recorded from the left and right side of the binaural headphone respectively, the channel 3 & 4 contained the sounds recorded from the two microphones. The sounds need to be filtered from the disturbances to proceed further.

The objective of filtration was to remove the unwanted background. To achieve this, it was necessary to know how the characteristics of the recorded sounds when there was no excitation - the sound produced on a flat tarmac on HPG, chamber of KSK 4 and IP rig without the excitation signals applied to the actuators and the shaker table - to see its effect on S&R sound signals. This was analysed in an FFT diagram to understand the frequency range constituting the background noise, which helped to base the judgement on filters used. The next step was to collect a sample set of S&R clips amongst the collected data, which included all the tracks, cars and test methods.
Once this set of clips was compiled, a low pass filter of 10,000 Hz was applied to remove all the disturbances above it. Since no audible S&R occurs above this frequency (Kavarana, F. and Rediers, B., 1999), it was decided to apply the low pass filter of 10,000 Hz to all of the test methods, and track recordings. It was seen from the FFT diagram, there was a specific frequency of background noise present in the IP rig test and few of the KSK 4 rig test. The recordings had a certain continuous disturbance from outside of the test rig. To remove this disturbance from the recording, a band stop filter of 300 Hz was applied to all recordings from IP rig and KSK 4 rig test.
Next, each of the clips was heard and tested with high pass filters varying from 300 to 500 Hz. To understand the effect of filters, the 95^{th} percentile value for loudness, sharpness and level were noted for all the samples with no filter applied. And then,

with the low pass of 10kHz and a high pass filter which suited the best – by not losing any S&R characteristics but a damped or silenced background noise - and a band stop wherever was applicable for that particular recording was noted. The effect of the filter on the sound clip, before and after applying the filter on FFT can be seen in appendix D, fig. D.1. And how the filter affects the values of loudness can be seen inappendix D, fig. D.2, similarly for sharpness in appendix D, fig. D.3 and sound level in appendix D, fig. D.4.
By observing the pattern of the high pass filters chosen for each car or component and track, it was decided to go on with the following as final high pass filters as seen in table 4.1 for the three test methods. These values were kept constant and followed for all of the recordings.

Tracks	HPG (in Hz)	KSK4 (in Hz)	IP Rig (in Hz)
Comfort Track	450	400	350
Country Road Track 1	400	400	300
Country Road Track 2	450	450	300
Durability Track	450	450	350

Table 4.1: Final high pass filters applied on the sound clips

The clips after this filtration process contained more pronounced S&R sounds and little to no background noises interfering with the loudness, sharpness and level values. With proper applicable filters applied to the S&R clips, the signals were exported as an excel workbook containing values with respect to time. Each sound clip has a respective excel workbook with three sheets, each sheet containing loudness, sharpness and level values. An example is shown in appendix E.

4.2 Statistical analysis

The workbook containing values of loudness, sharpness and level values vs time was used as an input to the MATLAB script written to analyse the clip for various measures and calculations. The script used the time signal values and respective values from each page of the signal's workbook and calculated the outputs. One of the inputs required for the script which was decided for this particular study was Delta T, which will be discussed in the upcoming section.

4.2.1 Functions and inputs for the script

Delta T: Delta T is the small division of time where one rattle or squeak could be heard by the human ear. For this study, few of the randomly selected clips were chosen and analysed as to which had the least amount of time where a single rattle can be distinctively heard. Upon looking into a number of clips, the time of a distinct single rattle heard in a continuous rattle sound was chosen to be 0.05 seconds.

Number of Peaks: The *findpeaks* function is a built-in function in MATLAB which gives out the number of peaks in a signal based on the limitations and conditions given for the function. The number of peaks for the S&R sound is actually the number of rattles or squeaks heard. This objectively measures how many distinguishable rattle peaks make up one rattling sound. Similarly, applies for squeak too.

Few of the following values were given as limiting conditions during the analysis:

- **Minimum Peak Height:** It is the minimum height or absolute value of a signal peak above which it would be counted as a peak. This was to ensure that no other noises were counted, and only distinctive rattles were counted as peaks. This value was hard-coded in the script and was decided by observing the graphs the loudness, sharpness and level graphs with respect to time of randomly sampled rattle sounds pertaining to all three test methods in ArtemiS Suite.
- **Minimum Peak Distance:** Even though the peaks are separate, they are generally not distinguishable to human hearing and two of the peaks could be heard as a single rattle tick. To avoid these close peaks, it was decided to give a minimum distance between two peaks which are distinctively heard to a human ear. Since the reasoning behind the choice was similar to that of Delta T, hence the Minimum Peak Distance was kept same as Delta T.
- **Minimum Peak Prominence:** Minimum Peak Prominence is the value which determines the minimum vertical height of the peak with which it will descend on either side of the peak. These values give how isolated the peak is, and avoid minor bumps on the ascend or descend towards the maximum value of the peak.

Relative Prominence: It is an input value given for this study which acts as a second round of check for the already obtained peaks by *findpeaks* function. The motivation for using this is to check if the peak value is above the average of the values between -Delta T/2 and +Delta T/2 at that peak. This rejects the peaks which are relatively less prominent.

Each of the above values are decided separately for loudness, sharpness and level analysis and are as follows:

Constant	Value(Loudness)	Value(Sharpness)	Value(Level)
Minimum Peak Prominence	0.4	0.2	0.1
Minimum Peak Height	1.51	0.9	45
Relative Prominence	1.1	1.1	1

Table 4.2: Values for constant used for loudness, sharpness, and sound level

4.2.2 Output of the script

The script uses the standard MATLAB functions to calculate the following - which are defined in the section 2.3.1 - Standard Deviation, Variance, Skewness, Kurtosis,

Mean, Median, Crest Factor, Number of Peaks, Peak Value, Time of Peak, Width of Peak, Peak Prominence, Average Relative Prominence, Max Relative Prominence, Relative Prominence, Average Width, Average Peak Value, and Max Peak Value. Each of these is from the standard MATLAB library or obtained as an output from the *findpeaks* function. All the metrics are calculated for loudness, sharpness and level values of each sound clip.
All these values are then exported and written on to sheet 4 in the same excel workbook containing the loudness, sharpness and level values sheets for every clip. Example of the fourth sheet can be referred from appendix E. The sheet also contains the graphical representation of the signal vs time with the peaks found in the signal. There are three graphs, one each for loudness, sharpness and level.
Once the excel workbook is complete the script also prints a pdf of sheet 4 containing all the calculated values, a graphical representation of the sound signal and other details about the name of the clip, date of recording, channel number on SQuadriga II (Acoustic Head, Channel 3 or Channel 4), etc. Thus, one pdf per S&R clip would provide all the necessary documentation for that particular sound clip.

4.2.3 Result compilation

For every S&R clip, there is one excel workbook and one pdf with several metrics of loudness, sharpness and level. This amount of data is overwhelming to carry out any further analysis of the sounds. Thus, a script was developed which compiled and created a new excel sheet from all the excel workbooks in any given folder. appendix E shows an example of result compilation sheet.

4.3 Limitations

In this section, the challenges faced during the course of study and the ways in which it was approached and tackled is discussed. This includes some of the limiting factors during the tests, and problems occurred in the data processing phases.

4.3.1 Limitations within data collection

As mentioned in section 3.1, the test procedure was determined through an iterative process. During this process, multiple positions for recording devices were tested. For instance, one microphone was fixed and the second was kept close to the source of the sound and the second microphone was moved from one sound source to another. In the initial stages, the acoustic head was bound to the headrest of the front passenger seat as it would replicate the ergonomic position of the passenger. A disturbance in the recording was found as the position of the head would change upon excitation of the car due to the slack found in the retrains. This was due to the non-availability of a large surface area at the back of the headrest to hold the restrains in place. Hence the head was placed on the seat with cushions placed in-between the contact surfaces of the acoustic head and the seat to avoid squeaks produced by the constraints or contact between them.
The initial tests at HPG were conducted at a lower speed to reduce the engine noise

inside the cabin and also to reduce the impact of the engine vibration produced at higher RPM. The signal that was recorded for the KSK4 test rig was preset for a specific speed. This was not favourable as the speeds used in the rig, shown in table 3.3, are much higher than the desired speed. Hence the speed at which the test conducted at HPG had to change and had to be combined with lower speeds as well as the speed available at KSK4. The resultant speeds used at HPG can be seen in table 3.1. The hybrid SUV which was considered for the test had already clocked over 25,000 kilometers on the odometer. The brake pads on the car were worn out in the car due to which it was producing a squeak each time the brakes were applied which would also be recorded by the microphones inside the car. Due to this issue, all the tests at HPG had to be repeated for this car with the installation of new brake pads.
During the research study, there was access to only one of the 4 poster rig (KSK4) at Volvo Cars Corporation. The rig was mostly occupied to rectify production issues or test new cars. Due to these reasons, availability of the test rig at the desired time was not possible. As the time at KSK4 was limited, few of the tests had to be omitted. When the car is mounted onto the KSK4 rig, the tyres are in direct contact with the plate on the hydraulic piston. When the rig is excited with high-frequency signals, the wheels used to get displaced from the previous position. During this process, the contact between the tyre and the plate used to produce squeaks which are picked up by the microphones in the cabin. A Large number of sound clips had to be discarded due to the presence of the squeaks in them. This problem could not be resolved throughout the research study which resulted in loss of valuable data.
As the IP rig is used for individual components, removal of parts from the same car became challenging. The initial plan was to test the instrument panel of the hybrid SUV in the IP rig. But due to technical difficulties, the panel was unable to remove in time. Due to this, the instrument panel of the SUV was chosen for the test. To simulate the same sturdiness of the parts in the IP rig as it is seen in the car, a fixture is used to hold the parts in place. During the test of the door of an SUV, the fixture did not have the structural stability required to hold the door in place as it caused a lot of vibration in the door. Upon excitation, the fixture itself produced noise which masked all the noises from the door. As a result, the data recording from that test becomes unusable. This problem was fixed after multiple iterations of tests but took more time than scheduled which in-turn increased cost and time spent at the rig.

4.3.2 Limitations within data processing

The amount of data collected at HPG was large compared to other test methods. This is because the speeds were not limited at HPG and the test speeds were more in number as seen in table 3.1. There were three repetitions done - for data consistency - for at least two of the speeds in each of the tracks. And all the track recording was heard three times, once for the head recording, once for each of the microphones. This resulted in an enormous database of sounds, which, due to the limited time available for the thesis period this was not processed entirely. Only the speeds common to all three test methods were taken into consideration for the processing. ArtemiS Suite is limited to exporting the values to excel workbook one sound-clip at a time, with loudness, sharpness and sound level in three separate sheets. Thus every clip had to be individually exported and then processed at once in MATLAB. The MATLAB script written for this thesis was heavy on computer RAM and often took around six to ten hours for each car. All this unintended time expense could have been planned better.

5

Results and Discussion

This chapters deals with the results and discussion about the objectives achieved during the thesis period. Each section describes the set objectives individually.

5.1 Sound database and categorisation

At the end of the clipping process, the total number of clips amounted to be 1640 in HPG, 682 in KSK4 and 950 in IP rig which includes all cars and tracks at room temperature.
Below table 5.1 and table 5.2 gives a summary of the entire sound database of squeak and rattles measured during the thesis study for all cars in all four tracks at room temperature conditions.

Tracks	HPG	KSK4	IP Rig
Comfort Track	1026	267	264
Country Road Track 1	154	131	150
Country Road Track 2	131	146	214
Durability Track	319	127	285

Table 5.1: Number of rattles found for each test methods on each of the test track

Tracks	HPG	KSK4	IP Rig
Comfort Track	9	2	1
Country Road Track 1	0	0	1
Country Road Track 2	0	0	0
Durability Track	8	1	0

Table 5.2: Number of squeaks found for each test methods on each of the test track

5.2 Comparison of test methods

The second objective of the thesis study was to compare the outcomes from the three test methods of S&R tests. Each of these have certain aspects which make them better, or convenient or both. But also suffer a few drawbacks. With sound clips and their characteristics from all three test methods performed under various conditions, it could be seen how the sound clips behave with respect to their properties in different ambient conditions, test method and drive mode.
Before discussing the sound clips' properties it is important to know the input excitation signal characteristics of all three test methods.

5.2.1 Comparison of excitation frequency

The idea behind using a test rig over the actual full vehicle test at HPG is for the flexibility it provides to test anytime and for the control over the test conditions. It becomes important to have the same excitation frequency at the rigs as measured at HPG tests. The fig. 5.1 shows the data from the accelerometer in Z direction which was placed at the seat rail of the front passenger seat. It is clear that the signals recorded at KSK 4 test is not the same as it was in the HPG test. Even though the trend is followed for all the rigs, there is a difference found in the absolute values of the excitation frequency. These output values were recorded on the hybrid SUV for comparison purpose. This is so, because the input signals for the KSK 4 test rig was pre-recorded with hybrid SUV and the same signals were used for other cars as well for testing.
Since the signal from comfort track deviates more than other tracks, it was chosen for further discussion. The fig. 5.2 gives a comparison of the signal for the same track in different test methods for comfort track. Even though the absolute value varies, the same trend is followed until 40 Hz after which there are multiple peaks found at HPG test spanning up-to a 1000 Hz but it fails to show on the input signal from the KSK 4 or the IP rig test. This is due to the manner in which the recording of input signal was done for KSK4 test rig. The hybrid SUV was mounted with several accelerometers distributed through out the body. Since the tyres are the first member to be excited by the unevenness, the closest member where the accelerometer could be mounted was close to the wishbone. This input signal does not included the losses from the tyre and the suspension before the signal being transferred to the body. This becomes hard to replicate in the rig since the body is stationary and only actuated in the Z direction. Another observation is that the excitation frequency above 40 Hz is not kept the same, this is due to the sudden change which might occur during the test and test rig might not be able to handle the signal above 50 Hz.
The fig. 5.3 shows better visual on how the input signal varies in each of the test methods on comfort track alone. It can be seen that even though the input signals for IP rig was taken from KSK 4 test, there is a observable difference in the input signals and needs to be investigated further for IP rig to provide similar results as KSK 4.

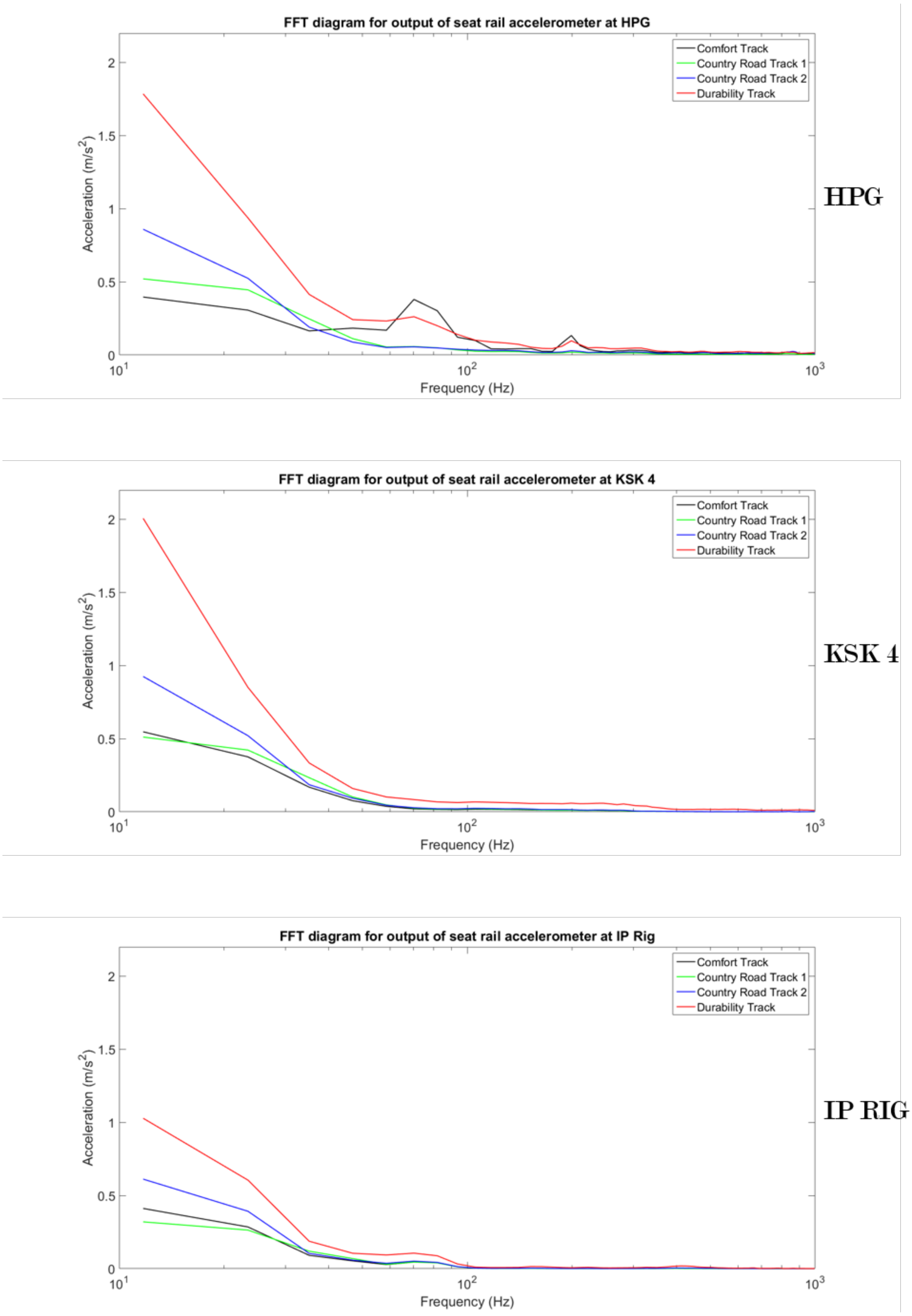


Figure 5.1: Comparison of accelerometer output for each test methods at all track

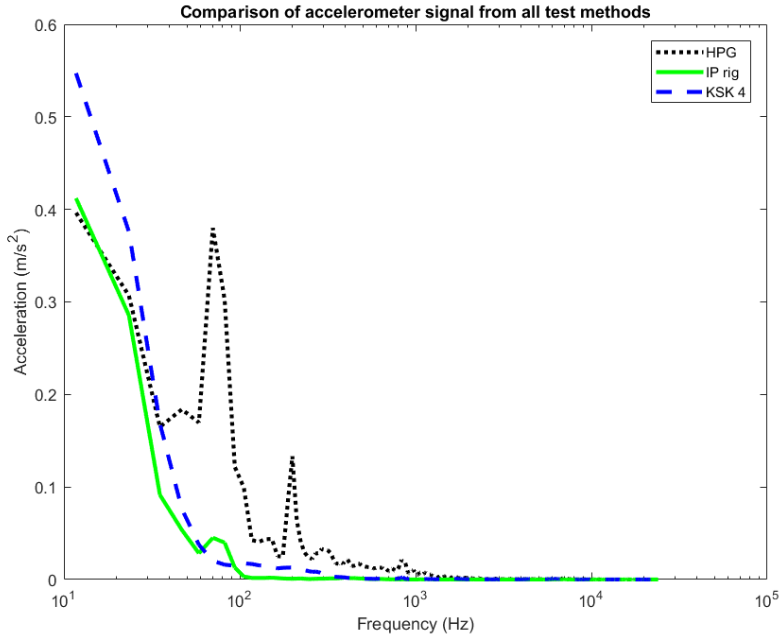


Figure 5.2: Comparison of accelerometer (placed in the instrument panel) signal for all the test methods at comfort track

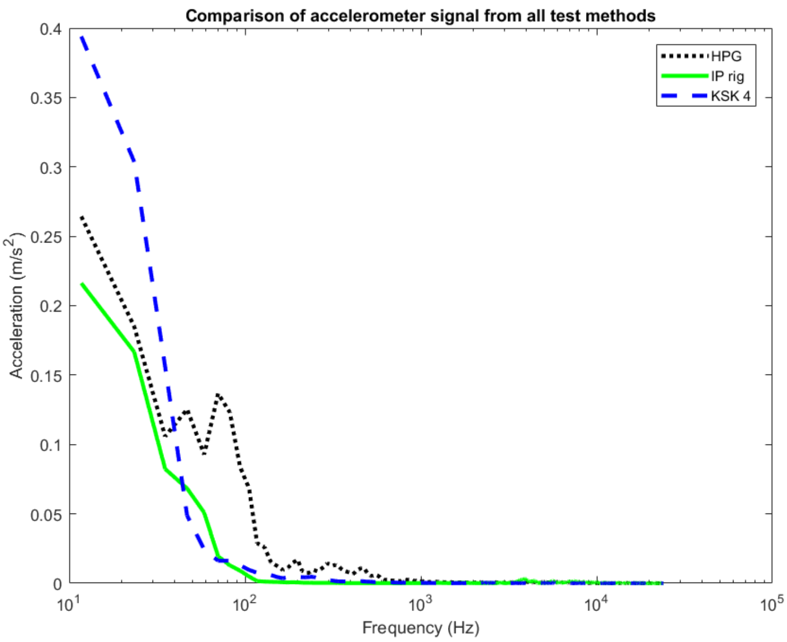


Figure 5.3: Comparison of deviation in the accelerometer (placed in the instrument panel) signal for comfort track

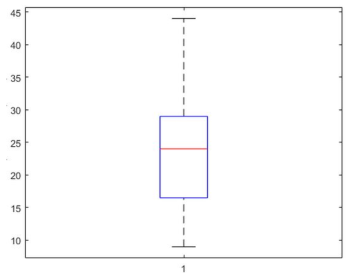
5.2.2 Results from room temperature measurements

The data collected from the tests was enormous and to display this big set of data, it is convenient to use graphical representation. Thus two methods of graphical representation were chosen, box-plots and scatter plots.

5.2.2.1 Box-plots

Box plots are a type of plots which shows how the data has been spread and where the median of the distribution is situated at. It is a convenient tool to analyse a huge set of distributed data. As seen in section 5.2.2.1 the y-axis represents the values and x-axis denotes the category of the data being presented.

The box hold the values from Quartile 1 to Quartile 3 of the normally distributed data. By default it covers +/- 2.7σ of a normal distribution, but since the requirement was to display +/- 3σ the whisker length from the default value of 1 was changed to 1.7239 to accommodate the 6σ values. The distribution of values beyond Quartile 1 and 3 are shown as dashed lines on either side of the box-plot.



In this particular case of data collected for this study, there are some outliers found in the data distribution. These are represented outside the dashed lines as red stars located with respect to the value they represent on y-axis.

5.2.2.2 Scatter plots

Scatter plots are 2 dimensional and 3 dimensional graphical representations of a data set, with 2 or 3 axis each representing a category or a certain metric and each mark/dot on this chart represents a data point corresponding to the axes.

5.2.2.3 Conventions followed for graphical representation of the collected data

The tests were carried out for all three test methods at room temperature and this contributes to major part of the results. Thus, the same set of sound clips collected from HPG, KSK and IP Rig for Loudness and Sharpness is presented in two different ways in box plots. One with respect to the four tracks - Comfort Track, Country Road 1, Country Road 2 and Durability Track- which they were driven in HPG/ or stimulated on KSK4 and IP Rig and other with respect to the cars and components tested. The plots were generated for loudness and sharpness. Below are the few conventions which have been kept consistent for all plots.

- All the axes lengths are kept consistent to each other for easier comparison of the results.
- The colours representing tracks have been maintained the same for box and scatter plots, i.e. Comfort Track represented in black, Country Road 1 as green, Country Road 2 as blue and Durability Track as red.

- All the box plots representing the cars (or component belonging to a respective car) have been colour coded as follows. SUV as magenta, SUV2 as red, estate as green, hybrid SUV when driven with electric engine as blue and with combustion engine as cyan.
- The over all mean value of the population is represented by a red star inside the box, and the tiny horizontal line gives the median value of the population inside the box.
- For loudness box-plots the metrics, crest factor and average relative prominence, were scaled up by 3 and 5 respectively and max peak value was halved. And for sharpness box-plots the crest factor and average relative prominence were scaled up by 3.

5.2.2.4 Comparison of test results from each of the test methods

The plots below in fig. 5.4 and fig. 5.5 show how the 7 metrics - 95^{th} Percentile, Mean, Crest Factor, Number of Peaks per second, Average Peak Value, Maximum Peak Value and Average Relative Prominence – of all the S&R clips, vary with respect to the track excitation.
Each metric has a set of four boxes representing the tracks, Comfort Track, Country Road 1, Country Road 2 and Durability Track. Every Box shows how the values of that particular metric of all the S&R clips applicable to that track, behave when the car is imposed with excitation on these four tracks.
It can be seen from fig. 5.4 and fig. 5.5 that the values of the metrics from the three test methods seem to move with a same trend over all. But with few noticeable points.

- For Loudness, durability track has the highest 95^{th} Percentile, Mean value, Number of Peaks per second, Average Peak Value and Maximum Peak Value in all three methods, which implies the noises are heard the loudest in the Durability Track. Numerically, 95^{th} Percentile of loudness decreases by 35% at KSK rig and 37% at IP rig compared to HPG. While for Sharpness the case seems the same at HPG and IP Rig but not in KSK4. The Comfort Track produced more higher 95^{th} Percentile Value in KSK4, i.e. 95^{th} Percentile of sharpness increases by 22% at KSK rig and 45% at IP rig compared to HPG.

- The 95^{th} Percentile values (Loudness Level) in IP Rig is seen to be the highest with 35 sone. These outliers' values beyond quartile 3 are present in all three test methods but are particularly more in number in IP Rig.

- Number of Peaks per second both in Loudness and Sharpness seem to follow similar trend in HPG and IP Rig – more peaks in Country Track 1 in comparison to Country Track 2- but is opposite in KSK4. Numerically,
- A general trend of higher mean values than the median values (represented by red star and tiny horizontal bar in the boxes) shows that there is a positive skewness observed in Number of peaks in both loudness and sharpness in all the tracks.

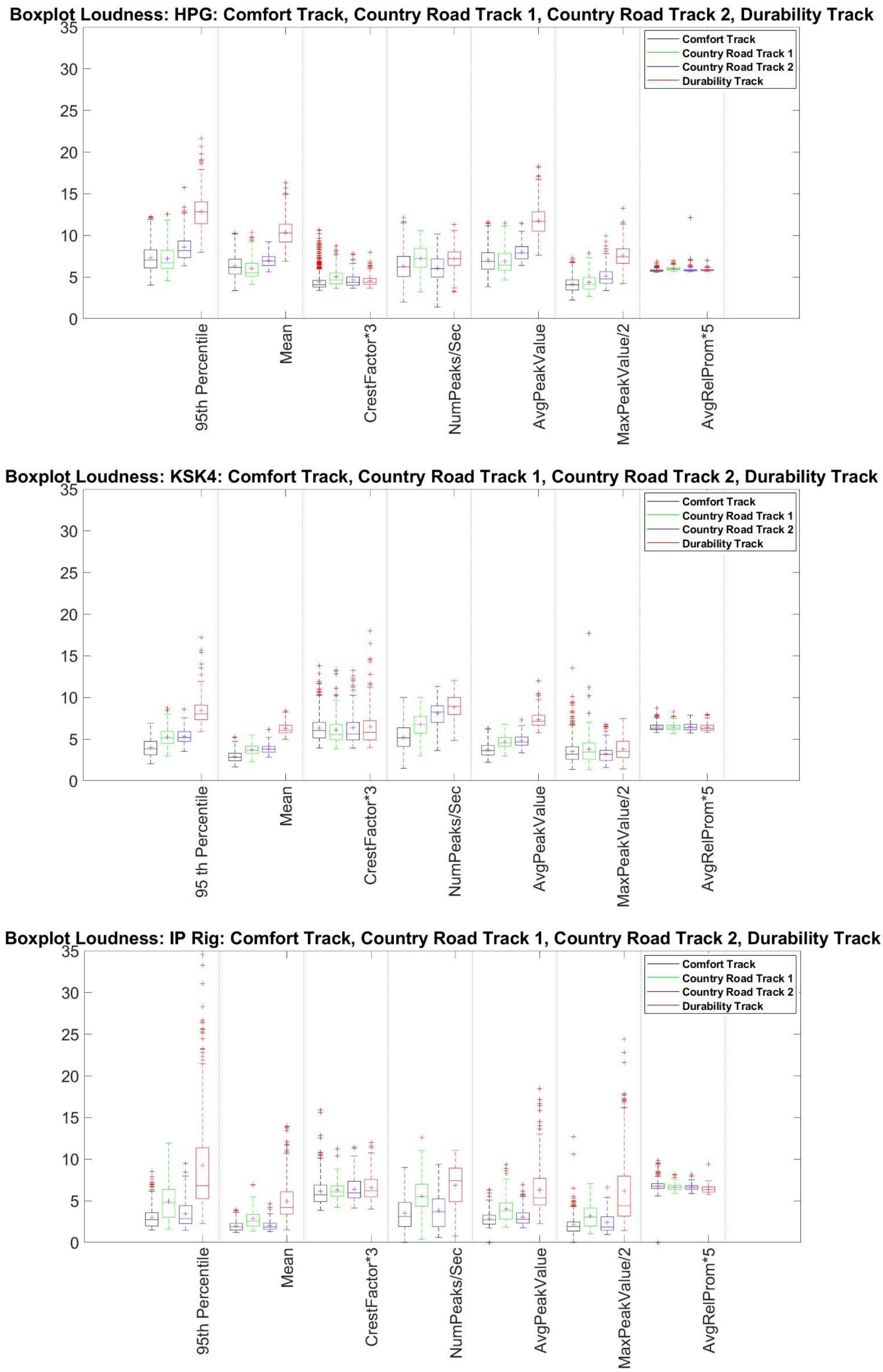


Figure 5.4: Box-plots for Loudness on Tracks: Comfort Track, Country Road Track 1, Country Road Track 2, Durability Track

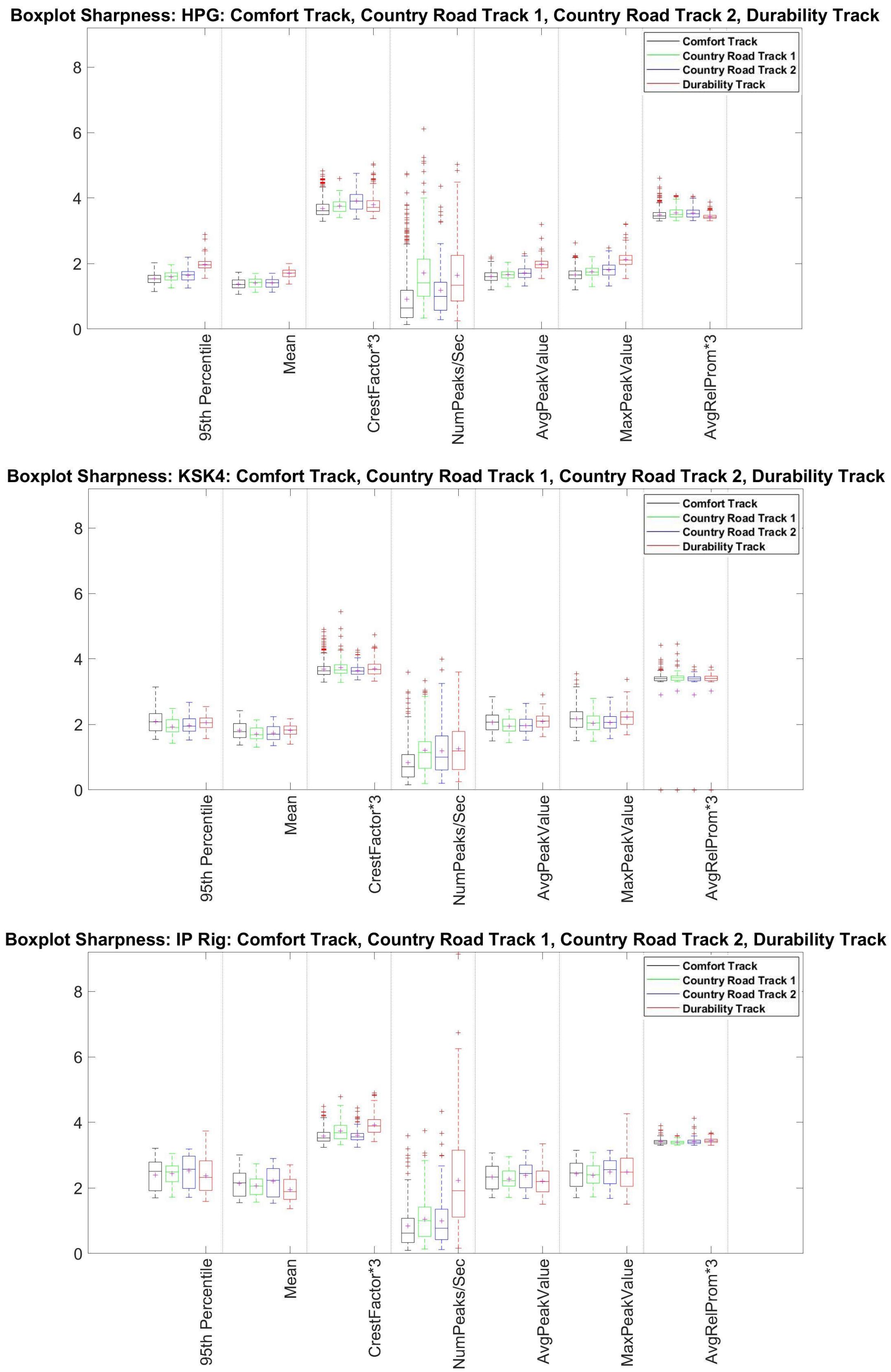


Figure 5.5: Box-plots for Sharpness on Tracks: Comfort Track, Country Road Track 1, Country Road Track 2, Durability Track

Similar to that of box plots, scatter plots were plotted for the metrics which varied from one result to another and did not follow any trend. The metrics chosen for the scatter plots were 95^{th} percentile, number of peaks, crest factor, and average relative prominence.

The fig. 5.6 shows a comparison between all the test methods with respect to loudness scatter plot between 95^{th} percentile and average relative prominence. Even though the trend between the KSK 4 and IP rig is the same, it does not follow the trend of results obtained from the HPG test. This could be due to the variation in the input signal found. There is a shift seen in the trend of the country road track 2 at IP rig. It is seen that the 95^{th} vales for that track has reduced and overlaps more with the results from comfort track. As the results from each of the test tracks are clustered and distinguishable, if a sample of particular property is needed, it becomes easy to choose the track in which the test needs to be carried out.

The fig. 5.7 shows a comparison between all the test methods with respect to loudness scatter plot between number of peaks and crest factor. This comparison shows that data is normally distributed for all the tracks. Hence proving that these four chosen tracks are sufficient to obtain all types of S&R data. The results from the KSK 4 seems less clustered, due to loss of data during testing. This was due to the squeaks produced from the tyres and the plates on the hydraulic actuators in the rig. This made the data unusable for the result compilation.

The fig. 5.8 shows a comparison between all the test methods with respect to sharpness scatter plot between 95^{th} percentile and average relative prominence. The 95^{th} percentile of sharpness value is seen to vary from each of the test methods. The reason behind this could be due to the less presence of the background noise at the test rigs and due to less dispersion of sound.

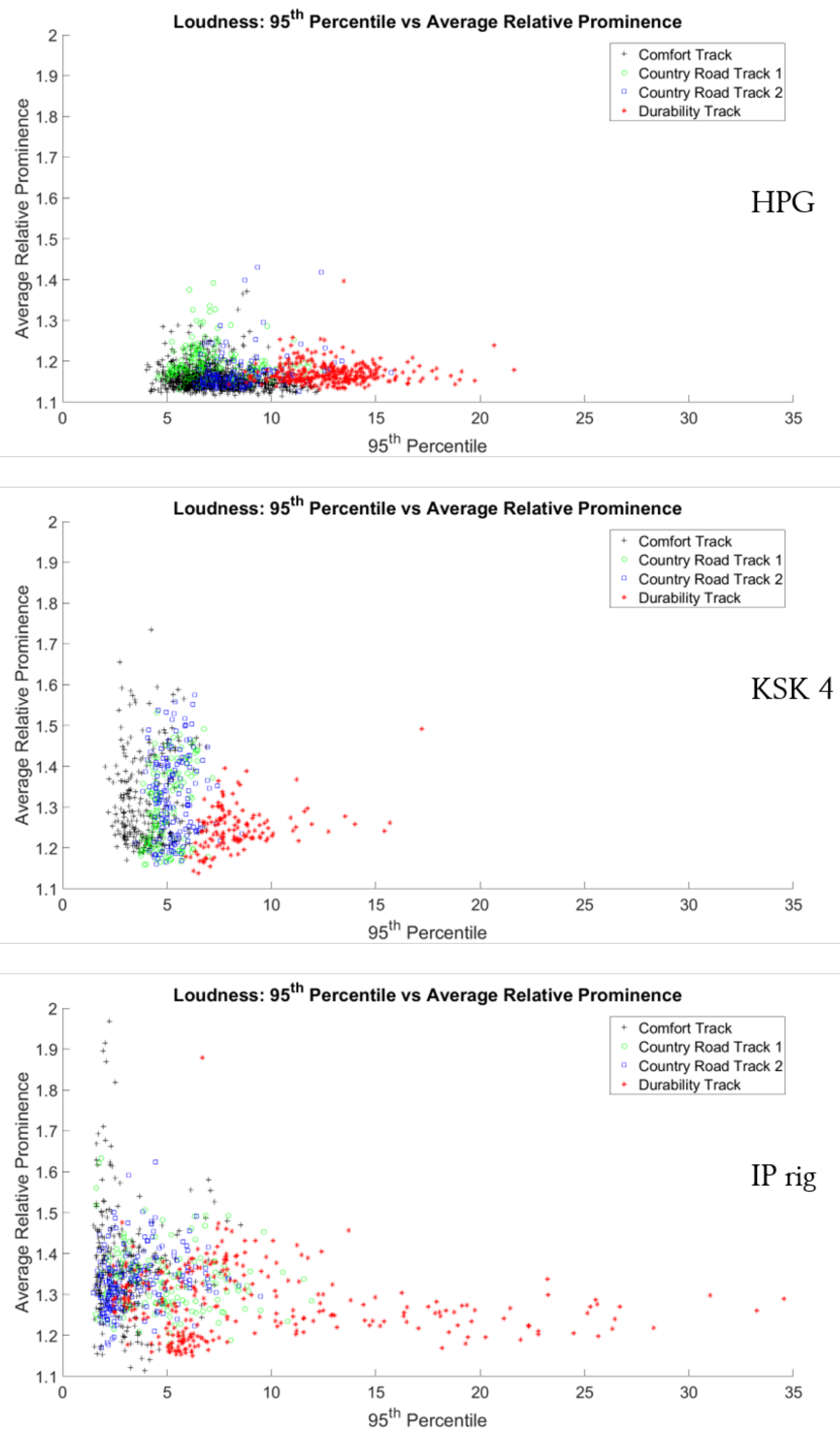


Figure 5.6: Comparison of loudness scatter plots between 95^{th} percentile and average relative prominence between the test rigs

Figure 5.7: Comparison of loudness scatter plots between number of peaks and crest factor between the test rigs

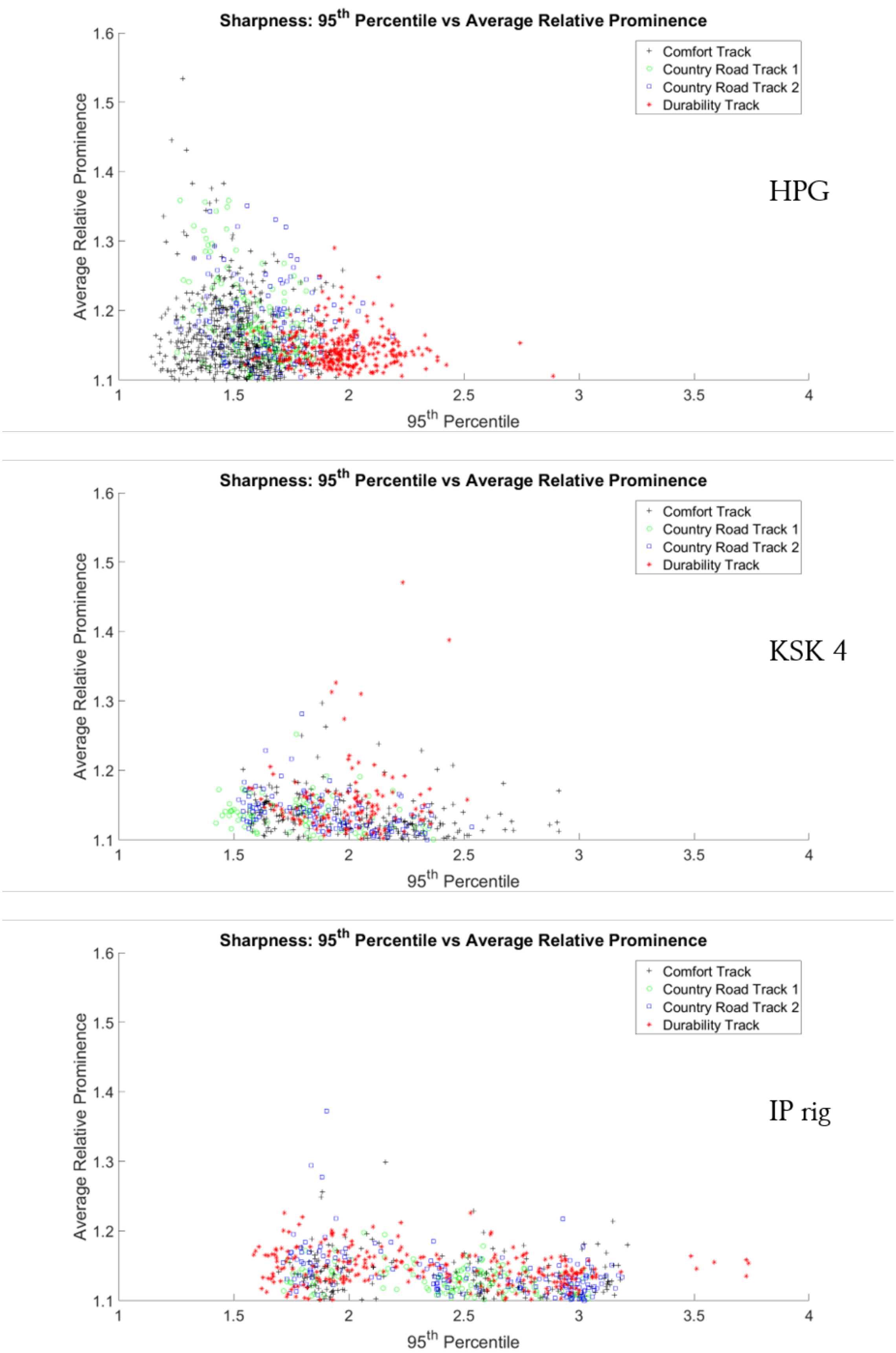


Figure 5.8: Comparison of sharpness scatter plots between 95^{th} percentile and average relative prominence between the test rigs

Thus, it can be observed that, there are metrics which follow certain trend irrespective of test methods, while some metrics are dependent on the track and method used.
Below fig. 5.9 gives an overall trend of how the mean and median values of entire population of the S&R clips for all the seven metrics from all the three methods of testing.

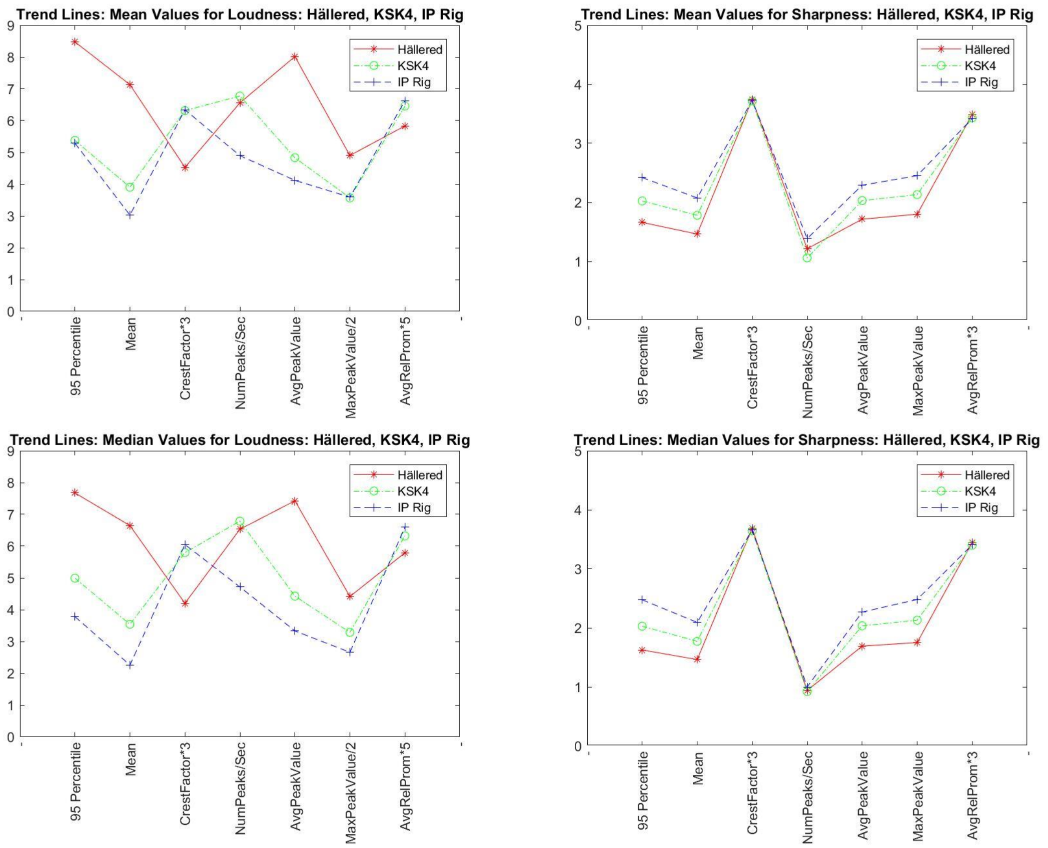


Figure 5.9: Trend Lines: Means and Medians of the all S&R Clips for Loudness and Sharpness at Hällered, KSK4, IP Rig

Results with cars/components as frame of reference
Another perspective of analysing would be with respect to Cars and components and how they behave as a system, in room temperature conditions. This would help to assess which car or component is comparatively better when it comes to S&R.
The S&R metrics of the sound clips obtained from the cars at HPG and KSK4 and the selected components from these cars chosen for IP Rig Test, each can be seen as an individual system and can be compared.
The below fig. 5.10 and fig. 5.11 shows box-plots for Loudness and Sharpness with cars and components as frame of reference.
These plots potentially serve as support to fig. 5.4 and fig. 5.5 to determine which car produced the outliers, and which car or component is accountable for the observed skewness of mean and median values of each of the metric. For example the outliers observed in the Loudness box-plots of IP Rig can be tracked from the below graph that most of the data-points came from the instrument panel of SUV2.

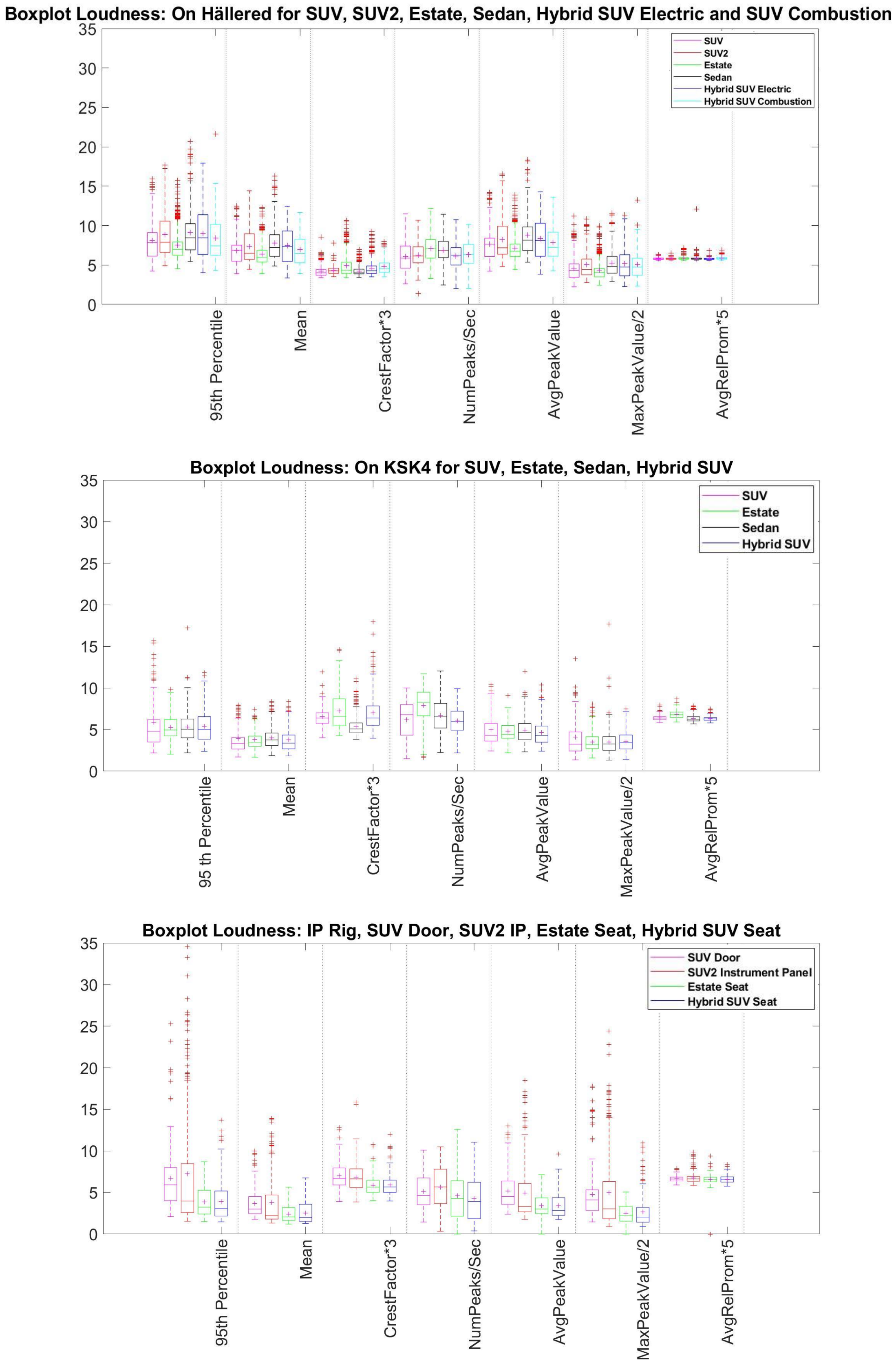


Figure 5.10: Box-plot for Loudness: SUV, SUV2, Estate, Sedan, Hybrid SUV Electric, Hybrid SUV Combustion

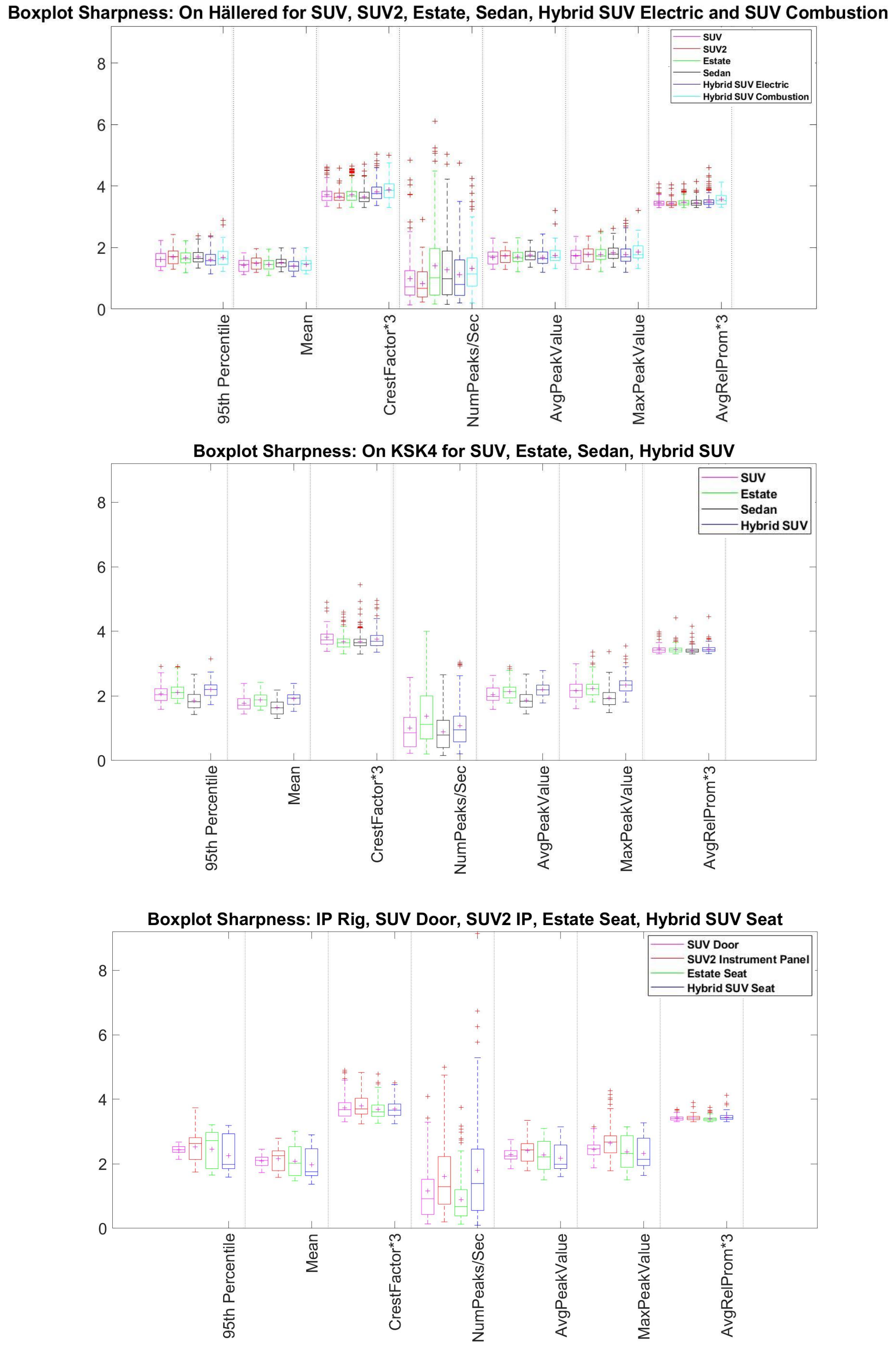


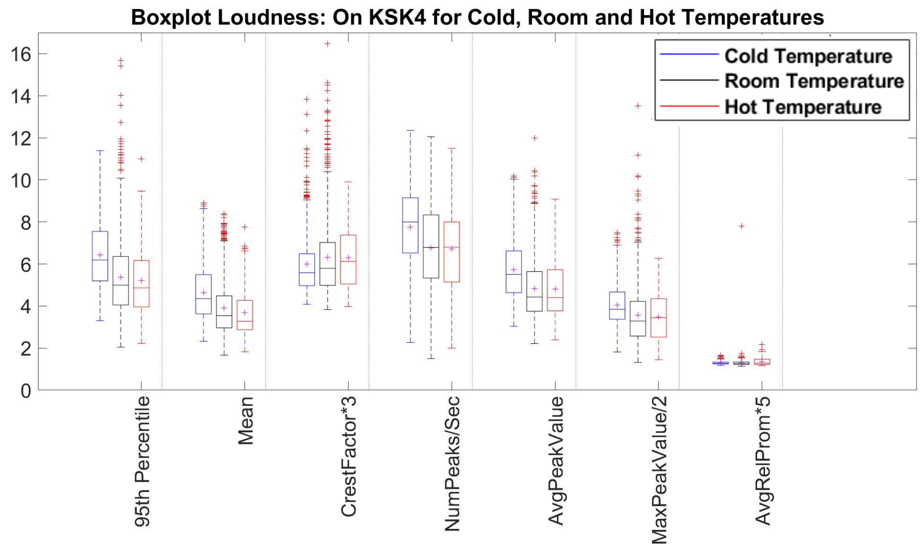
Figure 5.11: Box-plot for Sharpness: SUV, SUV2, Estate, Sedan, Hybrid SUV - electric engine, Hybrid SUV - combustion engine

5.3 Comparison based on temperature conditions

Certain experiments mentioned in section 3.2.6were carried out to understand the effect of temperature on S&R sounds in a car. The subsections below show how the effect of temperature can be observed.

5.3.1 Temperature effect on S&R in KSK4:

To understand the effect of temperature, the cars were tested in three different temperature conditions. Cold temperatures of -5℃and -10℃, room temperature (23℃) and hot temperature of 35℃and 40℃. The below box plots show the effect temperature has on S&R sounds.



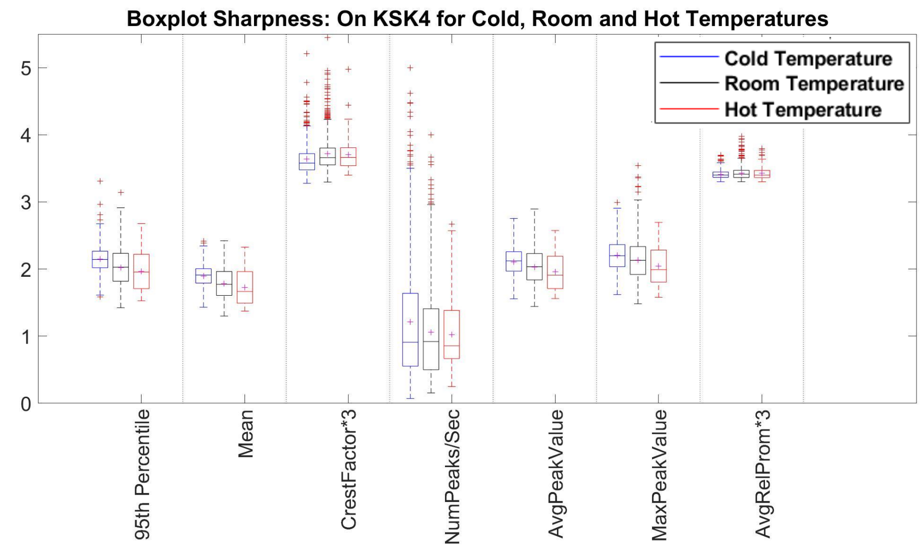


Figure 5.12: Box-plots for Temperature effect on S&R in KSK4 at cold, room and hot temperatures

As seen in fig. 5.12 we see cold temperatures have higher loudness. There is a 21% increase in 95^{th} percentile of loudness and sharpness value also increases by 8%. The number of peaks for loudness is seen to be increased by 14% at cold temperature.

5.3.2 Temperature effect on S&R in IP Rig:

As mentioned in section 3.2.6, in IP Rig, the instrument panel of SUV2 Model was tested for higher temperature - 45°C - to test the affect of temperature on S&R sounds and properties of the clip in-terms of the seven metrics. The instrument panel was already tested for room temperature, and with the S&R clips measured at 45°C, below fig. 5.13 shows the box-plots of the two ambient conditions compared together.

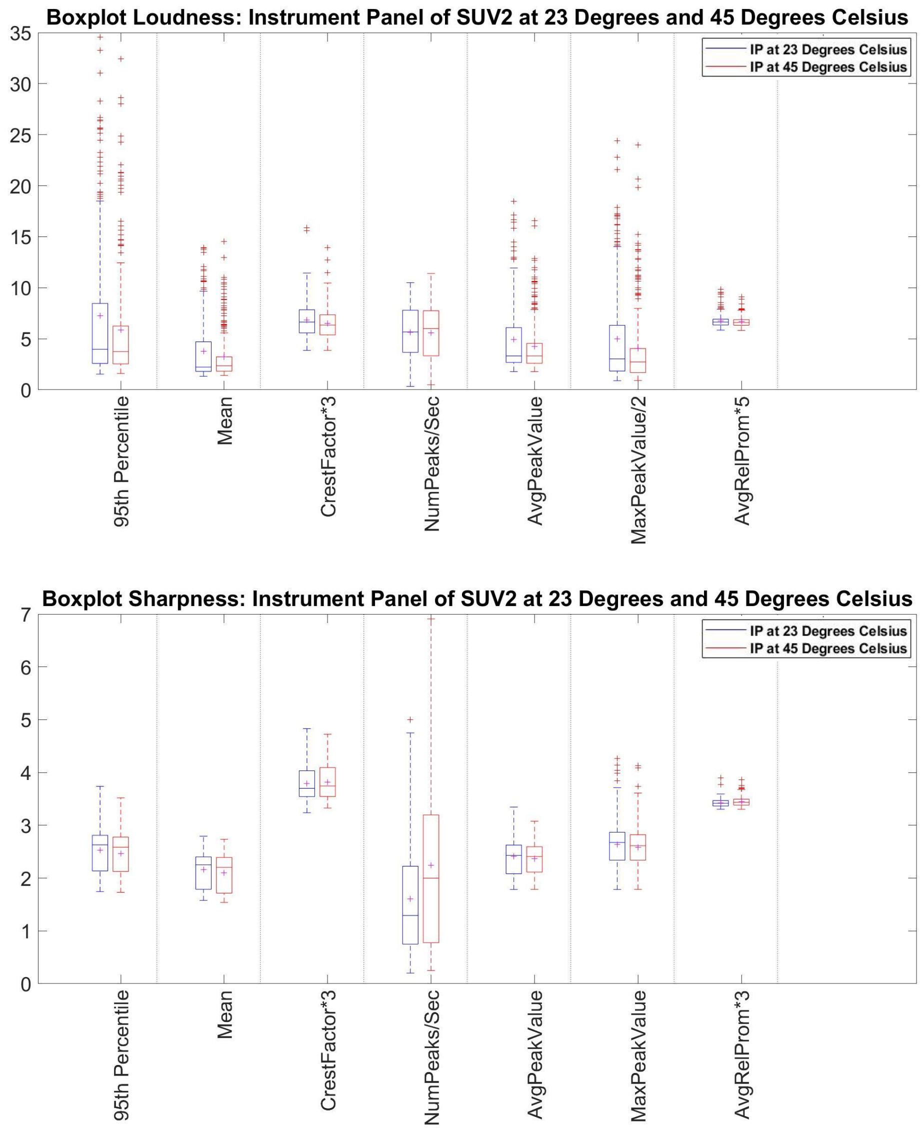


Figure 5.13: Box-plots for Instrument Panel of SUV2 at 23℃and 45℃

Thus, in a general trend of metrics from the plots, it could be said that the Loudness of the sounds is comparatively more in colder temperatures, but sharper in hotter temperatures. The results can also be visualised specifically for few of the metrics in Scatter Plots as show below.

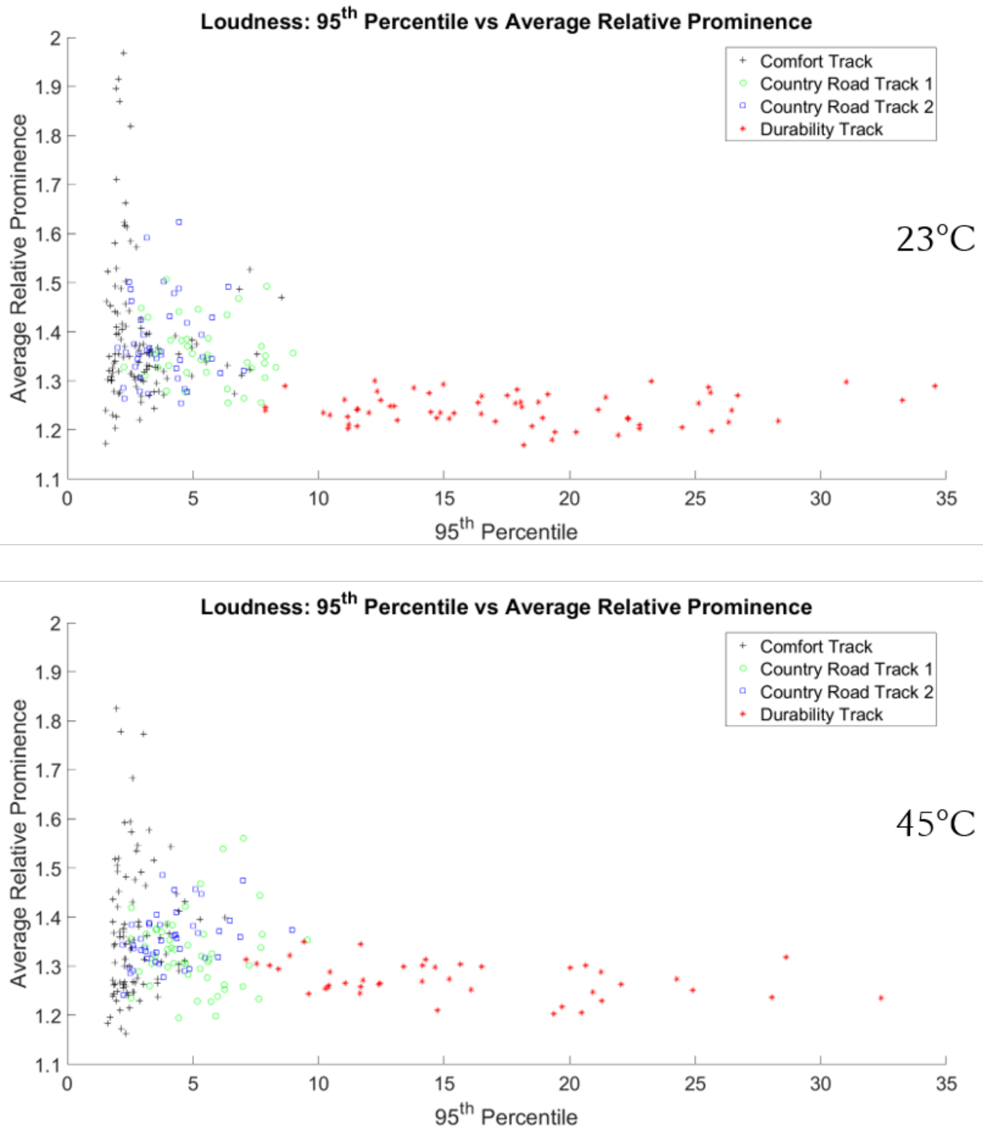


Figure 5.14: Comparison of loudness scatter plots between 95^{th} percentile and average relative prominence for instrument panel at 23°C and 45°C

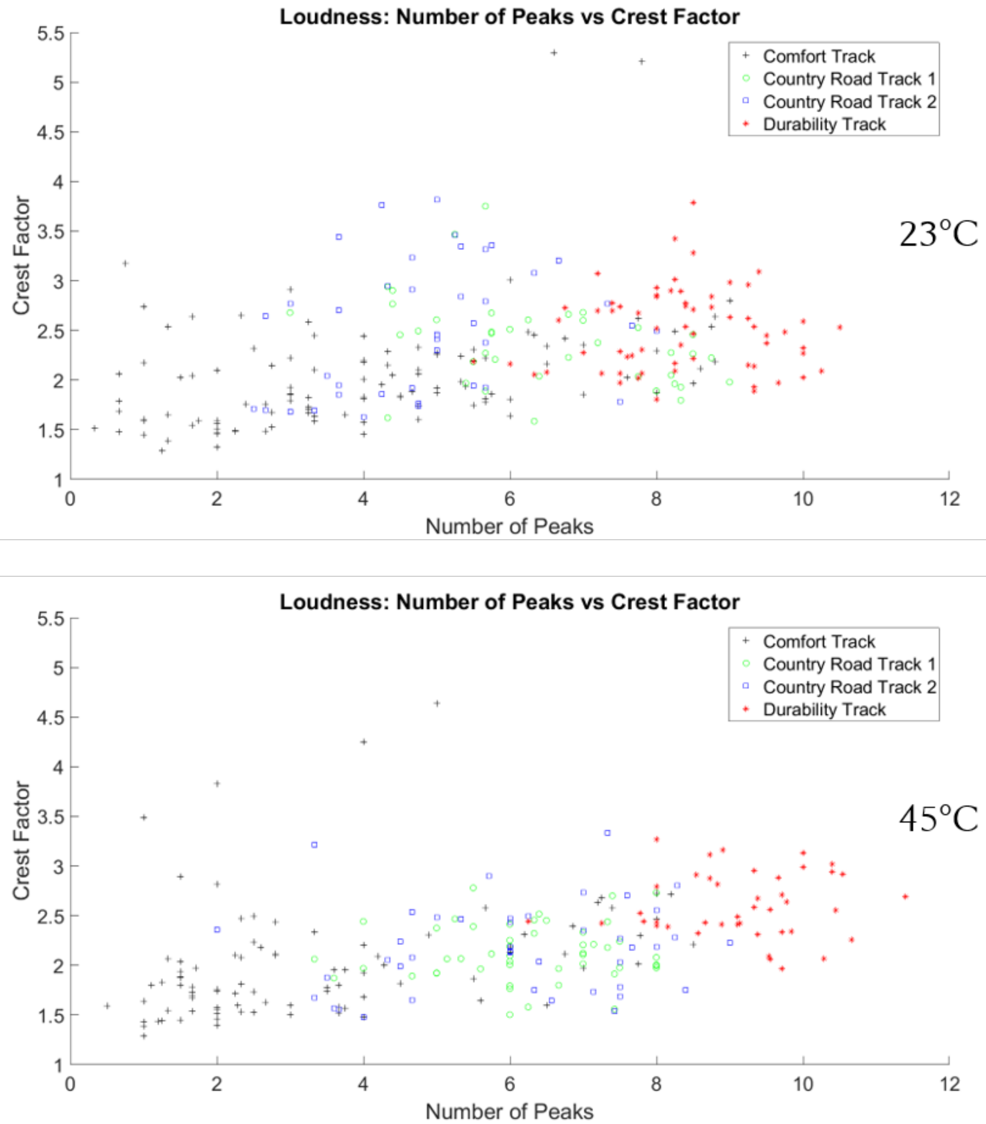


Figure 5.15: Comparison of loudness scatter plots between number of peaks and crest factor for instrument panel at 23°C and 45°C

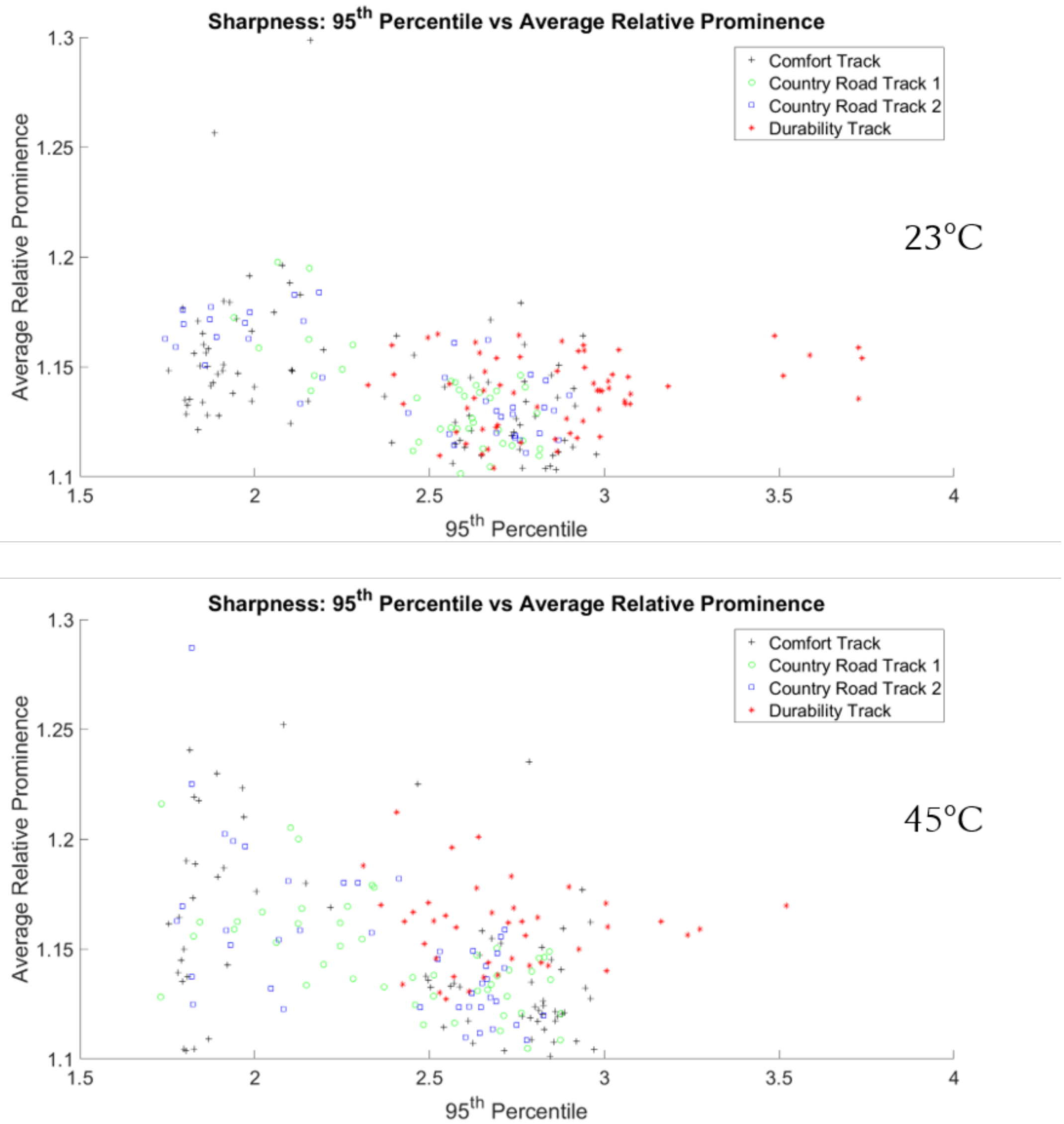


Figure 5.16: Comparison of sharpness scatter plots between 95^{th} percentile and average relative prominence for instrument panel at 23°C and 45°C

With the help of the fig. 5.14, fig. 5.15, and fig. 5.16, it is seen that there is not much change in the results gathered from the instrument panel at room temperature and at 45°C. This could mean that it is not necessary to carry out hot temperature test for individual components. But this needs to backed by more tests specifically concentrating on the effect of temperature change in components at IP rig.

5.4 Comparison of electric engine and combustion engine

While the cars were tested at HPG, the hybrid SUV was driven using electric engine and combustion engine. It was considered as separate system in fig. 5.10 and fig. 5.11. But this also would show how the S&R sounds are impacted with the engine noise.

The filters applied on sounds as discussed in section 4.1 do suppress the background noise, but it cannot take out inherently all the engine noise. And a harsher filter might take away few S&R sounds as well.
To see this effect of engine noise, it was decided to drive the car purely on electric energy. Below box-plots in fig. 5.17 shows the comparison of S&R metrics of loudness and sharpness of hybrid SUV driven with electric engine and combustion engine.

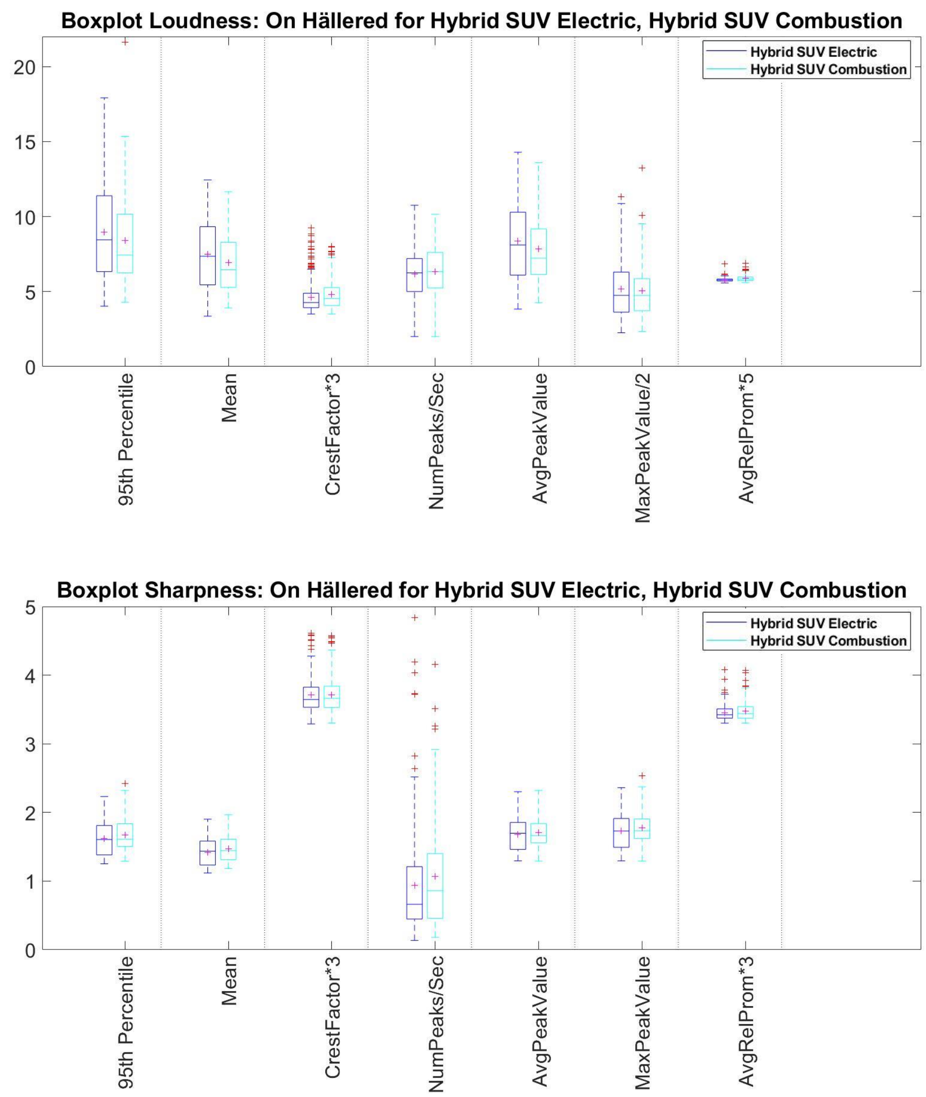


Figure 5.17: Box-plots of HPG clips for Hybrid SUV Electric, Hybrid SUV Combustion

The results can also be visualised specifically with scatter plots as well as shown below.

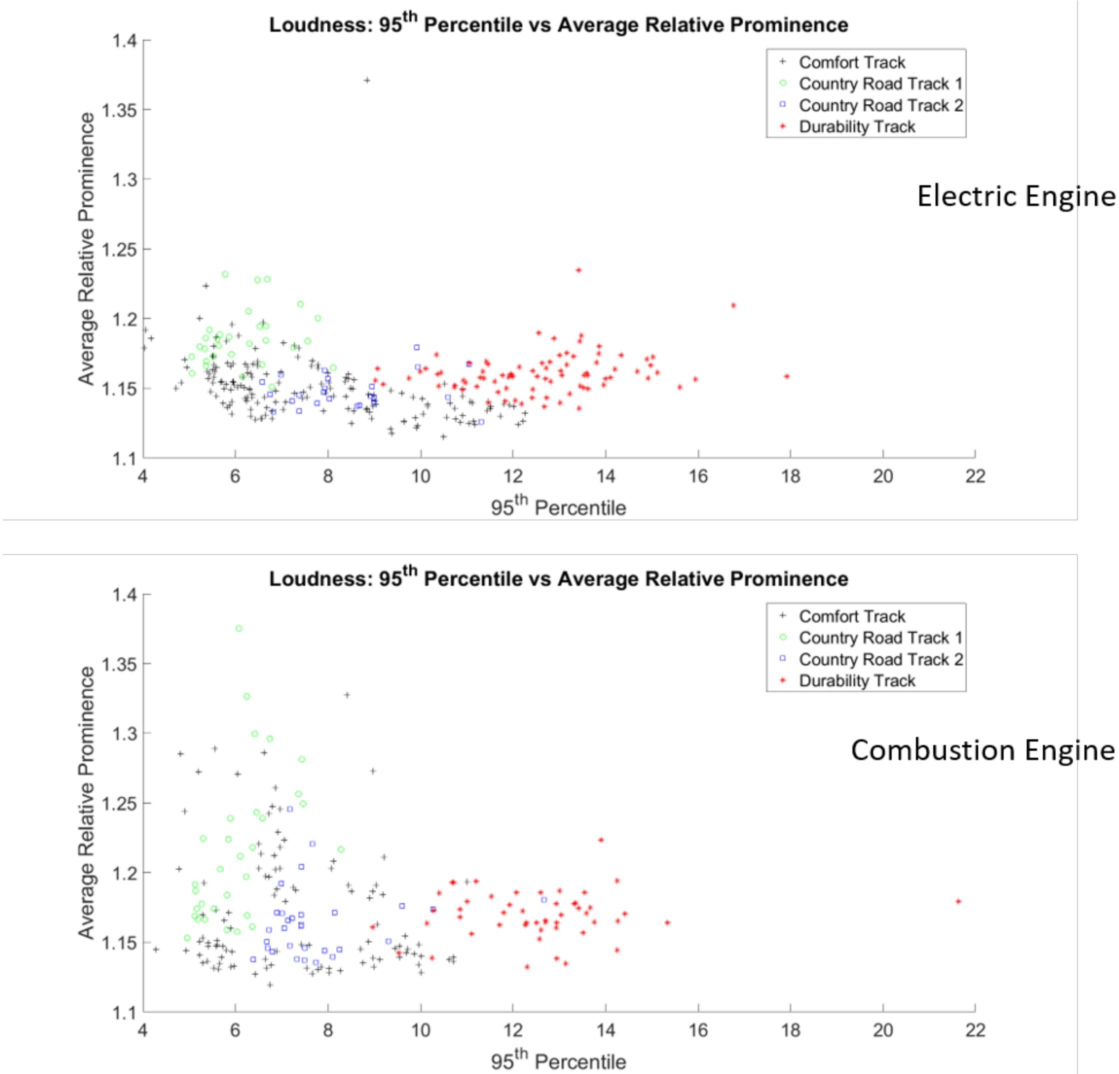
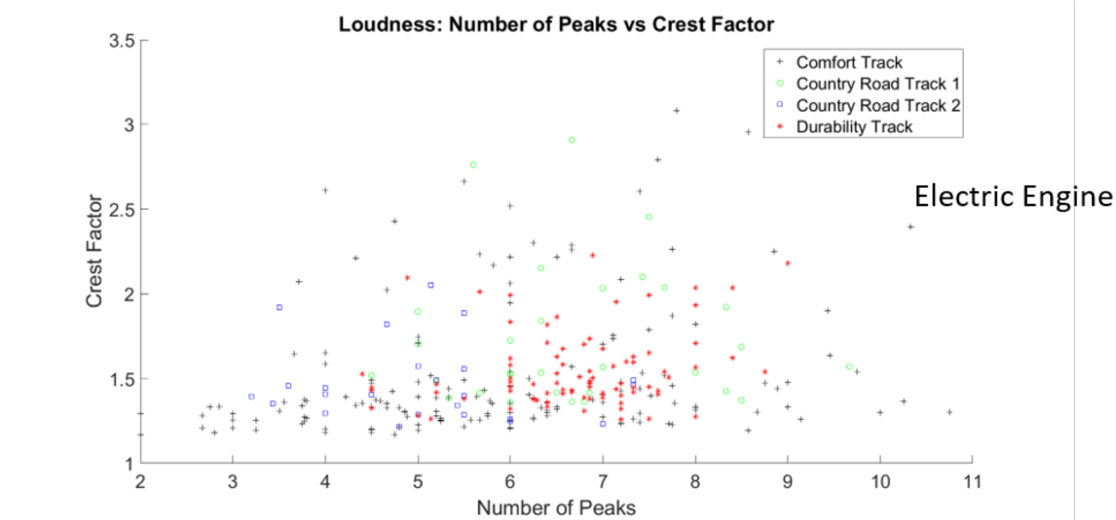


Figure 5.18: Comparison of loudness scatter plots between 95th percentile and average relative prominence for hybrid SUV on electric engine and combustion engine



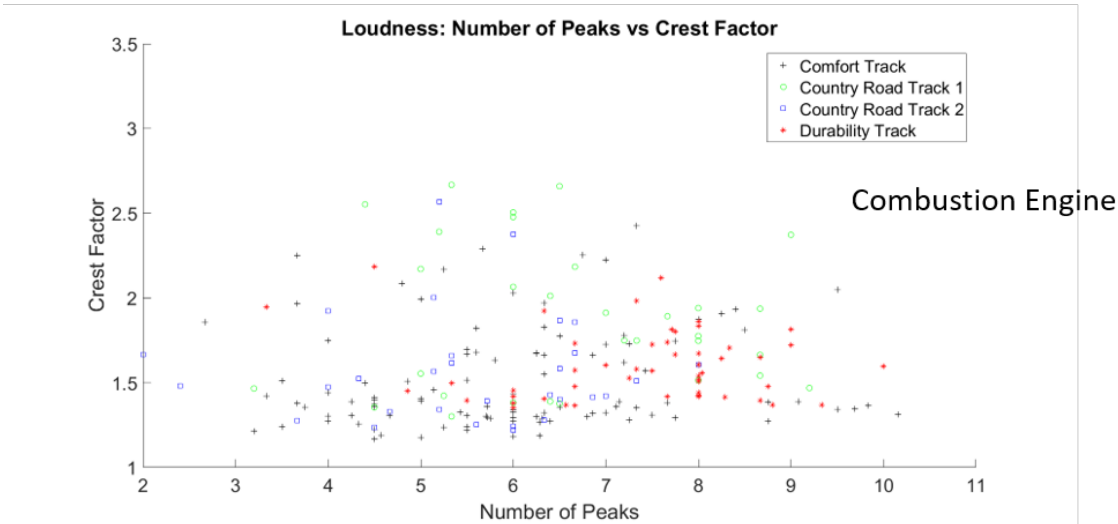
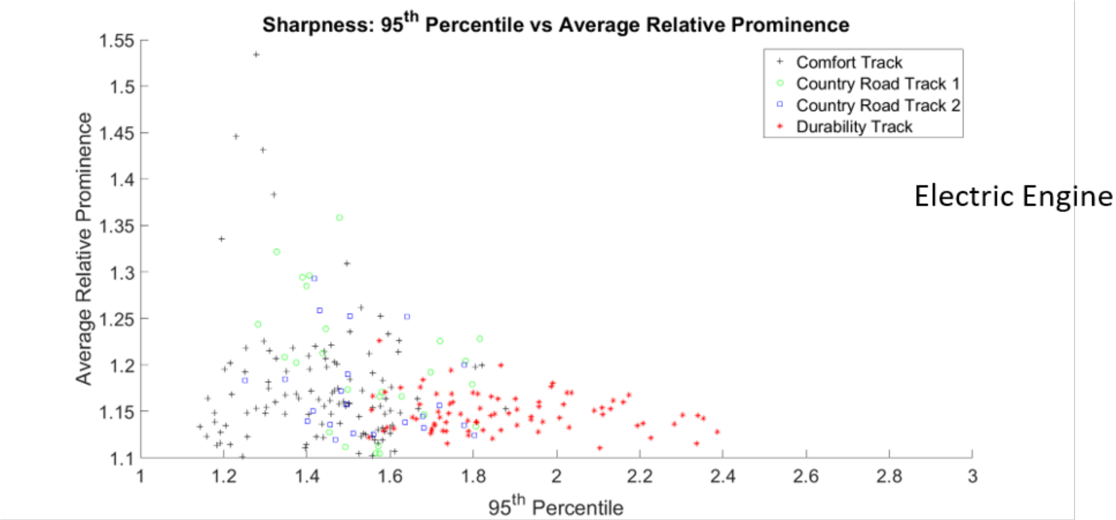


Figure 5.19: Comparison of loudness scatter plots between number of peaks and crest factor for hybrid SUV on electric engine and combustion engine



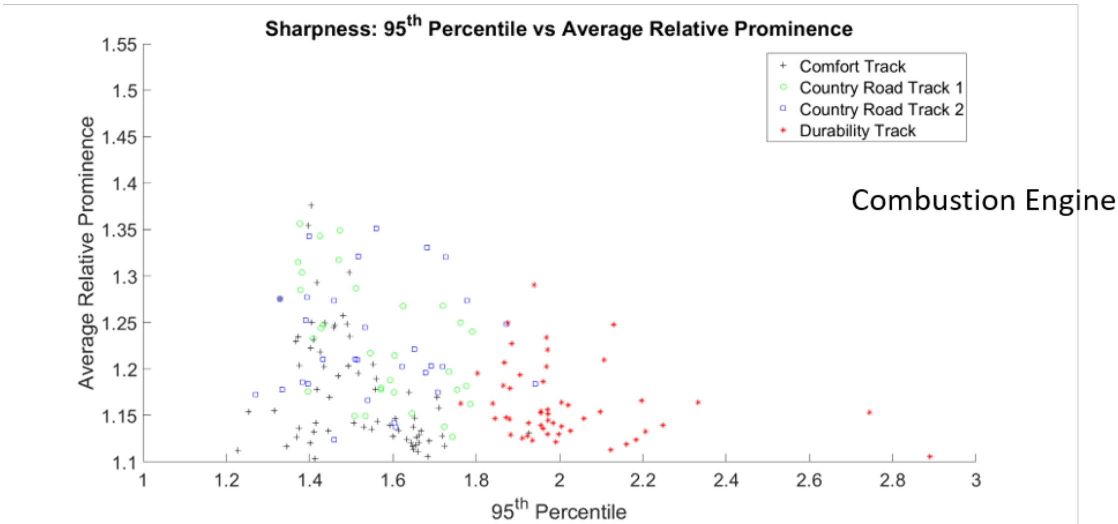


Figure 5.20: Comparison of sharpness scatter plots between 95^{th} percentile and average relative prominence for hybrid SUV on electric engine and combustion engine

Track name	Parameter	Result value
Comfort Track	Number of rattle	102
	Average subjective rating	1.4
Country Road Track 1	Number of rattle	32
	Average subjective rating	1.22
Country Road Track 2	Number of rattle	30
	Average subjective rating	1.17
Durability Track	Number of rattle	50
	Average subjective rating	1.76

Table 5.3: Subjective rating values for combustion engine on hybrid SUV

Track name	Parameter	Result value
Comfort Track	Number of rattle	164
	Average subjective rating	1.49
Country Road Track 1	Number of rattle	30
	Average subjective rating	1.1
Country Road Track 2	Number of rattle	24
	Average subjective rating	1.08
Durability Track	Number of rattle	84
	Average subjective rating	1.67

Table 5.4: Subjective rating values for electric engine on hybrid SUV

It is seen that, in a general trend of metrics from the plots, the loudness of the sounds is comparatively more when driven with electric engine, but sharper when driven with combustion engine. Engine noise could arguably be the reason trend seen in loudness. With lesser ambience noise inside the cabin, S&R could be more pronounced and observably annoying. This can also be backed by the subjective rating provided in the table 5.3 and table 5.4. The subjective rating for comfort track was higher when driven with electric engine while the rest were high when driven with combustion engine.

5.5 Comparison of acoustical properties of rattles and squeaks

The data collected shows that the number of rattles found, outnumber the number of squeaks. To get an overall picture on how rattles and squeaks found differ, the following plots can be helpful to visualise. The data used is from from HPG for all cars.

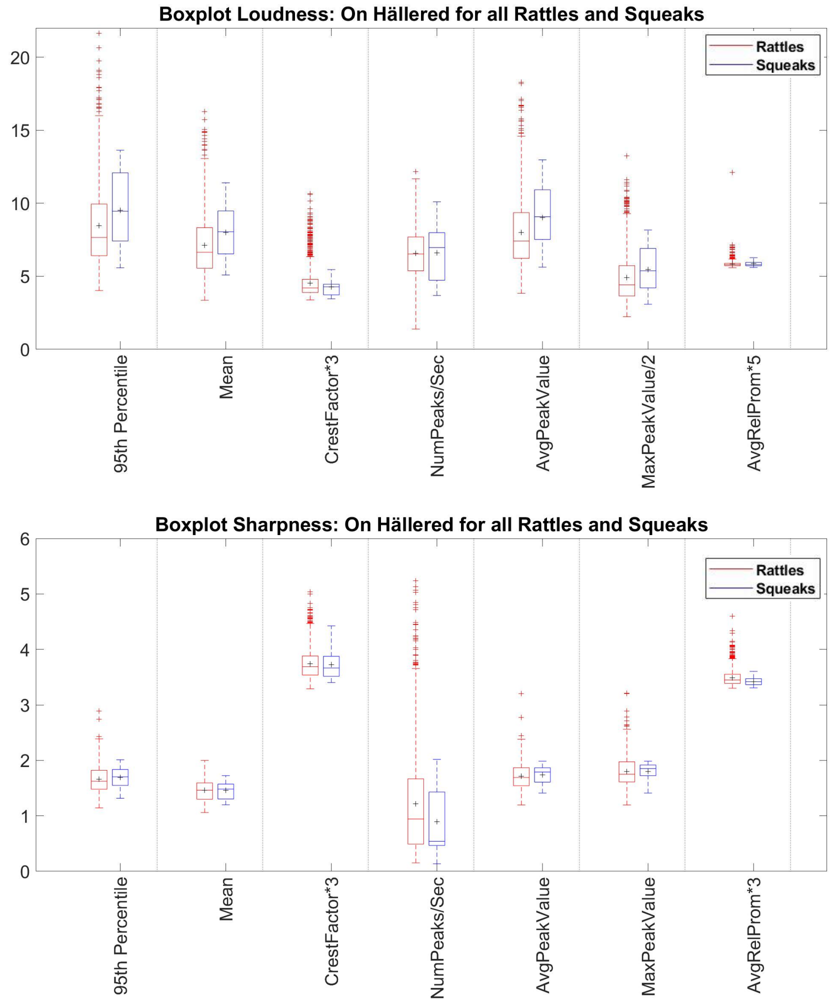


Figure 5.21: Box-plots of HPG clips for rattles and squeaks

The results can also be visualised specifically with scatter plots as well as shown below.

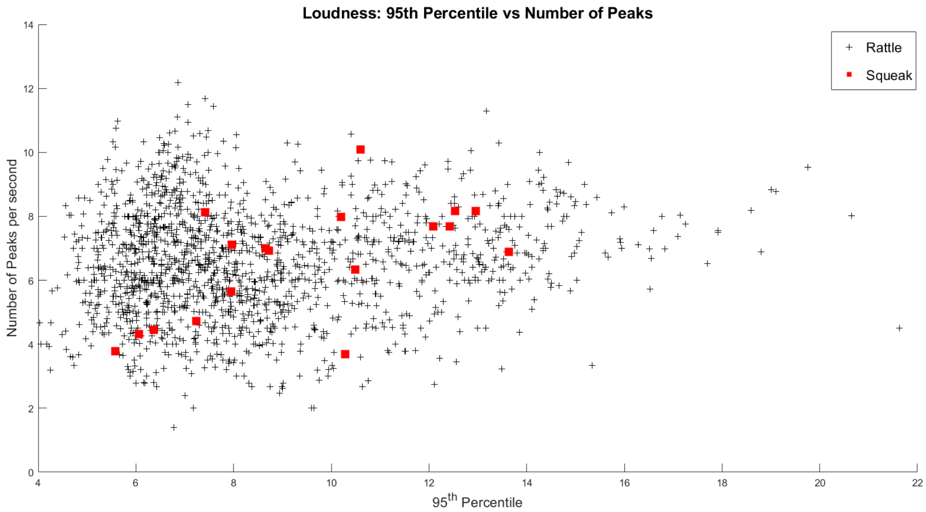


Figure 5.22: Scatter plot of HPG clips for rattles and squeaks

The fig. 5.22 showcases how the properties of the S&R vary with respect to the 95^{th} percentile and number of peaks. Just like the rattles, the squeak also spread equally and does not portray any specific trend or characteristics with respect to the chosen psycho-acoustic property.

6
Conclusion

The scope of the thesis was to create a database for S&R sounds to effectively facilitate in achieving the upfront engineering activities to address the S&R issue in the cars produced at Volvo Cars Corporation. With a total of more than 3000 collected S&R sound clips, the sound database created during the thesis period would serve as the first step in this process. From this study, it can be seen, how each of the test methods available to assess S&R at Volvo Cars Corporation shapes the obtained results, from the comparison study of the three test methods – HPG, KSK4 and IP Rig – made during the thesis period.
The results point out that there are several advantages with testing of cars on the track - which is closest to the real-life scenario - but the engine noise might mask few of the S&R sounds which may lead to loss of data-points in the frequency range of the engine noise.
With electrification of cars it is important to consider lower range of S&R loudness levels too. The track testing can give accurate results, but it is highly dependent on weather conditions and other external factors which cannot be controlled. And accessibility of test tracks is a drawback too.
All these drawbacks from track testing make the test rigs, KSK4 and IP Rig feasible and convenient. The ambient conditions - temperature, humidity and sun light control - can be controlled with KSK4. And IP rig can test the sub-systems individually to evaluate component-wise issues of S&R. But, as seen in the study, the test rigs have excitation frequency which does not completely match the road test excitation. Thus it cannot be distinctively said that the excitation on the rigs is exactly simulated as on the tracks.
The comparison of test rigs and results obtained from room temperature can be used to judge which of the methods would be viable to use, based on the type of S&R sounds one might be looking for. The box-plots and scatter plots can be used to understand which of the tracks produce the S&R sounds, on the bases of the several metrics used in the study. It can also be seen that there is an effect of temperature and engine type on the S&R sounds. The data collected could be helpful in several ways as discussed in the following section.

6.1 Continuation plan

From the initial scope of the thesis and with knowledge on overall project, there is further scope to conduct more tests and improve the quality of the results that are obtained. The following suggestions are believed to enhance the reliability of the

results.
The track recordings collected at HPG was enormous and due to time limitations, only recordings with speeds which matched already programmed KSK4 and IP Rig speeds (table 3.3) was considered for HPG as well. These low speed recordings and repeated recordings at certain speeds (table 3.2) could not be clipped for S&R sounds. These recordings will help to judge the consistency of the S&R sounds in a car and can provide a greater number of data points for analysis.
Few of the S&R sounds could be strategically picked and can be used to create a jury test in a sound clinic, which could help evaluate these sounds subjectively. If the jury tests can be conducted for enough data points, using some of the statistical methods or by defining a neural network, a metric can be derived. This metric would give perceived sound levels of any S&R sounds, which can effectively replace repeating the jury testing and the squeaks and rattles can be automatically detected and analysed with subjective evaluation.

6.2 Final remarks

With the collected sound database of S&R recordings and the results obtained from the processed data, it can be observed that S&R could potentially be a concerning factor when it comes to perceived quality and on the brand value of the product and it's quality. With Volvo Cars Corporations' goal toward electrification and the importance of a S&R-free products, addressing about S&R earlier in the development phase can help in producing more robust product.

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A
Appendix

Master Thesis at Volvo Cars Corporation
Squeak and Rattle Sound Database and Acoustic Characterization

Planning Report

Sharath Monappa Nairy
Vishal Kulkarni

Examiner: Prof Rikard Söderberg
Supervisor: Mohsen Bayani
Co-supervisor (Volvo Cars Corporation): Anneli Rosell
Co-supervisor (Chalmers University of Technology): Casper Wickman

May 13, 2019

Contents

1 Introduction

1.1 Background

Volvo Cars Corporation is a Swedish car manufacturer based at Torslanda, Gothenburg, Sweden. The company is currently owned by Geely Holding Group. At Volvo Cars Corporation, the vision is "To be the world's most progressive and desired premium car brand".

With this vision, the engineers around the world at Volvo cars Corporations' Research and Development division are building the next generation of outstanding premium cars by creating creating innovative human-centric car technology that makes life less complicated and more enjoyable for people.To achieve this, various teams are working in conjunction with each other.

Solidity as an important attribute of Perceived Quality within Craftsmanship and Durability Centre. It is responsible for Squeak & Rattle (S&R) and solid feeling. One of the important aspect when it comes to Premium cars, is to avoid S&R . And to address this, the team is working to improve the competence for attribute verification in early phases, to meet shorter lead-time with reduced number of physical tests of complete vehicle prototypes.

Squeak & Rattle (S&R) is often an issue in the present day trend when it comes to premium cars. These are unwanted noises experienced by the passenger inside the car cabin. Squeaks are friction induced noises caused by two parts sliding relatively to each other. Usually stick-slip between 2 interfaces is the cause of Squeak. Rattle on the other hand is a impact induced noise caused by insufficient forces holding the parts together or over flexible or loose connection between two parts. The Road Induced vibrations makes the parts move perpendicular to each other resulting in Rattle.

These sounds affect the customer perception of premium build quality. In today's competitive and informed market, a positive feedback from a satisfied customer helps the manufacturer to reach more customers and vice versa. Hence the companies tend to achieve better Perceived Quality by reducing the annoying sounds of Squeak and Rattle to maximum extent in their premium offerings.

1.2 Purpose

S&R Problems are considered as quality inefficiency. And with present day emphasis on electrification of automotives, these S&R problems are more pronounced since there is lot less engine or background noise. Hence, the problem becomes more critical. Currently the methods to tackle S&R problems involve 'Find and Fix'. Where in the cars are tested post production.

Volvo Cars Corporation is aiming to shift engineering activities to early phases of product development in this category. This strategy implies all the quality aspect should be evaluated up front, early in the process, instead of post production checks.

And to objectively evaluate S&R problems, there is a need understand the mechanisms behind the creation of these sounds. Therefore, a study of different scenarios where S&R occurs is the first step in this process. Once the root cause of these annoyances are found is it also required to categorize these sounds based on their psycho-acoustic properties for further analysis.

1.3 Objectives

As defined by the purpose the main objectives of the work are:

1. To create a comprehensive database of S&R sounds in car cabin in different driving/excitation/ambient conditions.
2. To categorize the sounds based on their acoustical properties.
3. Compare different test methods used.

1.4 Limitations

The project is to be completed in 20 weeks, starting on January 22, 2018 till June 15, 2018, which is calculable to fix only certain number of experiments to collect the sounds, in the scope, since more experiments on various specimens requires facility, time and resources. Hence the study will be limited to specimens decided in the beginning of experiments or project.
The road signals, excitation range and other conditions are predetermined in the full vehicle test rig, and these conditions have limited range.
Availability of the Test rig, equipment and assisting personnel could be limited for repetitive testing. And since the data to be collected depends on the platform and the car to be tested, there are two scenarios to be accounted for:
1. If the exact same model is to be used for all kinds of planned experiments, it is to be noted that any assembly or production error could skew the results slightly, which might not be the case in the cars of that model.
2. If the same model of the car is to be set as specimens, the data accuracy could be skewed.
Hence, we have to bare that trade off in hindsight during the analysis and further study.

1.5 Stakeholders

The Thesis work will be carried out at Volvo Cars Corporation by Vishal Kulkarni and Sharath Monappa Nairy, Master's Students from Product Development, Department of Industrial and Materials Science, Chalmers University of Technology, Gothenburg. The work will be supervised by Mohsen Bayani and co-supervised by Anneli Rosell both from Solidity Group at Volvo Cars Corporation. Prof Rikard Söderberg, Head of Department of Industrial and Materials Science, will be the supervisor and examiner from Chalmers University. The results will mainly be used and analysed by Volvo Cars Corporation, which makes them the significant stakeholder in this project.

2 Methodology

2.1 Literature Survey

The literature study will be carried out in three parts.
1. Study of Fundamentals of Squeak and Rattle and psycho-acoustics.
2. Study of existing Test Methods for S&R.
3. Study of Statistical methods of comparison and categorization

2.2 Design of Experiments

To build a comprehensive database of S&R sounds, physical measurements should be done both at complete vehicle and system levels of different cars. Component level measurements are supposed to be done in laboratory (Test rigs) while complete vehicle measurements include both road tests (proving ground) and Rig tests (4-poster). The data can be gathered for different classes of cars and in different ambient condition (if time allows) using binaural technology.

The next step will be to analyse the recorded data and categorize different sounds. It can be done by the aid of using psycho-acoustic parameters and time structure properties of the signals. The recorded sounds can be used to run listening clinics with the aim of finding subjective terms and description for different S&R sounds. And possibly the results from listening jury tests, can be used to categorize the recorded sounds.

3 Discussion

Upon selecting the vehicle that is to be tested, it will be put through a series of tests to gather data with respect to S&R inside the cabin. With the available testing options at Volvo Cars Corporation, the vehicle will be put through multiple tests at the proving ground. This means that the vehicle will be tested on different tarmac surfaces producing a known set of frequency. This test can be iterated based on changes in temperature and humidity.

The above will be followed by a full vehicle test simulation at Volvo Cars Corporation. This is done to add additional data to the gathered data from the proving ground and to eliminate the anomalies from the former test such as engine noise and wind. The track data set from the test at proving ground is fed to the simulator. After running the tests, the vehicle can be further tested for varied temperature and humidity to understand the behaviour of the S&R inside the car. Here in this test, the IP's can be classified based on the sound they produce and can be singled out for further tests.

Individual IP tests are later conducted to narrow down the part producing sound and based on the characteristics of the sound produced, it can be classified under squeak or rattle.

Once all the data is collected, with the help of statistical models, the sound data is classified and characterized into squeak and rattle. Furthermore, the results obtained can be put across a jury test where few number of people forming a panel will undertake the jury test and based on the feedback they provide, the tolerable loudness can be marked and can be be treated as a benchmark in the sound reduction process.

4 Project Plan

4.1 Continuation Plan

The data obtained from this thesis will be considered as sound database for the project which will help in building a bridge between design and psycho-acoustics. This database will be used to understand what is missed by IP rig in comparision to Full Vehicle Test on track. This will help in mapping the IP rig.

The overall idea is to avoid the process of building a prototype to test S&R in the panels, and to reduce S&R, as more and more car manufacturers are moving to produce EV's, the S&R will be more pronounced with lesser engine noise. On implementation, this will help in gaining some lead time in the overall development process and will also save majority of warranty service expenses with respect to S&R in cars.

4.2 Deliverables

The following milestones are expected to be met during the course of this thesis.

1. Test Results and analysis: The data collected from all the tests and the methods used to analyze the signals. The data collected needs to be tagged along with the test conditions and environment in which it was tested.
2. Database categorized on Sound Characteristics.
3. Thesis Report: A detailed report of the complete project.

4. Presentation of Results to VCC and University.

4.3 Time Plan

The above mentioned work was described and discussed among the thesis members as well as the supervisors. With the limited time period allocated to this thesis, the project is designed for a span of 20 weeks. The major tasks to be undertaken are literature study, planning of the tests and tasks, conduct tests, collection of data, carryout a jury test, categorize the sound and compile the database. These tasks are further split and mentioned in the Gantt chart that can be seen below.

Master Thesis at Volvo Cars Corporation

Squeak and Rattle Sound Database and Acoustic Characterization

Period Highlight: 2 | Plan Duration | Actual Start | % Complete | Actual (beyond plan) | % Complete (beyond plan)

Week no.: Jan: 4, 5 | Feb: 6, 7, 8, 9 | Mar: 10, 11, 12, 13 | Apr: 14, 15, 16, 17 | May: 18, 19, 20, 21 | June: 22, 23

ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Literature review on Squeak and Rattle sound characterisation	1	3	1	0	50%
Detailed planning report	1	2	1	0	50%
Plan for the experiments: choosing cars and subsystems, test tracks, test rigs and load cases in cooperation with Volvo Cars experts	2	2	0	0	0%
Doing the experiments and collecting sound signals	4	9	0	0	0%
Compare the test tracks, test rigs and load cases as in Road test, FV Rig and Sub-System Rig (test results)	4	9	0	0	0%
Analyse sound signals, both spectral and time structural properties	7	6	0	0	0%
Performing extra experiments (if needed)	12	3	0	0	0%
Preparing sound signals for jury tests	12	3	0	0	0%
Design jury experiments and run them	13	3	0	0	0%
Analyse the data of jury tests	15	3	0	0	0%
Combine and compare the results of jury tests with spectral and time structural analyses	15	4	0	0	0%
Categorise collected sounds based on performed data analyses	16	3	0	0	0%
Report writing	2	19	0	0	0%

B
Appendix

SQUEAK AND RATTLE SOUND DATABASE AND ACOUSTIC CHARACTERIZATION
RECORDING DATA SHEET

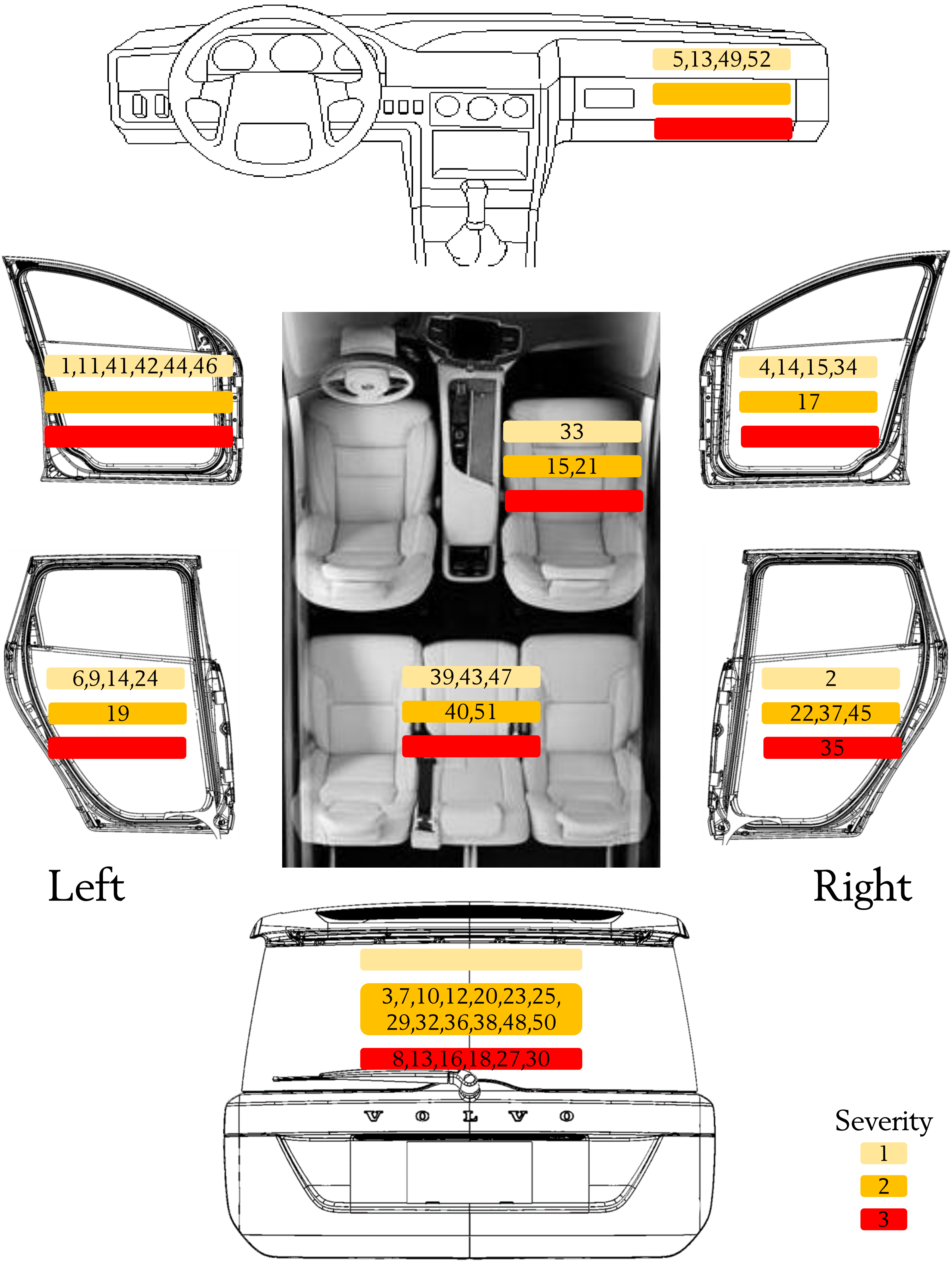
Comments:	

Sl No.	Rec No.	Sound level	Instance	Time	Sl No.	Rec No.	Sound level	Instance	Time
1	Rec 004	1	1	0:06	31	Rec 015	1	1	0:17
2	Rec 004	1	2	0:13	32	Rec 015	2	2	*Cont.
3	Rec 004	2	3	0:33	33	Rec 016	1	1	0:21(C)
4	Rec 004	1	4	1:08	34	Rec 016	1	2	0:38
5	Rec 004	1	5	1:28	35	Rec 016	3	3	0:53
6	Rec 005	1	1	0:14	36	Rec 016	2	4	*Cont.
7	Rec 005	2	2	0:23	37	Rec 017	2	1	0:15
8	Rec 005	3	3	0:29	38	Rec 017	2	2	0:55
9	Rec 005	1	4	1:09	39	Rec 018	1	1	0:20
10	Rec 005	2	5	*Cont.	40	Rec 018	2	2	0:22
11	Rec 006	1	1	0:08	41	Rec 018	1	3	0:33
12	Rec 006	2	2	0:15	42	Rec 018	1	4	1:13
13	Rec 006	3	3	0:30	43	Rec 019	1	1	0:15
14	Rec 006	1	4	0:42	44	Rec 019	1	2	0:40(C)
15	Rec 006	2	5	0:52	45	Rec 021	2	1	0:12
16	Rec 006	3	6	*Cont.	46	Rec 021	1	2	0:30(C)
17	Rec 007	2	1	0:10	47	Rec 021	1	3	0:34
18	Rec 007	3	2	0:17	48	Rec 021	2	4	0:57
19	Rec 007	2	3	0:19(C)	49	Rec 022	1	1	*Cont.
20	Rec 007	2	4	0:46	50	Rec 022	2	2	*Cont.
21	Rec 008	2	1	0:57	51	Rec 023	2	1	0:56
22	Rec 008	2	2	0:57	52	Rec 023	1	2	*Cont.
23	Rec 008	2	3	*Cont.					
24	Rec 012	1	1	1:36					
25	Rec 012	2	2	*Cont.					
26	Rec 013	1	1	0:05					
27	Rec 013	3	2	*Cont.					
28	Rec 014	1	1	0:12					
29	Rec 014	2	2	0:20					
30	Rec 014	3	3	*Cont.					

*C, Cont.: Continuous sound from the source

SQUEAK AND RATTLE SOUND DATABASE AND ACOUSTIC CHARACTERIZATION

CAR LAYOUT - TEST DATA SHEET



C

Appendix

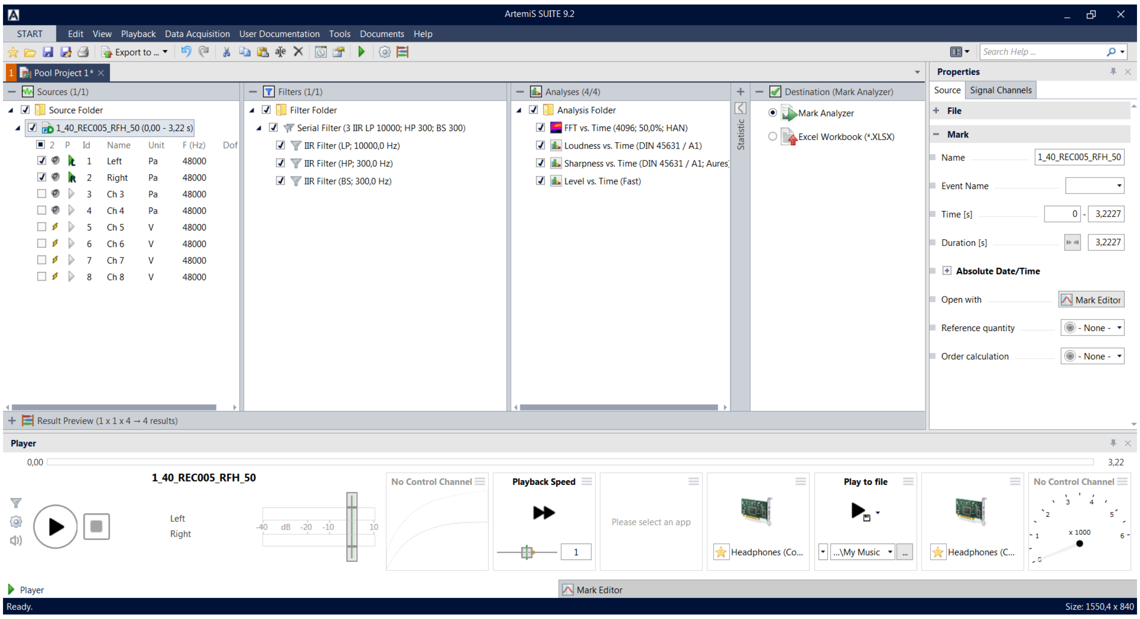


Figure C.1: ArtemiS Suite user interface

D

Appendix

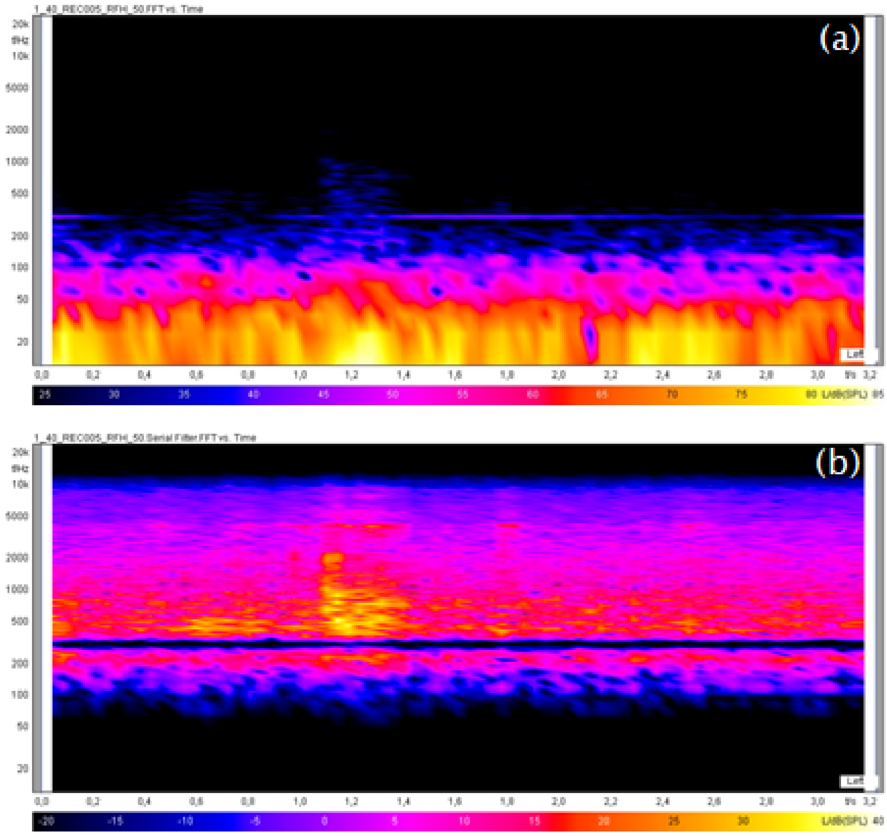


Figure D.1: Before (a) and after (b) filter results

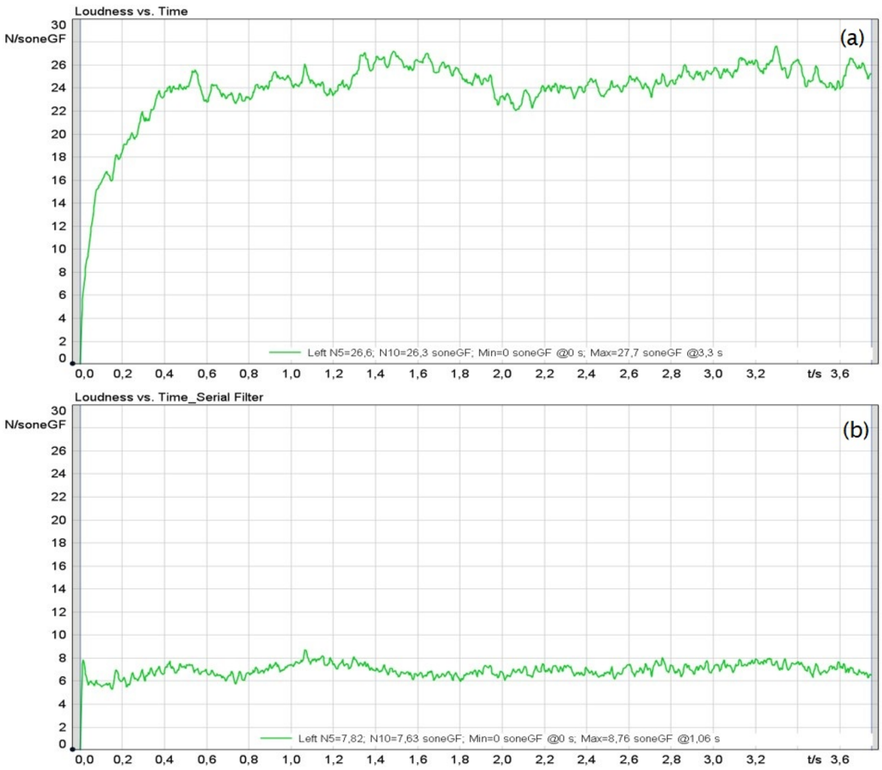


Figure D.2: Before (a) and after (b) filter results for loudness

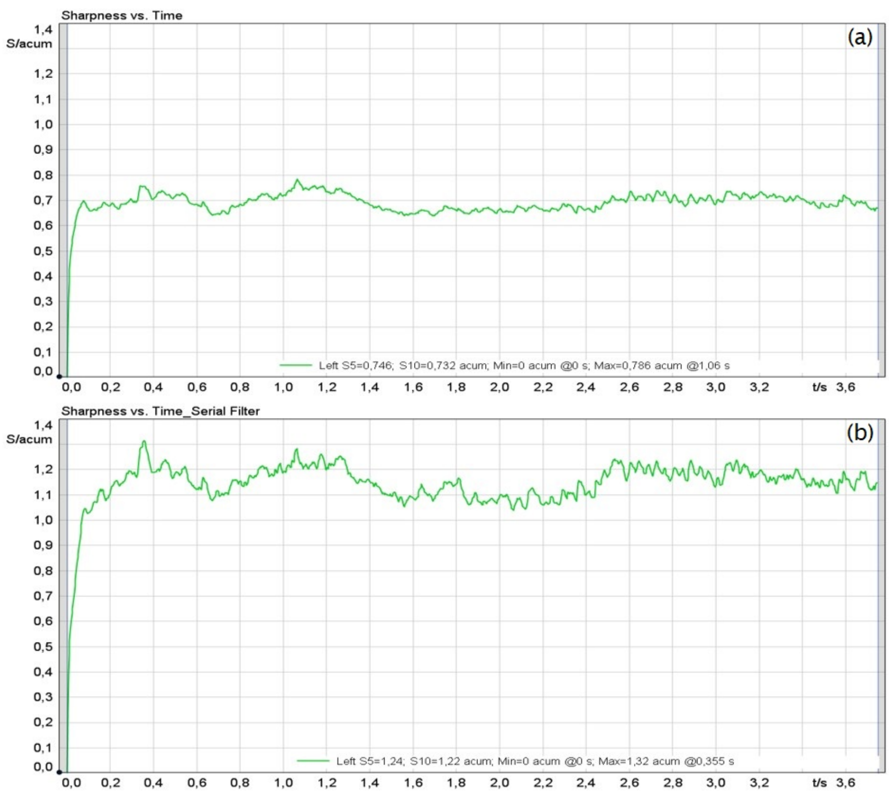


Figure D.3: Before (a) and after (b) filter results for sharpness

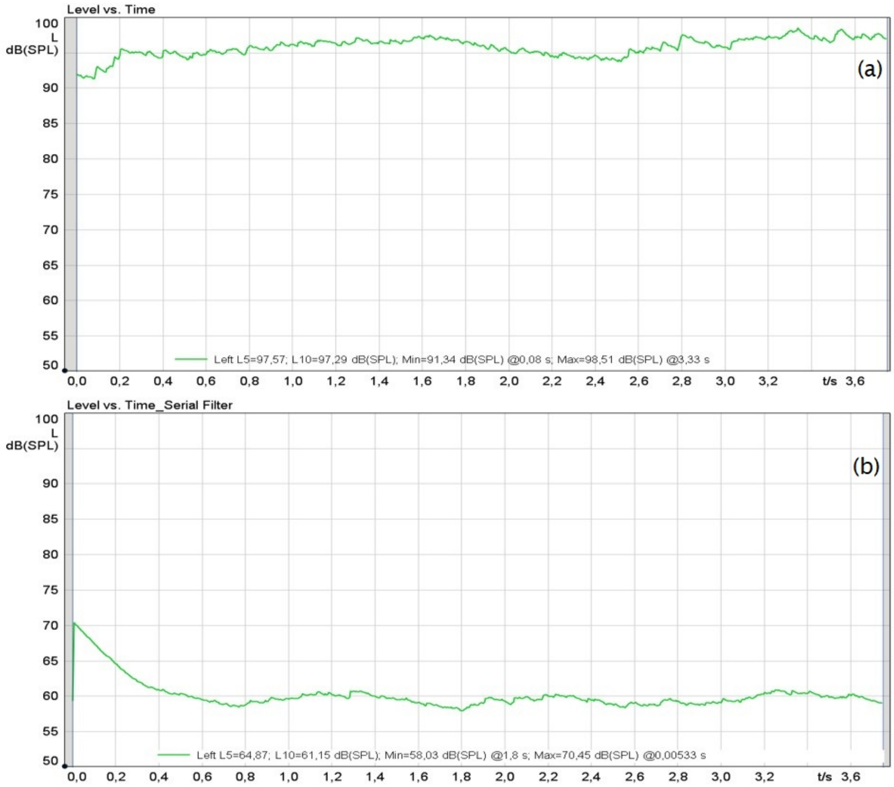


Figure D.4: Before (a) and after (b) filter results for level

E
Appendix

First row:	15			**Comment:**	SQuadriga II SD recording		Ch8: -16 dB(V) ICP	
Data rows	822	**Date of re**	########		S/N 33201494 Name Volvo FW 2		[User Information]	
Data cols:	1	**Date of re**	########		Ch1: 124 dB(SPL) ICP			
Time file:	D:\Analysis Sound Data\Hällered\0316_YW\				Ch2: 124 dB(SPL) ICP			
Mark:	1_40_REC008_LRM_45 (0.00 - 2.19 s)				Ch3: +4 dB(V) ICP			
Filter:	Serial Filter (2 IIR LP 10000; HP 450)				Ch4: +4 dB(V) ICP			
Analysis:	Loudness vs. Time (DIN 45631 / A1)				Ch5: -16 dB(V) ICP			
Statistic:					Ch6: -26 dB(V) ICP			
Kind:	Loudness				Ch7: -16 dB(V) ICP			

Single Valu	
Time	Loudness
t	N
s	sone
	Ch 3
0	0
0.002667	4.164016
0.005333	8.028062
0.008	10.34445
0.010667	11.40614
0.013333	11.71972
0.016	11.52239
0.018667	11.04493
0.021333	10.23668
0.024	9.285196
0.026667	8.497284
0.029333	7.863236
0.032	7.435356
0.034667	7.331532
0.037333	7.328698
0.04	7.249681
0.042667	7.024649
0.045333	6.775019
0.048	6.705174
0.050667	6.681854
0.053333	6.663057
0.056	6.711066
0.058667	6.716756
0.061333	6.751622
0.064	6.660538
0.066667	6.609638
0.069333	6.691222
0.072	6.663198
0.074667	6.555621
0.077333	6.578578
0.08	6.629897
0.082667	6.582088
0.085333	6.501275

First row:	15			**Comment:**	SQuadriga II SD recording		Ch8: -16 dB(V) ICP	
Data rows	822	**Date of re**	########		S/N 33201494 Name Volvo FW 2		[User Information]	
Data cols:	1	**Date of re**	########		Ch1: 124 dB(SPL) ICP			
Time file:	D:\Analysis Sound Data\Hällered\0316_YW\				Ch2: 124 dB(SPL) ICP			
Mark:	1_40_REC008_LRM_45 (0.00 - 2.19 s)				Ch3: +4 dB(V) ICP			
Filter:	Serial Filter (2 IIR LP 10000; HP 450)				Ch4: +4 dB(V) ICP			
Analysis:	Sharpness vs. Time (DIN 45631 / A1; Aures)				Ch5: -16 dB(V) ICP			
Statistic:					Ch6: -26 dB(V) ICP			
Kind:	Sharpness				Ch7: -16 dB(V) ICP			

Single Valu	
Time	Sharpness
t	S
s	acum
	Ch 3
-6.9E-17	0
0.002667	0.27422
0.005333	0.44027
0.008	0.535752
0.010667	0.590406
0.013333	0.630948
0.016	0.664254
0.018667	0.692322
0.021333	0.717143
0.024	0.737616
0.026667	0.760254
0.029333	0.787922
0.032	0.827177
0.034667	0.854939
0.037333	0.883681
0.04	0.913462
0.042667	0.939922
0.045333	0.969937
0.048	1.000434
0.050667	1.022593
0.053333	1.045433
0.056	1.068457
0.058667	1.087
0.061333	1.113252
0.064	1.136789
0.066667	1.143642
0.069333	1.151565
0.072	1.16024
0.074667	1.165249
0.077333	1.177333
0.08	1.196163
0.082667	1.208705
0.085333	1.223053

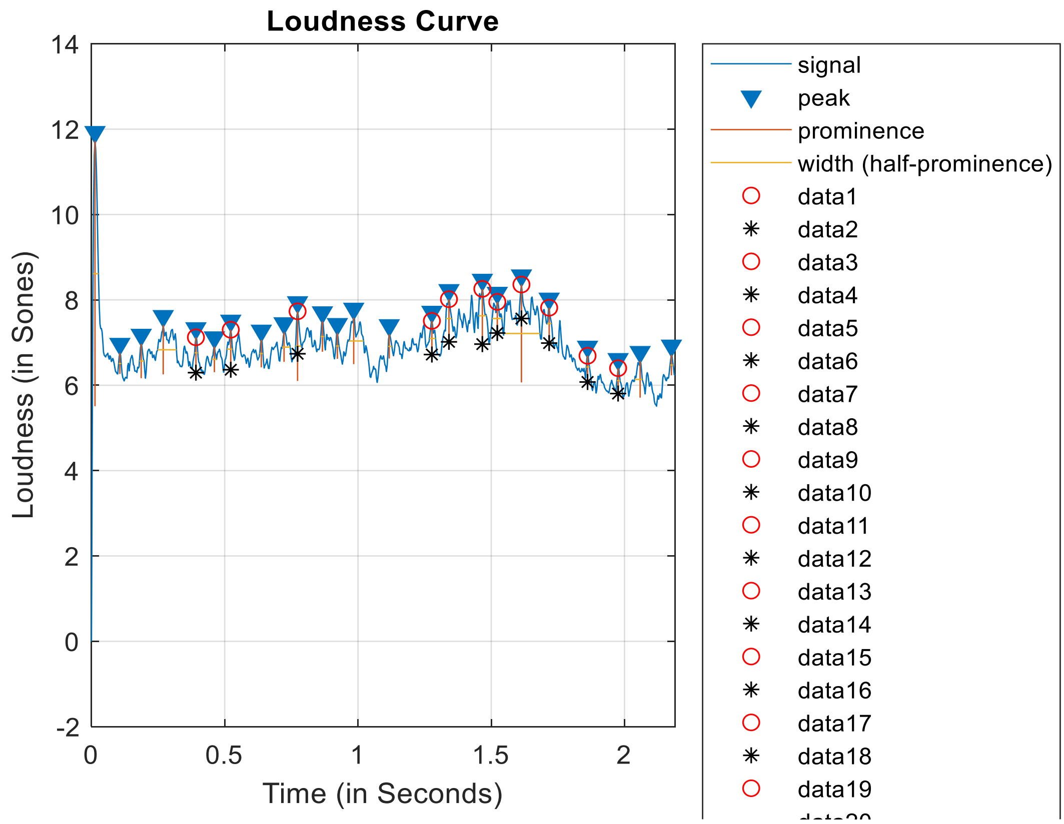
First row:	15			**Comment:**	SQuadriga II SD recording		Ch8: -16 dB(V) ICP		
Data rows	411	**Date of re**	########		S/N 33201494 Name Volvo FW 2		[User Information]		
Data cols:	1	**Date of re**	########		Ch1: 124 dB(SPL) ICP				
Time file:	D:\Analysis Sound Data\Hällered\0316_YW\				Ch2: 124 dB(SPL) ICP				
Mark:	1_40_REC008_LRM_45 (0.00 - 2.19 s)				Ch3: +4 dB(V) ICP				
Filter:	Serial Filter (2 IIR LP 10000; HP 450)				Ch4: +4 dB(V) ICP				
Analysis:	Level vs. Time (Fast)				Ch5: -16 dB(V) ICP				
Statistic:					Ch6: -26 dB(V) ICP				
Kind:	Level				Ch7: -16 dB(V) ICP				
Single Valu									

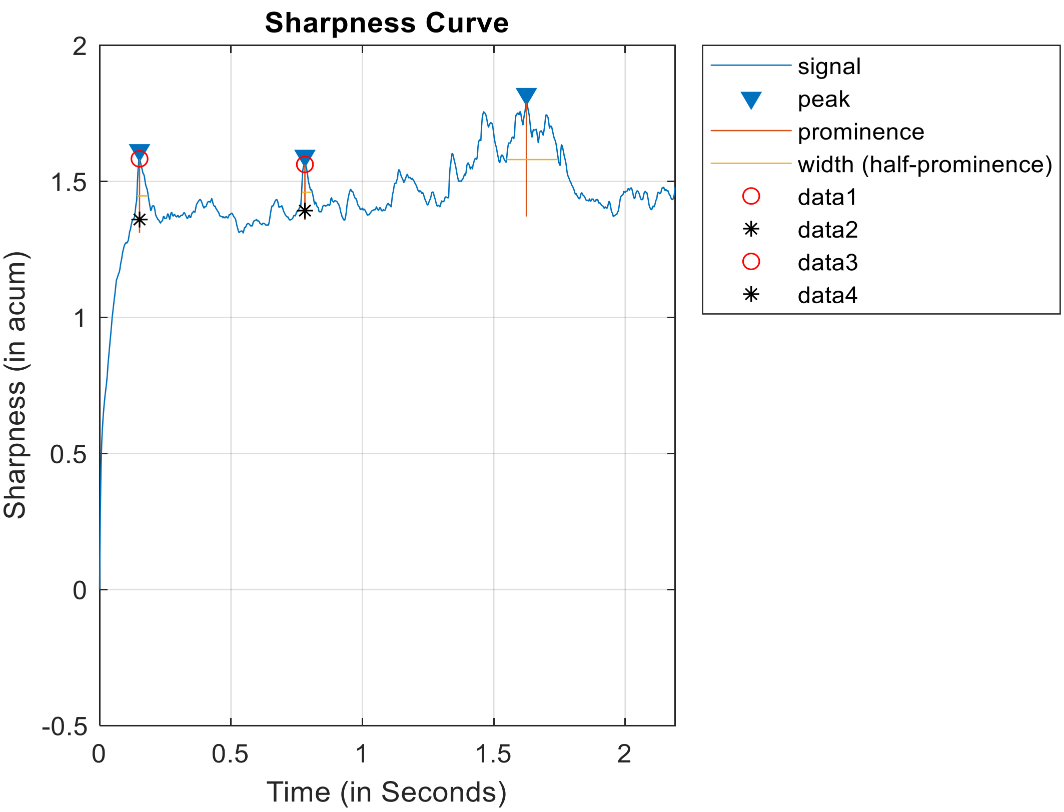
Time	Sound Pressure
t	L
s	dB(SPL)
	Ch 3
0	59.05315
0.005333	77.105
0.010667	76.92436
0.016	76.74355
0.021333	76.55943
0.026667	76.38098
0.032	76.20042
0.037333	76.01553
0.042667	75.83285
0.048	75.6495
0.053333	75.46873
0.058667	75.28702
0.064	75.10417
0.069333	74.92422
0.074667	74.74285
0.08	74.56142
0.085333	74.37908
0.090667	74.19629
0.096	74.02248
0.101333	73.84109
0.106667	73.65911
0.112	73.47687
0.117333	73.29393
0.122667	73.11025
0.128	72.92928
0.133333	72.74683
0.138667	72.56594
0.144	72.38233
0.149333	72.204
0.154667	72.02277
0.16	71.83978
0.165333	71.66178
0.170667	71.48226

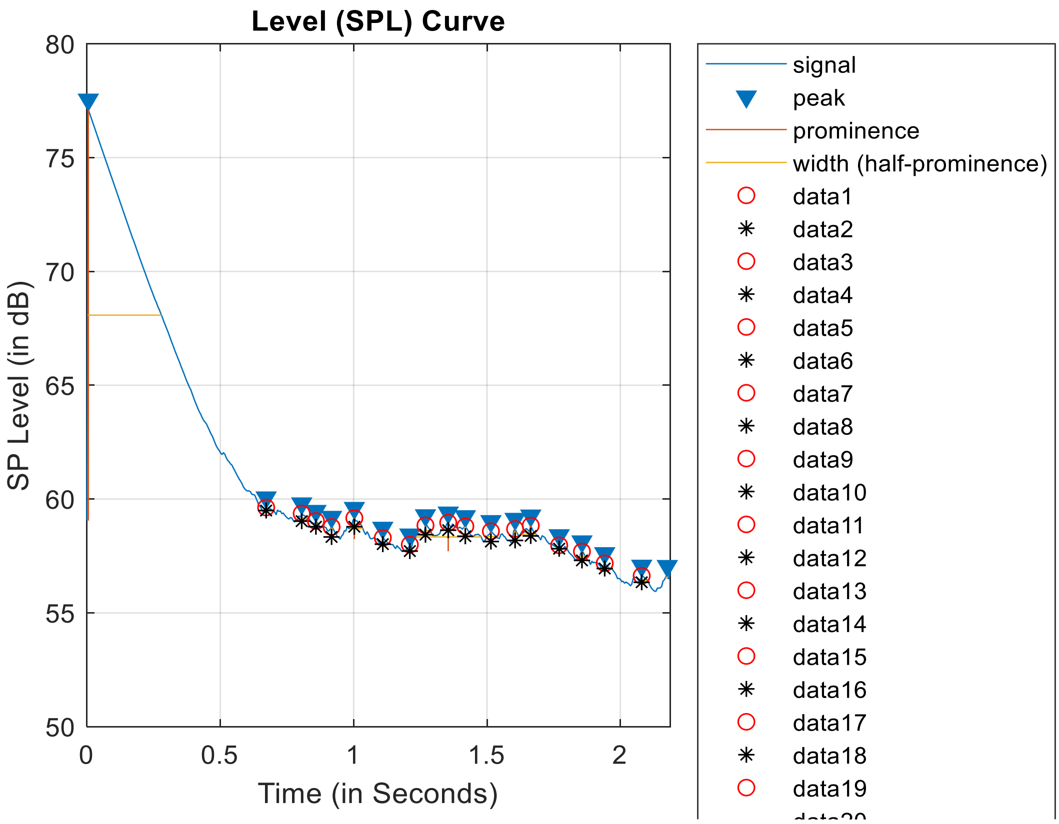
D:\Analysis Sound Data\Hällered\V90 CC\0316_YWW686_01\1_40_REC008\1_40_REC008_LRM_45.hdf

1_40_REC008_LRM_45 (0.00 - 2.19 s)

Channel:	Ch 3					
	Loudness	(Unit)	Sharpness	(Unit)	SP Level	(Unit)
95th Percentile	7.8836	sone	1.7074	acum	73.4677	dB
Sigma	0.7123	sone	0.1676	acum	5.0961	dB
Variance	0.5073	sone^2	0.0281	acum^2	25.9699	dB^2
Skewness	0.4521		-2.4189		1.7183	
Kurtosis	21.4843		18.0357		4.8603	
Mean	6.8796	sone	1.4409	acum	60.8109	dB
Median	6.8264		1.4278		58.6883	
Crest Factor	1.6945		1.2336		2.0317	
Number of Peaks	11		2		17	
Average Peak Value	7.5596	sone	1.5727	acum	58.4978	dB
Max Peak Value	8.3594	sone	1.5829	acum	59.6282	dB
Average Relative Prominence	1.1272		1.143		1.0058	
Max Relative Prominence	1.1858		1.1641		1.0087	
Average Width	0.0309	second	0.0418	second	0.0353	second


Loudness Curve
Loudness (in Sones)
Time (in Seconds)
14
12
10
8
6
4
2
0
-2
0
0.5
1
1.5
2
signal
peak
prominence
width (half-prominence)
data1
data2
data3
data4
data5
data6
data7
data8
data9
data10
data11
data12
data13
data14
data15
data16
data17
data18
data19


Sharpness Curve
Sharpness (in acum)
Time (in Seconds)
2
1.5
1
0.5
0
-0.5
0
0.5
1
1.5
2
signal
peak
prominence
width (half-prominence)
data1
data2
data3
data4



Level (SPL) Curve
80
75
70
65
60
55
50
SP Level (in dB)
0
0.5
1
1.5
2
Time (in Seconds)
signal
peak
prominence
width (half-prominence)
data1
data2
data3
data4
data5
data6
data7
data8
data9
data10
data11
data12
data13
data14
data15
data16
data17
data18
data19