Experimental evaluation of vehicle cabin noise from suspension induced vibrations using transfer path and psychoacoustic analysis techniques

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EXPERIMENTAL EVALUATION OF VEHICLE CABIN NOISE FROM SUSPENSION INDUCED VIBRATIONS USING TRANSFER PATH AND PSYCHOACOUSTIC ANALYSIS TECHNIQUES

By

Nebojša Radić

A Thesis
Submitted to the Faculty of Graduate Studies
Through the Department of Mechanical, Automotive and Materials Engineering
In Partial Fulfillment of the Requirements for the
The Degree of Master of Applied Science at the
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Windsor, Ontario, Canada

2008

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ABSTRACT

Given the automotive industry’s awareness of the importance of the perception of NVH emissions, there is an increased focus on the psychoacoustics, or sound quality, of vehicle cabin noise.

The present work aims to qualitatively evaluate and compare automobile cabin noise by measuring the road-induced noise and vibration of a driven and motored vehicle. Evaluation of transmission paths and psychoacoustic analysis of the cabin acoustics are primary objectives.

A psychoacoustic analysis using the acoustic pressure measurements taken inside the vehicle cabin was performed using both subjective and objective approaches. Testing also included vibration measurements from several structural positions to evaluate vibroacoustic excitations. Using this noise and vibration data, it was possible to evaluate the transfer path of the excitation energy into the vehicle cabin. Further, an attempt to establish a correlation between the noise and vibration measurements and the psychoacoustic observations was also proven possible with some inherent limitations.
DEDICATION

This work is dedicated to my parents for all their love and support.

Ovaj rad je posvećen mojim roditeljima za svu njihovu ljubav i podršku.
ACKNOWLEDGEMENTS

I would like to express my gratitude to the entire NVH group especially to Dr. Colin Novak for everything from his supervision, great level of enthusiasm and encouragement as well as Ms. Helen Ule for her assistance and help that was always there when needed.

Also acknowledgement is due to my entire thesis committee for their time and assistance that was given.

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NOMENCLATURE

$A(f)$: Fourier Spectrum
APT: Active Path Tracking
ARC: Application Research Center
ASQ: Airborne Source Quantification
AU: Annoyance Units
B&K: Brüel & Kjær
BSR: Buzz, Squeak and Rattle
cpsd: Cross Power Spectral Density
dB: Decibel
dBA: A-weighted Decibel
$E$: Relative Change in Intensity
$E_{RQ}$: Excitation Level at Reference Intensity
$E_{TQ}$: Excitation Level at Threshold of Quiet
$f_{mod}$: Modulation Frequency
FFT: Fast Fourier Transform
FRF: Frequency Response Function
F.S.: Fluctuation Strength
$G_{AA}$: Autospectrum of Signal A
$G_{AB}$: Cross-spectrum Between A and B
$G_{BB}$: Autospectrum of Signal B
H(f): Frequency Response Function
h(r): Impulse Response Function
ICP: Integrated Circuit Piezoelectric
$k$: Proportionality Constant
kHz: Kilo-hertz
$L_{p}[dB]$: Sound Pressure Level in Decibels
$m/s^2$: Meter per Second Squared
$mscohere$: Magnitude Squared Coherence
$N'_{max}$: Maximum Values of Specific Loudness
$N'$: Total Loudness
$N$: Specific Loudness
$N'_{min}$: Minimum Values of Specific Loudness
NCE: The Network of Centers of Excellence
NPA: Noise Path Analysis
NVH: Noise, Vibration and Harshness
Pa: Pressure
PC: Personal Computer
$P_{REF}$: Reference Pressure
$pwelch$: Power Spectral Density
R: Roughness
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>RMS</td>
<td>Root-Mean-Square</td>
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<tr>
<td>RPM</td>
<td>Revolution per Minute</td>
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<tr>
<td>S</td>
<td>Sharpness</td>
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<td>TPA</td>
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<tr>
<td>UBA</td>
<td>Unbiased Annoyance</td>
</tr>
<tr>
<td>WOT</td>
<td>Wide Open Throttle</td>
</tr>
<tr>
<td>$\gamma^2(f)$</td>
<td>Coherence function</td>
</tr>
<tr>
<td>$\Delta f$</td>
<td>Frequency Resolution</td>
</tr>
<tr>
<td>$\Delta L$</td>
<td>Temporal Masking Depth</td>
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<tr>
<td>$\omega_0$</td>
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Chapter 1

1. INTRODUCTION

1.1. Background

In terms of noise generation, the automobile is simply a set of different systems that when excited at specific frequencies will eventually lead to the creation of noise. This statement was of course also true in the early days of automobiles, however, it was always taken to be a secondary issue that was simply accepted since more important factors had to be first addressed. Depending on how far back in automotive history one were to look, it can be seen that different components have been targeted as the predominant noise contributors for both interior and exterior noise. Between the 1960’s and 1980’s, intake noise was a main noise source of concern. Prior to this, exhaust was classified as the mayor contributor. Both technology improvements and legislative advancements have since led to the evolution of the modern automobiles and the development of new performance targets, including noise.

1.2. Motivation

Today, automakers invest significant time and money in research and development associated with the reduction of vehicle noise pollution. Since automakers are also more aware of the importance of the perception of noise, vibration and harshness (NVH) emissions, there is also an increased focus on the sound quality of vehicle cabin noise. Consumers now also demand safer and more comfortable vehicles, especially given the significant increased use of cellular phones, entertainment and interactive voice controls in vehicles. The Network of Centers of Excellence Auto21 (NCE Auto21) recognized the
CHAPTER 1. INTRODUCTION

need for research in these areas as part of its fundamental goal to enhance research within the Canadian automotive industry. As part of this, it is recognized that the investigation and performing of psychoacoustics analysis of vehicle cabin acoustics is essential in the improvement of today's vehicles.

1.3. Objectives

A significant source of unwanted cabin noise is the result of road-induced excitation of the vehicle suspension which propagates into the vehicle cabin. Keeping this in mind, the main objectives of this study were to:

1. Conduct NVH measurements on a vehicle equipped with a passive suspension system in order to benchmark it for future development of an active suspension system to be done by others. This active suspension system is presently being developed by the University of Sherbrook research team in association with this research.

2. Qualitatively evaluate and compare automobile cabin noise by measuring the road induced noise and vibration of a self-driven and motored vehicle at different driving speeds. This will be done using jury testing evaluation techniques and with numerical psychoacoustic analysis techniques.

3. Evaluate the transmission paths of the excitation energy into the vehicle cabin from road induced noise and vibration using frequency response functions.

4. Establish a correlation between noise and vibration measurements taken outside of the vehicle to noise and psychoacoustic observations inside the vehicle.
Chapter 2

2. LITERATURE SURVEY

The importance of vehicle’s interior comfort is large and can be a deciding factor to a consumer when it comes to choosing a specific automobile for purchase. This is more obvious when dealing with higher-end vehicles given the fact that sound attenuation packaging in luxury vehicles can contain over 100 lbs of materials that are specifically used for reduction of vehicle interior noise and vibration. Impressions on a vehicle’s occupants can range anywhere from minor such as being irritated due to a reduction of enjoyment of a sound system to the extreme of producing major effects such as driver’s fatigue which can eventually lead to accidents. Generally, unpleasant noise and vibration can be treated at the source, along the transmission paths and/or at the points of reception. To accomplish this, different analysis models and techniques are being used today in all areas of interior vibroacoustic investigation. This chapter will provide a literature survey on different aspects of vehicle noise and vibration analysis relevant to the present study.

2.1. Cabin Noise and Vibrations

Along with the quality of air, temperature and humidity within a vehicle cabin, the perception of sound and vibration can have a significant impact on the comfort of the vehicle’s occupants [12]. There are many different sources of noise generation which may eventually find its way to a vehicle’s interior through various paths, each of which may be comprised of many different component types. Examples of these sources include: wind noise, tire-surface interaction noise as well as noise generated from the engine shell and the vehicle’s intake or exhaust systems.
CHAPTER 2. LITERATURE SURVEY

In addition to noise, the presence of vibration can also be a source of unwanted energy. Despite the fact that vibration levels normally generated through engine mounts, suspension or exhaust hangers are relatively low, they can still be felt by occupants. Drivers can experience vibrations through the seat and controlling pedals, the steering wheel, shifter and dashboard.

Legislation and technology improvements have resulted in the reduction of exterior noise. With this significant reduction of engine and powertrain assembly noise, other previously unnoticeable sources of noise have become more perceptible. The vibration and noise perceptible inside the vehicle has become a problem that costumers are more aware of and are less complacent to its presence. What makes this fact worse is that costumers also associate the noise and vibrations levels to the perceived quality of the car. While some sounds are desirable to provide audible cues, for example to signal that the engine is running or that the signals indicators are functioning properly; wind noise or the noise caused from brake squeal and wiper blade squeaks is not desirable. In general, only sounds that are expected to be heard in the vehicle are those that give the driver meaningful information that the car and its systems are working properly [31]. Complains related to the Buzz, Squeak and Rattle (BSR) are also the cause of considerable money lost through the warranty claims. Even though a component may be functioning properly and that there is no safety issues related to the BSR, the costumer is often under the impression that something may not be operating correctly or safely. The importance of this is obvious given that a decision on buying specific vehicle is based largely on these perceptions. As a result, today’s engineers attempt to come up with different solutions to further the reduction of noise within the interior of the car. This is often done through the
CHAPTER 2. LITERATURE SURVEY

implementation of different types of sound absorption materials including shoddy, glass fibre, polymeric fibrous materials, and various types of foams [37].

2.2. Tire-Road-Suspension Noise and Vibration Generation

As with other vehicle components, suspension design has experienced extensive changes since the beginning and has evolved in very complex structure. This complexity has become necessary since this system needs to ensure both comfortable and smooth ride by absorbing road impacts as well as minimizing pitch and roll of the vehicle during cornering. Generally, a suspension system can be classified into being either a passive, semi-active or active suspension. A passive suspension is composed of traditional springs and dampers where a semi-active system usually employs air controlled springs and shock absorbers with dumping characteristics that can be controlled. A fully active suspension system electronically monitors the riding conditions and directly controls the ride of the car. Even though much of the road excitations are minimized by the suspension system, damage to the muscular and nervous systems of occupants in the vehicle may occur. It has been further documented that exposure to noise and vibration can result in other adverse affects including headaches, fatigue, shoulder’s stiffness, lower back pain as well as vision related problems [14]. Noise and vibration generation in the suspension system is very complex phenomenon composed of highly non linear elements. Sock absorbers along with springs and bushings that support different suspension elements are also sources of transient noise.

We can characterize road noise into two major categories [25]: airborne and structure borne noise. Airborne noise (above 400 Hz) is usually isolated easier through weather
CHAPTER 2. LITERATURE SURVEY

strip sealing of the car, noise absorbing materials and padding. On the other hand, structure borne (bellow 400 Hz) is more difficult to isolate. This is often generated from tire vibration, suspension stiffness, roughness of the road, resonance of the suspension system and the stiffness of different connecting points [25].

2.3. Sound Quality

Sound quality [22] is the term that describes an objective measure of the subjective and/or psychological perception to a radiated sound. Issues related to sound quality are very important for everyone from the buyers through to the car manufacturers to their suppliers. Since there is a large number of well-made cars available in the market, by incorporating superior sound quality practices in design, car makers gain an upper hand in marketing and selling their product. To determine the desired quality of sound it is not enough to only consider sound pressure levels (SPL), but instead other measures must also be considered. As seen in Figure 2-1, there has been a steady decrease in interior noise levels over past 20 years; however, that alone does not eliminate the problem.

![Interior Noise Levels](image)

**Figure 2 - 1:** Steady Interior Noise Level Decrease from 1980 to 2000 [42]
CHAPTER 2. LITERATURE SURVEY

Some of the unpleasant noise sources which may have been previously masked are now more apparent due to an overall reduction of sound pressure level (SPL).

The perception of quality and safety of a given vehicle can be influenced by different factors. One such factor is how a customer observes a sound that is produced by different components within the automobile such as doors, the safety belt retractor, windshield wipers and so on. All these sounds are for the most part composed of short-lived components that influence the feeling of loudness, duration, multiplicity and certain degree of synchronization [35]. But an observer does not break these auditory observations into individual elements but rather has an overall subjective impression of quality, reliability or safety. In order to address the subjective perception of sound, different psychoacoustic analysis techniques and perception models have been developed and are often implemented. When it comes to the evaluation of a given product, samples are selected and sound recordings are made. After the data has been processed, it is then evaluated through either jury evaluation and/or with the use of objective sound quality metrics. Both of these methods of evaluation are widely employed and both have advantages and shortcoming.

Subjective rating done by jury evaluation is often plagued with variations and inconsistencies of results. Another problem is that not all auditors are able to distinguish small differences, thus any testing setup must be carefully designed. If one were to add the cost and complexity of conducting a jury evaluation it is obvious why objective evaluations using psychoacoustic metrics is gaining popularity [3]. On the other hand, the use of objective metrics in the evaluation of a noise can be difficult to correlate with a specific preference to a particularly desirable sound. This is especially true given the role
CHAPTER 2. LITERATURE SURVEY

that subjective perception has on the perceived overall quality of the product. Historically, both highly subjective and highly objective methods have come in and out of favour. In the 1960's and early 1970's, listening juries were primarily used for interior sound comparison in vehicles [33]. According to the same source, the mid of 1970’s experienced a greater utilization of single point SPL measurement along with so called “blind ride” tests where the evaluation was no longer conducted in a listening room but rather in a fully equipped vehicle under various driving conditions. For the period between the late 1980’s to the late 1990’s, an increase in the use of objective analysis techniques became evident. By this point, improvements in the recording of binaural sounds and playback started to play an important role since better subjective comparison was possible. However, there is now again an increase in the use of jury testing when it comes to defining customer’s preferences. This is then often followed by the use of objective analysis to provide additional and necessary feedback.

2.3.1. Jury Testing

Otto, N., et al. [30] gave an overview of specific guidelines with respect to the implementation of jury evaluation for sound generated within automobiles. He addressed the following areas related to the proper utilization of the jury testing technique.

Listening Environment

Listening room characteristics including the acoustics of the room, permissible ambient noise during the listening sessions, the decoration and ambiance of the listening room as well as the temperature, humidity and quality of air circulation can affect a subject’s preferences during a test. As such, these need to be addressed.
CHAPTER 2. LITERATURE SURVEY

Subjects
Depending on the specific goals of the test, jury members need to be appropriately selected and may need to be trained for the particular task that is ahead of them. Company employees or outside costumers may be recruited to give their opinion on specific products that are under the investigation.

Sample Preparation
It is important that proper recording and calibration of the noise source be made. Further, a representative selection of samples must be made otherwise good jury testing results may not be realized.

Test Preparation and Delivery
The order in which the sounds are played, the importance of the environment in which the data is collected and the specific instructions that are given to the test jury needs to be monitored to insure consistent and valid results.

Jury Evaluation Methods
By implementation of specific methods that fit the particular assessment in combination with a predetermined scope of the test, it is better to insure that the obtained results will represent the customer’s judgment in the area of interest.

Analysis Methods
There are many special methods that can be employed when we are dealing with data evaluation. Depending on the given situation, different methods such as “paired comparisons” or “rank order” are frequently used.
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Subjective to Objective Correlation

In the process of validation of the results, different tools such as scatter plots and/or linear or nonlinear regression techniques are often used. Further, the instincts and the experience of the evaluators also can be valuable since in most instances, one is dealing with completely, or at least partially, a different set of problems.

Each of the given areas is further divided in specific topics that can be addressed with the intention of obtaining optimal results when it comes to use of the given technique. For more details see [30].

As far as the specific use of the jury testing goes, there are numerous studies that were done using this approach. Studies range from, for example, comparisons between different interior packaging solutions [36] to the analysis of the sound quality of specific vehicle components such as glove-box compartment closure. Other applications could include correlations with objective metrics such as sharpness [43] to the assessment of different engine noise controlled using an active noise control system [28]. To give an illustration from one of the studies [11] available in the literature, jury testing was implemented to address the problem of gear whining through the use of in-vehicle noise data. Four different automobiles were tested to determine a subject’s preference using statistical ranking. It’s not uncommon that original data is altered in order to eliminate different sources and give jurors a better perception of the sound characteristics that are under investigation. In this case, filtering was done to eliminate low frequency noise that was mainly road induced in order to accent the phenomenon of high frequency gear whine [11]. The jury was able to clearly distinguish between individual cases and give consistent inputs for various testing conditions. Repeatability and consistency are very
important terms that need to be addressed in order to extract meaningful results out of any experiment that is associated with subjective jury testing. It is common practice that any subjects that show low repeatability (in some cases this can be taken to be 60% [36], [2] or 70% [24]) are removed from further analysis. Consistency is treated in the same manner and percentage also varies between 60 and 70 depending on who is doing the study.

2.3.2. Use of Objective Psychoacoustic Metrics

There are many different sound quality metrics that are used today in order to try to characterize different properties of sound. On one hand, there are some that are well defined and standardized and on the other, there are many whose definition is a bit more ambiguous and are proprietary for the internal use by manufacturers in the evaluation of their own products. Since sound quality metrics are intended to investigate phenomenon related to human sound perception, they can be divided and grouped in different categories, most by those related to the various phenomena. There are more then a few dozen different metrics that are presently in use, however, since their classification is not a primary objective of this study only a brief overview of these is given in Figure 2-2, according to Van Deer Auwerer and Wyckaert [40].

Sound quality metrics can be for the most part classified into one of four major groups: Zwicker-Fastl’s metrics, Technical metrics, Speech Intelligibility and Binaural Metrics. Technical Metrics can further be divided into “Elementary/Combined Sound Level Metrics”, “Impulsiveness or Shock Related” and “Tonality Related Metrics”. Some of the more common ones are listed below; however, this list is by no means exhaustive. For
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more details, refer to Van Der Auweraer and Wyckaert [40] who provides an excellent
summary on the topic.

![Diagram of commonly used Sound Quality Metrics]

Figure 2-2: Summary of commonly used Sound Quality Metrics

The most common analysis related to unwanted sound is Sound Pressure Level (SPL) with units of decibel (dB) or A-weighted Sound Level (dBA). A-weighting is a correction factor which compensates for the non-linearity of the human hearing system. It has proven to be a very valuable and important tool for the assessment of products for the protection of the human hearing system. SPL represents the strength or "magnitude" of a signal and is based on that fact it can be classified in the same group as Loudness or Speech Interference Level (SIL). Limitations are present though since not all information can be extracted from this particular analysis metric. For example, a refrigerator or vacuum cleaner noise will not usually damage the hearing system but can still be perceived to be a very irritating noise.
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Other metrics are intended to assign some kind of specific annoyance value to a sound depending on various characteristics. Examples include Roughness (fast modulation), Fluctuation Strength (slow modulation), Sharpness (ratio of high frequency level to overall level) and Tonality (frequency sensation). There are many different sensations that can be extracted from sounds. Examples include whine, beat, rattle, speech interference to name a few. Since the psychoacoustic analysis of sounds is a very complex problem, the use of only one metric is often not adequate. There have been many recent studies that have attempted to tie together and express subjective human sound perception with objective parameters as a single metric. They have tried this using some of above mentioned metrics in combination with different statistical approaches. Zwicker proposed that “Unbiased Annoyance” (UBA) [40] can be expressed in dimensionless Annoyance Units (AU) and calculated as:

\[ UBA = d \left( \frac{N_{10}}{\text{[sone]}} \right)^{1.3} \times (1+s+f) \]  

(2.1)

Where:

\[ d = \text{factor(day / night)} \Rightarrow \left\{ \begin{array}{l} \text{l = day} \quad \& \quad \left(1+\frac{N_{10}}{5[\text{sone}]}\right) = \text{night} \end{array} \right\} \]  

(2.2)

\[ s = 0.25 \times \left( \frac{S}{\text{[acum]}} \right)^{-1} \times \log \left( \frac{N_{10}}{\text{[sone]}}^{-10} \right) \]  

(2.3)

\[ f = 0.3 \times \left( \frac{F}{\text{[vacil]}} \right) \times \left( \frac{1+\frac{N_{10}}{\text{[sone]}}}{0.3+\frac{N_{10}}{\text{[sone]}}} \right) \]  

(2.4)

For the above, S is sharpness in “acum”, F is fluctuation strength in “vacil” and N_{10} is value of loudness that is exceeded 10% of time in “sones”. Immediately, one can see
some of the limitations that can arise because of use of “day/night factor”. How vehicle occupants perceive sound from the engine, for example, at any time of the day or night is not as important as in the case how a neighbour would observe, for example, the sound of a circular saw running in the middle of the night. Another psychoacoustic metric that represents a global measure is known as “melodiousness”, or “non-annoyingness” according to [16] or “Sensory Pleasantness” according to [40]. Some of the metrics mentioned are more applicable for certain problems than others. As such, for this study, we focused our attention to 3 different psychoacoustic metrics: “Fluctuation Strength”, “Roughness” and “Zwicker Loudness” in addition to the A-weighted Sound Level. The first two metrics are chosen since this work aims to characterize low frequency noise of the road-tire-suspension interactions, which there are ideal for, and last two based on the fact that they are well defined, standardized and very often used.

The use of sound pressure level or A-weighted sound pressure level can be found in many different areas including traffic noise (road, railroad, aircraft related), residential, workplace or noise from consumer products. When dealing with the physical quantity of sound, this is usually the metric considered. A measured SPL can be filtered to better represent how we perceive the sound. The most common is the A-weighting filter either directly during the recording or it can be calculated later during the post-processing stage. This concept will be expanded in the following chapter.

There are a few proposed methods for calculating Loudness, and as a result, there are two commonly employed standards: ISO 532B and DIN 45631. Zwicker Loudness (ISO 532B) is the most common of the two psychoacoustic metrics. It takes into account the critical band spectrum of human hearing, tonal components as well as the masking
properties of the sound [20]. It is given in units of "Sones" rather than dB where the pure tone of 1000 Hz has a SPL of 40 dB equals 40 Phons or 1 Sone. This value is taken to be "loudness unity". Practical applications of loudness can vary anywhere from the measurements of impulsive sounds such as for example, estimation on how we perceive the quality of door slams of the vehicles [20] to the estimation of a customer's annoyance caused from steady-state wind noise through a door frame [4].

Modulation Metrics such as Fluctuation Strength and Roughness quantify amplitude fluctuation between specific frequencies. Hearing sensations that describes modulation of sound in the frequency range between about 0.5 Hz to about 20 Hz is referred to as Fluctuation Strength (FS). The unit of measure for FS is "vacil", with 1 vacil arbitrarily defined as the FS associated with a 60 dB SPL, 1 kHz tone 100% amplitude-modulated at 4 Hz [16]. Usually signals that are fluctuating sound louder and are perceived to be more annoying compared to steady signals. A fluctuation frequency of 4 Hz is the most annoying modulation frequency to the human ear [40]. Fluctuation Strength can also be used to determine "Unbiased Annoyance" which is another psychoacoustic metrics that was addressed earlier. Zwicker outlined a model on how to determine FS, but so far this metric is not standardized and according to Blommer and Otto [5] gave an unacceptable number of false positive/negative outputs (large/small FS value when there were small/large sound fluctuations) while analyzing different types of electric motors in one of their studies.

In addition to Fluctuation Strength, another metric that describes sound modulation is Roughness. This is used to characterize modulations in the frequency range of 20-300 Hz. The first known study on this subject was done by Helmholtz in 1877 [41] and after
him Aures and Zwicker tried to further explain this phenomenon. Sensation of roughness, or what is sometimes referred to as “rumbling noise” or “rap noise”, is a very unpleasant noise characteristic. The reference value for roughness is a 100% modulated 1 kHz tone. According to Feng and Otto [13]: “If the modulation is periodic and its frequency is gradually increased from 0 Hz three distinct sensations are experienced”. With modulation frequencies below 20 Hz level, the sensation is described as fluctuation. It is above 20 Hz that the sensation of roughness begins. This sensation increases with increased modulation frequency up to approximately 70 Hz. After this point, decreased roughness level is experienced with the sensation then of three separated tones which are referred to as “carrier” and two “modulation sidebands”. The reference value for roughness of 1 "asper" is defined as that generated by a 60 dB 1 kHz tone which is 100% amplitude modulated by a 70 Hz tone [13].

2.4. Transfer Path Analysis

Noise that is felt in the vehicle cabin can be classified as airborne and/or structure borne noise. Noise that is generated from road inputs and powertrain is generally the main source of structure borne noise. Besides road and powertrain inputs, wheel and tire unbalance can create different vibro-acoustic effects that can be felt in the vehicle cabin as illustrated in Figure 2-3. For proper evaluation of different noise and vibration sources specific techniques have been developed. Since road excitation is not a constant, statistical techniques such as “Principal Component Analysis” or “Partial Coherence” is usually employed for evaluation. On the other hand, powertrain contributions are treated
in a different manner. This is where Transfer Path Analysis (TPA) is used since it deals with the total noise from all individual contributors.

![Graphical representation of Transfer Path Analysis](image)

Figure 2-3: Graphical representation of Transfer Path Analysis [19]

The process of defining the noise and vibration sources as well as the forces that the source is generating, energy transmission, and the reaction at the point of interest is an important aspect of evaluation of noise and vibration performance of any mechanical system. This technique of transfer path analysis is usually implemented for this purpose. One of the main applications for transfer path analysis is in the area of automotive noise ranking of single components of noise or vibration propagation from a main noise and vibration source, such as from powertrain or suspension components.

Transfer Path Analysis can have different forms depending on whether sound pressure and/or accelerations are the outputs of interest. In addition, different analysis methods can be used in combination with TPA. A Source-Transfer-Receiver Model may be implemented to understand the noise generation and transfer to the vehicle cabin. Osawa and Iwama [17] used TPA in conjunction with the Airborne Source Quantification
(ASQ) method to quantify the intake system noise of an 8 cylinder engine vehicle. In this study, ASQ was applied to measure acoustic sources as well as airborne transmission paths from source to the receiver. It was shown that “the required data is the acoustic source strengths, characterized by their volume velocities and acoustic-acoustic transfer functions between source and receiver” [17] is the major difference between conventional structure-borne Transfer Path Analysis.

Another concept that is closely related to TPA is “Component Sensitivity” which measures how much a response varies due to a change in one of the system’s components. Haste and Nachimuthu [18] used this principle to relate the partial contribution to the sensitivity of the component in the case of a linear elastic isolator. TPA can be applied to both acoustic and physical problems but is most popular in applications related to acoustics. As such, the term Transfer Path Analysis is often replaced by the term Noise Path Analysis (NPA). According to same author any NPA study consists of three phases:

- Identification of the noise paths
- Computation of the partial contribution of each path
- Noise path ranking

Bray and Genuit [15] used a method that employed a combination of two technologies: “binaural transfer path analysis (with vibration transfer path analysis) and a real-time interactive multi-channel acoustic and vibration simulation system”.

A total binaural acoustic response that is obtained through the use of an artificial head was mathematically defined as the sum of different acoustical and mechanical sources as well as the propagation waves which imposed upon the head [15]. Beside the fact that
CHAPTER 2. LITERATURE SURVEY

one is able to calculate parameter data, use of this technique allows us to also listen binaurally to the generated noise which can help in the identification of sound quality issues. The obtained samples can be then used for individual listening sessions to allow the subjective judgment of the effect of modification on the perceived sound samples.

A technique that is becoming more common for many NVH applications is the Reciprocal Technique which is used for the determination of the acoustic transfer function. This method operates on the simple principle that the transfer path in one direction is equal to the transfer path in the opposite direction. This statement is valid in mechanical, electrical and acoustical systems [38]. Because of the different space requirements of sound sources and receivers, in many cases it is easier to measure the transfer functions reciprocally. A good example to illustrate the advantage of the reciprocal technique would be a measurement of the acoustic transfer paths of sound radiating from a vehicle’s engine to the driver’s ear. In modern cars, the engine compartment is almost completely packed with the engine and various subsystems with very little extra room. It is much easier to install a microphone than a speaker, where on the other hand in the vehicle cabin there is enough room for a sound source. Another advantage of the method is the fact that the measurements obtained are usually more accurate simply due to the fact that small sensors can be placed much closer to the sound radiating objects from which the transfer function is required. There is very little restriction in regard to the measurement positions. Therefore, "the local sound field is sampled better than by the direct measurement, which employs a sound source (inside the engine compartment) that usually cannot be placed at the exact point of interest" [38]. Because of this, the reciprocal transfer function may give the real transfer path better than
a direct measurement. Besides, when measuring reciprocally, for example with a sound source inside the cabin, all transfer paths are excited and as a result, they can be measured at the same time. Measuring all transfer paths at the same time save significant time during the course of the measurement in comparison with the direct method where all transfer functions of interest need to be measured separately.

In the study conducted by Rust and Edlinger [34], the Active Path Tracking (APT) method was used as a variation of the Transfer Path Analysis technique. According to the author, its main advantage is the ability to apply the technique very fast and get an instant confirmation of the different contributions of all the identified chassis transmission paths to the vehicle cabin. Adaptation of active noise cancellation techniques and immediate verification of the results by active vibration cancellation procedures are used in the proposed method to determine all sources as well as all transmission paths.

Tools that are fast and easy to apply, provide reliable results, and at the same time don’t require the tedious task of dismantling the vehicle are of great importance to acoustic engineers. This is why transfer path analysis techniques are constantly under development and refinement since they are critical tools for the evaluation of structure borne harmonic noise.

2.4.1. Frequency Response Functions and Coherence

A particularly important tool used for vibration testing and analysis is the “Frequency Response Function” (FRF). This is a transfer function expressed in the frequency domain [23]. When interested in the relationship between the input and output of a system, a dual channel FFT analysis can be performed allowing us to calculate the functions that
describe the dynamic behaviour of a system which is assumed to be linear [6]. If one was to look at two signals "a" and "b", as shown in Figure 2-4, which represent the input and output of a signal respectively, it is seen that the Impulse Response Function, \(h(\tau)\), and the frequency response function, \(H(f)\), are related through the Fourier transform and have the same information about the system, other than the fact that they are in two different domains.

**Figure 2 - 4:** System with input signal \(a(t)\) and output signal \(b(t)\). The Fourier Transform of \(a(t)\) and \(b(t)\) are \(A(f)\) and \(B(f)\) respectively [6]

Despite the fact that the system is assumed to be linear and time invariant, this may not have to be necessary. If nonlinear, calculations are still valid as long as the other independent variables of time and input [1] are present. According to the same source, a conditional FRF is obtained as a function of other independent variables plus frequency. They are complex functions composed from real and imaginary parts and can be represented by magnitude and phase. FRFs can be created either from analytical functions or measured data. The following Table 2-1 is an illustration of FRF formulations that are often seen in engineering.
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Table 2-1: Examples of Frequency Response Function formulations [1], [23]

<table>
<thead>
<tr>
<th>Name</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Admittance”</td>
<td>Displacement</td>
</tr>
<tr>
<td>“Compliance” [Dynamic Compliance]</td>
<td>Force</td>
</tr>
<tr>
<td>“Receptance”</td>
<td>Force</td>
</tr>
<tr>
<td>“Mobility”</td>
<td>Velocity</td>
</tr>
<tr>
<td>“Accelerance”</td>
<td>Acceleration</td>
</tr>
<tr>
<td>“Inertance”</td>
<td>Force</td>
</tr>
<tr>
<td>“Dynamic Stiffness”</td>
<td>Force</td>
</tr>
<tr>
<td>“Mechanical Impedance” [Impedance]</td>
<td>Displacement</td>
</tr>
<tr>
<td>“Apparent Mass”</td>
<td>Force</td>
</tr>
<tr>
<td>“Dynamic Mass”</td>
<td>Acceleration</td>
</tr>
</tbody>
</table>

The function that shows the degree of causality in a frequency response function is called “Coherence” [1]. The referenced author also states that coherence can range from zero to one such that if equal to one at given frequency, the system has perfect causality at that specific frequency and that the output is simply caused entirely by the input. On the other hand, if the coherence is equal to zero, the output is caused entirely by another uncorrelated source. For the case of low levels of coherence [6], this may be caused by some extraneous noise at either the input or the output of the system or that the some other non-correlated input may be passing through the system. Coherence is often used along with the frequency response function for validation and in to show the degree of linearity between an input and output signal in the frequency domain.

Kojovic [26] used this method in the attempt to evaluate the contribution of individual engine air-borne and structure-borne vibroacoustic sources and to investigate its effect on sound and vibration with respect to the total interior sound and vibration of the vehicle. In this particular study, 11 inputs (6 structure-borne and 5 air-borne engine sources) and 5
interior outputs (binaural head and 3D accelerometers) were considered creating a total of 55 different FRFs that were analyzed. White noise and mechanical impacts were used to excite the structure while the responses were measured in the vehicle interior. According to the author, some of the observations were that the vibration response in the vertical direction showed highest degree of sensitivity regardless of the type of excitation as well as the best coherence levels. It was also reported that due to the complexity of the system, the presence of sources not related to the engine and testing conditions showed lower than ideal levels of coherence. Vibration data with coherence levels over 70% and acoustic excitation data above 60% respectively, was used to successfully estimate interior sound and vibration levels.

2.5. Chapter Closing

In addition to the use of traditional analysis for the evaluation of general acoustics, psychoacoustics and sound quality are becoming very important criteria to the automotive industry. Buyers are demanding that products sound better which in turn motivates manufacturers to improve and adopt their products to better suit the customers’ preference. There are many different sound quality metrics that are used today to characterize the different properties of sound. Despite the fact that there are many different psychoacoustic metrics available, many more are expected to be developed in the future in order to describe additional properties of sound.

Automobile manufacturers, like many other industries, are continuously trying to gain an advantage over their competitors. Automotive customers demand that cars have both a pleasant sounding as well as a low interior noise level. When design cars for better
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acoustics, a good understanding of the source and transmission paths is paramount. To
describe the source, acoustic transmission behaviours and NVH reception characteristics,
the application of Transfer Path Analysis and FRFs are powerful tools. However, NVH
characteristics and sound quality of a product are not obvious in the early part of the
design process and do not become evident until final stages of development. By this time,
NVH improvement is more expensive and is often taken as a “band-aid” approach.
Having such tools which can predict and minimize some of these issues, one can improve
the consistency and practicality of original design estimations.
Chapter 3
3. THEORY

The following chapter will provide the necessary theory that need be considered for this thesis. It will consist of an examination of the chosen psychoacoustic metrics, frequency response functions and coherence. A discussion of sound and vibration transducers will also be given.

3.1. Fundamentals

Noise is defined as an undesirable sound. From a physical/acoustical perspective, both sound and noise are pressure variations about a reference value (Eq. 3-1). Subjective observations by a listener, however, are very much different. A source that may be pleasant to one may not be so to another and may or may not be appropriately classified as noise.

3.1.1. Sound Pressure Level

The human ear has the ability to detect an extremely wide range of sound pressures differences. When we compare, for example, the sound generated from a jet engine to the sound that perceived from rustling leaves; the sound pressure of the jet can be 1,000,000,000 times greater. Given that noise pressure oscillations are very small, they are often expressed on a logarithmic scale, or sound pressure level scale which is more widely used and accepted. Figure 3-1 below illustrates the comparison between sound pressure and sound pressure level. Due to this wide linear range, the logarithmic scale and sound pressure level is introduced and defined as:
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\[ L_P[dB] = 20 \log_{10} \frac{P_{RMS}}{P_{REF}} = 10 \log_{10} \frac{P_{RMS}^2}{P_{REF}^2} = 20 \log_{10} (P_{RMS}) + 94 \]  

(3.1)

where: \( P_{RMS} = \frac{P_{rms}}{\sqrt{2}} \) is the root-mean-square (RMS) of the instantaneous pressure and, \( P_{REF} = 20 \mu Pa \) is taken to be the reference pressure.

![Figure 3-1: Sound pressure and sound pressure levels (common sources)](image)

3.1.2. Frequency influence

The frequency of a sound also plays a significant factor in how the human ear is stimulated. Figure 3-2 illustrates the human auditory field between the frequencies of 20 Hz to 20 kHz. This is the frequency range where the normal healthy human ear can detect sound. Frequencies below 20 Hz are described as infrasound and above 20 kHz, ultrasonic. The human ear is most sensitive to the frequency of approximately 4000 Hz.
3.1.3. Frequency weighting

As illustrated in the previous figure, the sensitivity of the human ear varies significantly across the frequency range. In order to adequately represent for these variations, a "frequency weighting", or filtering, is used as illustrated in Figure 3-3. These filters take into account inputs at different frequencies by either increasing or reducing sound pressure levels before they are combined into overall SPL level. Out of the four illustrated weighting filters, the "A" and "C" weightings are most widely employed depending on the specific application.
3.2. Psychoacoustics

Webster defines *Psychoacoustics* as *the study of subjective human perception of sounds.* In other words, it aims to correlate physical acoustic parameters to actual sound perception. There are many different psychoacoustic metrics that are used today. The following section will describe the theory for the sound quality metrics used in this study, being Zwicker Loudness, Roughness and Fluctuation Strength.

### 3.2.1. Zwicker Loudness

Before one can understand the calculation of Loudness, an understanding about frequency sensitivity and masking is necessary. The following parameters need also to be considered:

- Frequency and SPL level influence
- Critical Bands and
CHAPTER 3. THEORY

- Temporal and Spectral Masking

As it was discussed previously, sound is not perceived equally across the entire frequency range. The human ear is most sensitive at frequency about 4 kHz. As we move away from 4 kHz in either direction, sensitivity for the most part decreases. In order to account for these differences, equal loudness curves (Fig. 3-4) have been developed based on experimental data which illustrate the human sensitivity of sounds at different SPLS versus frequency. Loudness unity is taken to be at a 1 kHz pure tone which has an SPL of 40 dB. The loudness at this point is given as 40 phons or 1 sone. Using the units of Sones has the advantage that loudness can be expressed in a linear manner. In other words given a noise source which is increased to be twice as loud, the perceived loudness value will also be doubled.

![Equal Loudness Curves](image)

**Figure 3 - 4: Equal Loudness Curves [27]**

It's interesting to note that a relationship exists between the equal loudness curves and the A weighting filter. The "A" network weights frequency in such a way that it approximates the loudness curve of 1 Sone or 40 phones.
CHAPTER 3. THEORY

It is common practice that the frequency content of a signal is given in terms of full or fractional octave bands. The human hearing system though instead filters the frequency excitation with an alternative bandwidth which Zwicker called “Critical Bandwidth” or “Critical Bands”. Zwicker developed a 24-band system. He further showed that masking of a sound will occur if two sounds occur within one band of each other. This brings us to the next important factor that needs to be considered: masking. Human ear is sensitive to two different kinds of masking: temporal as given in Figure 3-5 and frequency masking shown in Figure 3-6. A sound heard immediately before or after another loud sound (masker) will be more difficult to hear. This phenomenon is referred to as pre or post masking.

![Figure 3-5: Temporal Masking](image)

Frequency, or simultaneous masking, is the masking which occurs between two coexisting sounds. The term “frequency masking” comes from the fact that if two signals are present in the same frequency band, the stronger signal will overshadow the weaker signal. Heard separately, one is able to clearly distinguish between them. However, once they occur simultaneously, the sound with the lower SPL level will be inaudible.
CHAPTER 3. THEORY

Examination of the derivation of “specific loudness” \( (N') \) begins with the assumption that a relative change in intensity or excitation level \( (E) \) is proportional to a relative change in perceived loudness. We have:

\[
\frac{\Delta N'}{N'} = k \frac{\Delta E}{E} \quad (3.2)
\]

where: \( k \) represents proportionality constant.

Zwicker and Fastl gave an approximation for the specific loudness for each critical band as:

\[
N' = 0.08 \left( \frac{E_{TQ}}{E_O} \right)^{0.23} \left[ \left( 0.5 + \frac{E}{2E_{TQ}} \right)^{0.23} - 1 \right] \frac{sone}{Bark} \quad (3.3)
\]

where: \( E_{TQ} \) represents the excitation level at threshold of quiet and

\( E_{TQ} \) is the excitation level at reference intensity of \( 10^{12} (W/m^2) \).

The total loudness \( (N) \) can be found as the sum of specific loudness \( N' \) across all of the critical bands with critical band width \( (dz) \).

\[
N = \int_{0}^{2Bark} N'dz 
\quad (3.4)
\]
CHAPTER 3. THEORY

3.2.2. Modulating Metrics

Modulating sounds within a specific frequency range can produce two different hearing sensations. In the case of low frequency modulation (below 20 Hz) fluctuation strength is the relevant metric. For the frequency range between 20-300 Hz, the modulation may be described using Roughness. Both of these metrics are modeled in a similar manner (Fig. 3-7) and show proportionality with respect to both modulation frequency \( f_{\text{mod}} \) and temporal masking depth \( \Delta L \).

\[
\begin{align*}
F.S. & \sim \frac{\Delta L}{f_{\text{mod}} + \frac{4 \text{Hz}}{4 \text{Hz} + f_{\text{mod}}}} \quad \text{and} \\
R & \sim \Delta L \cdot f_{\text{mod}}
\end{align*}
\]  

(3.5)  

(3.6)

![Figure 3-7: Model for both "fluctuation strength" & "roughness" [7]](image)

3.2.2.1. Fluctuation Strength

Modulated sounds for modulation frequencies below 20 Hz are characterized using Fluctuation Strength and as was shown in the previous section, they are strongly dependent on the modulation frequency \( f_{\text{mod}} \) and temporal masking depth \( \Delta L \). Using experimental data it was determined that a modulation frequency of 4 Hz is found to be perceived as most annoying. Continuing from the previous section, (Eq 3.5), the temporal
masking depth ($\Delta L$) according to Zwicker and Fastl model can be approximated using both maximum ($N'_{\text{max}}$) and minimum ($N'_{\text{min}}$) values of specific loudness for each critical band. The term dB/Bark is simply a unit conversion.

$$\Delta L \approx 4 \log \left( \frac{N'_{\text{max}}}{N'_{\text{min}}} \right)$$  \hspace{1cm} (3.7)

Now substituting Eq. 3.7 into Eq. 3.5 fluctuation strength can be found to be:

$$F.S. = \frac{0.008 * \int_0^{24 \text{Bark}} 4 \log \left( \frac{N'_{\text{max}}}{N'_{\text{min}}} \right) dB}{\int_0^{4 \text{Hz}/f_{\text{mod}}} dB/\text{Bark}}$$  \hspace{1cm} (3.8)

### 3.2.2.2. Roughness

Even though the model shown in Figure 3-7 illustrates both fluctuation strength and roughness, the sensation of roughness when compared to fluctuation strength is actually quite different. The main difference with Roughness from a subjective perspective is the rapid amplitude modulation in the frequency range between 20 and 300 Hz. Temporal masking depth ($\Delta L$) depends on the critical band rate, so continuing from Equation 3.6, a more accurate proportionality is:

$$R \sim f_{\text{mod}} \int_0^{24 \text{Bark}} \Delta L(z) dz$$  \hspace{1cm} (3.9)

Finally, according to Zwicker and Fastl Roughness is calculated as:

$$R \sim 0.3 \int_0^{24 \text{Bark}} \frac{20 \log \left( \frac{N'_{\text{max}}}{N'_{\text{min}}} \right) dB}{1kHz}$$  \hspace{1cm} (3.10)
3.3. Time Domain Analysis

Time domain analysis is a tool used for the description of mathematical functions, or physical signals such as sound pressure or acceleration, with respect to time. Common signals are frequently sampled in the time domain in order to have a better insight on the signal’s amplitude and fluctuation with respect to time. If it is planned to later post-process the data in frequency domain, it can also be valuable to indicate the quality of the real-time signal visually before it is converted to the frequency domain for additional analysis.

3.4. Frequency Domain Analysis

As with time domain analysis, frequency domain analysis is used to analyze both mathematical functions and signals, only now with respect to frequency. Analysis in the frequency domain allows one to see how the signal within each of the frequency bands contributes to the overall signal. The frequency domain analysis is based on the Fast Fourier Transform (FFT) Analysis as described in the next section.

3.4.1. Fourier Analysis

Fourier analysis is based on the idea that most real world signals can be represented by adding together an infinite string of sine and cosine waves at different frequencies. A Fourier polynomial for a function with period $T$ can be expressed as:

$$f(t) = a_0 + (a_1 \cos(\omega_0 t) + b_1 \sin(\omega_0 t)) + (a_2 \cos(2\omega_0 t) + b_2 \sin(2\omega_0 t)) + \cdots$$  \hspace{0.5cm} (3.11)

which can be rewritten as:

$$f(t) = a_0 + \sum_{k=1}^{\infty} (a_k \cos(k\omega_0 t) + b_k \sin(k\omega_0 t))$$  \hspace{0.5cm} (3.12)
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where: \( \omega_0 = \frac{2\pi}{T} \) [Fundamental frequency] and

\[ 2\omega_0, 3\omega_0, 4\omega_0 \ldots \] [Harmonics]

Coefficients of \( f(t) \) (eq. 3.12) for \( k = 1, 2, 3 \ldots \) can be expressed as:

\[
a_k = \frac{2}{T} \int_{0}^{T} f(t) \cos(k \omega_0 t) dt \tag{3.13}
\]

\[
b_k = \frac{2}{T} \int_{0}^{T} f(t) \sin(k \omega_0 t) dt \tag{3.14}
\]

\[
a_0 = \frac{1}{T} \int_{0}^{T} f(t) dt \tag{3.15}
\]

A function’s periodicity is the main requirement for the evaluation of a Fourier series and since this is not always possible (i.e. transient signal), in order to capture the frequency content of the signal, one may need to use an exponential form of the Fourier series. Using Euler’s formula for the derivation of \( \sin (t) \) and \( \cos (t) \) (complex form) and substituting them into the Fourier series we get the complex form given as:

\[
f(t) = \sum_{n=-\infty}^{\infty} F(f) e^{\frac{2\pi n f}{T}} \tag{3.16}
\]

where:

\[
F(f) = \frac{1}{T} \int_{-T/2}^{T/2} f(t) e^{-j \frac{2\pi n f}{T}} dt \tag{3.17}
\]

The distance between components in a series is called the frequency resolution \( \Delta f \) and it represents a function of the period \( T \). We can define Discrete Fourier Transform:

\[
f(t) = \lim_{\Delta f \to 0} \sum_{n=-\infty}^{\infty} F(f) e^{\frac{2\pi n f}{T}} \Delta f \tag{3.18}
\]
When evaluating a given limit, one can obtain the transformation between time and frequency domains which is defined as the Fourier Transform and its inverse.

\[ F(f) = \int_{-\infty}^{\infty} f(t)e^{-j2\pi ft} \, dt \]  \hspace{1cm} (3.19)

\[ f(t) = \int_{-\infty}^{\infty} F(f)e^{j2\pi ft} \, df \]  \hspace{1cm} (3.20)

### 3.5. Transfer Path Analysis

Test based procedures used to assess the flow of vibroacoustic energy through a set of known structure-borne and an air-borne transfer paths from the excitation source to the receiver is known as transfer path analysis (TPA). Both structure and air-borne transfer path analysis is based on the fact that a separation exists in the vehicle that creates two neighbouring subsystems. If one subsystem is excited, it produces a corresponding NVH effect at the interface that can be felt by the second subsystem.

The total effect is given as the sum of the individual contributions. These contributions can be different in nature, such as contact forces and acceleration, noise radiating surfaces as well as surfaces that are exposed to irradiation [29]. One can express the sound pressure and acceleration as:

\[ P_r = \sum_i P_{rl} + \sum_j P_{rj} + \sum_k P_{rk} + \sum_l P_{rl} \]  \hspace{1cm} (3.21)

\[ \ddot{x}_r = \sum_i \ddot{x}_{rl} + \sum_j \ddot{x}_{rj} + \sum_k \ddot{x}_{rk} + \sum_l \ddot{x}_{rl} \]  \hspace{1cm} (3.22)

where:

- \( P_r \) is sound pressure at receiver or output ‘r’ \((\text{Pa})\)
- \( \ddot{x}_r \) is acceleration at receiver or output ‘r’ \((\text{m/s}^2)\)
and the following subscripts correspond to different contributors

\[ ri \] [Contact Forces]

\[ rj \] [Contact Accelerations]

\[ rk \] [Radiating surfaces]

\[ rl \] [Irradiating surfaces]

### 3.5.1. Frequency Response Functions & Coherence

When we're dealing with dual signal analysis, the frequency response function (FRF) is a particularly valuable tool. It is used to represent the relationship between the input and the output signal of the system upon the transformation of data from the time to frequency domain. Figure 3-8 illustrates an overview of the required steps for the estimation of FRFs. There are four main stages: recording, analysis, averaging, and post-processing.

![Figure 3-8: Schematic representation of dual signal analysis](image-url)
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The recorded time signal is transformed to the frequency domain via the FFT process. Auto-spectrums of both input and output signal individually as well as the cross-spectrum between them are obtained through the process of averaging. This finally leads to the derivation of the frequency response function and coherence.

The Fourier spectrum of the signal \( a(t) \) and \( b(t) \) is given as \( A(f) \) and \( B(f) \) respectively and can be found as:

\[
A(f) = \int_{-\infty}^{\infty} a(t)e^{-j2\pi ft} dt
\]  
(3.23)

This quantity is complex containing both modulus and phase. In order to find the auto-spectrum, \( G_{AA} \) (i.e. \( G_{BB} \)), Fourier spectrum \( A(f) \) (i.e. \( B(f) \)), is multiplied by its complex conjugate and averaged. This will produce a real and positive number because of the complex squaring.

\[
G_{AA} = A^*(f) * A(f)
\]  
(3.24)

Similarly, the cross-spectrum \( G_{AB} \) is defined as:

\[
G_{AB} = A^*(f) * B(f)
\]  
(3.25)

Because of the fact that this term is complex, it contains the phase between the output and the input of the system.

Once we have all three fundamental spectra \( (G_{AA}, G_{BB} \) and \( G_{AB} \)), the frequency response function can be found as:

\[
H_1(f) = \frac{G_{AB}}{G_{AA}}
\]  
(3.26)
CHAPTER 3. THEORY

Finally, to show the degree of linearity between the two signals in the frequency domain, and to validate frequency response function, the Coherence function is used. It can be calculated in the following way:

\[ \gamma^2(f) = \frac{|G_{AB}|^2}{G_{AA} \cdot G_{BB}} \]  

(3.27)

where: \( 0 \leq \gamma^2(f) \leq 1 \)

3.6. NVH Transducers

One of the first steps in the process of obtaining meaningful results from physical excitations, such as sound and/or vibration, is the proper selection of the transducers which are necessary to convert the physical quantity into an electrical signal for further analysis. Depending on the given application, use of a particular sensor type may be more suitable and preferred to another type. The following sections will cover the fundamental basics regarding the most commonly used transducers for noise and vibration acquisition.

3.6.1. Microphones

The microphone is a transducer used to convert an acoustical energy signal into an electrical signal. These are usually referred to as "condenser" ("capacitor") microphones. There has been little change in the construction of the measurement microphone in the past 50 years. The microphone has 5 basic elements being the diaphragm, diaphragm protection grid, microphone casing (or cartridge), backplate and insulator as shown in Figure 3-9. The air capacitance which is formed between the parallel diaphragm and backplate is polarized from a charge on the backplate. When the diaphragm is excited
CHAPTER 3. THEORY

from an acoustic pressure generation, a corresponding output voltage is created due to the variation of the capacitance that is obtained in the air capacitor.

![Diagram of a microphone](image)

**Figure 3 - 9:** *Basic elements of measurement microphone* [32]

As long as the charge on the backplate is constant, the pressure variation of the sound can be expressed by the equivalent voltage signal. Depending on how the charge is fixed on the backplate, one can distinguish two categories of either an “externally polarized” or “pre-polarized” microphone. An externally polarized microphone requires an external power supply (DC voltage) to fix the charge in the air capacitor between the diaphragm and the backplate. For the second case, the charge is produced from a thin layer of material that can hold a charge on the backplate. These options each have a trade-off between convenience and cost. Pre-polarized microphones are usually used for sound level meters. However, if several microphones are required and if not too inconvenient to externally charge them, then externally polarized microphones are a more cost effective solution. Other characteristics including directivity, size, open-circuit sensitivity and dynamic range are critical characteristics which need be taken into account when selecting a microphone for a given application. In terms of directivity, microphones can classified as either unidirectional (sound aimed directly into the center) or omnidirectional (sensitive to sounds coming from all directions). 1/8” or 1/4”
CHAPTER 3. THEORY

microphones respond the best to all frequencies coming from all directions partly because their size has minimal effect on the sound field. For general purpose measurements, the 1/2" microphone is the best trade-off between very high and very low sound pressure levels. The open-circuit sensitivity of a microphone defines how much of the output voltage is realized for the given unit of sound pressure that is sensed on the microphone’s diaphragm without a preamplifier. This is one of the fundamental characteristics used as a reference for the calibration and frequency response characteristics (range of frequencies where the sensitivity is constant for its defined limits). Dynamic range is simply the range between the lowest and the highest sound pressure levels that can be measured.

The type of the sound field is another criterion for the classification of microphones, these being: pressure field, free field and diffuse field microphones. In the case of the sound pressure being of the same phase and magnitude for the entire field, the pressure field microphone is best used. If a plane wave is being measured, and it is known to freely propagate in one defined direction only, then the free field microphone would be the most appropriate choice. This type of microphone performs best in the anechoic room where the levels of background noise and the presence of reflecting surfaces are minimal. They are also most sensitive for sound that is captured in the axial direction. Finally, diffuse field microphones are used for the case when the sound waves are propagating from all directions. Typically they are used for the measurement of ambient or background sounds or where the noise is coming from different directions such as in the cases of a reverberant room. Here, the environment is highly reflective with equal energy in all directions.
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Depending on the application, it may be more desirable to record the sound as it would be perceived by the human ear. For this purpose, a binaural head is ideal. Given that humans have binaural hearing, they are capable of determining the location of where a sound is coming from. If the source is not located directly in front of us, the brain can detect the location based on the interaural delay between the two ears. The upper part of the human body or torso can also affect the way we perceive a sound. For playback of a recorded signal, this spatial impression and the affects of the torso can only be captured by the use of binaural recording. An artificial or binaural head resembles the human head and torso and contains two free field microphones in the corresponding left and right ears. For sound quality evaluation of sounds, acquisition using a binaural head is paramount for most meaningful results.

3.6.2. Accelerometers

The second sensor that need be considered is the vibration accelerometer. Accelerometers are used for measuring the vibration of a system. They are available in different forms and can be capable of measuring vibrations for up to three axes. The most common type of accelerometers includes the piezoelectric, capacitance, null-balance, resonance, piezoresistive, strain gage, and magnetic induction. In general, the accelerometer is composed of housing, sensing element and seismic mass. As the sensor's housing accelerates, the seismic mass applies a force on the sensing element which in turns generates a charge proportional to the force created by the acceleration of the mass. The charge is then converted into a voltage in specific way depending on whether the accelerometer is an “Integrated Circuit Piezoelectric” (ICP) or “Charge Amplified” type accelerometer. The ICP accelerometer has both an onboard microelectronic chip and
signal conditioner that provides a constant current. This enables the system to provide a good signal quality for the case where long cable lengths are used. The main drawback of the ICP sensor is that the presence of the electronics limits the useful temperature range, otherwise damage will occur. For high temperatures applications, charge amplified accelerometers are used instead since there are no internal electronics. To accommodate for the lack of an electronic circuit, an external charge amplifies is required to condition the signal. Here, the high impedance output signal is converted into a low impedance voltage signal. Because of this, low noise cabling should be used to avoid signal contamination caused from electromagnetic effects and cable movement.

When selecting an accelerometer one must consider the required amplitude and frequency range as well as the ambient conditions that the sensor must withstand. The ambient conditions that need be considered include temperature and ability to resist shock.

Accelerometers can be mounted in one of several different ways. The best way to attach an accelerometer is with a screwed stud. Other methods include magnet, glue, tape or wax depending on the application, required permanence and necessary frequency range. It is also not uncommon to attach the cables as well so as to minimize flexing which can cause errors in the resulting frequency response.
Chapter 4

4. EXPERIMENTAL DETAILS

The following chapter will provide the specific details regarding the testing procedure implemented in the study. For this investigation, acoustic pressure measurements were taken inside the vehicle cabin at the driver’s left ear location using conventional microphones as well as at the passenger’s ears position with a binaural head for the evaluation of the resulting sound quality. Preliminary tests were first performed on an automotive test track approximately 1 km long using a self propelled and towed vehicle. For both cases, acquisition was performed while maintaining a speed of 50 km/hr. The acquisition recording time was 15 seconds per run. Additional tests were also performed in a hemi-anechoic chamber with the vehicle driven and motored on a 4-wheel-drive dynamometer. The vehicle was driven and motored at six different steady speeds as well as under an acceleration sweep.

4.1. Vehicle Description

The vehicle used for the experiments was a 4 Door 2004 Chevrolet Epica Notchback LS (Figure 4.2). The Epica is a front wheel drive vehicle powered by an inline six-cylinder engine mounted transversely. The overall body dimensions are given in Figure 4.1. The engine has a displacement volume of 2.5 L producing 155 horsepower at 5,800 RPM and 177 pound-feet of torque at 4,000 RPM. The Epica has a fully independent suspension system consisting of “double wishbone” on the front and a “multi link” configuration at the rear end that consists of longitudinal and trailing links along with an upper A-arm.
Gas charged shock absorbers, anti roll bars and McPherson’s struts offer additional handling control. The car has 15 inch alloy wheels 205/65R15 all-season radial tires. The vehicle’s interior consisted of cloth covered seats and plastic dashboard with centered armrests both at the front and rear (fold down).

4.2. Modifications & Set Up

In order to collect the necessary data, certain modifications needed to be implemented first on the car. To prevent rattling, loose and damaged body parts were removed and
CHAPTER 4. EXPERIMENTAL DETAILS

secured as shown in Figure 4.3. The vehicle’s airbags were also removed as illustrated in Figure 4-4.

![Figure 4-3: (Left) original rear end; (Right) modified rear end](image)

The firewall was modified to allow the running of the measurement cabling from the accelerometers located outside of the cabin to data acquisition system placed on the rear seat during the preliminary test sessions. For the final round of testing this opening was used to accommodate the microphone cables from the inside of the vehicle to the data acquisition system now located outside of the vehicle in the dynamometer room.

![Figure 4-4: (Left) original Epica's interior; (Right) modified interior-airbag removed](image)
CHAPTER 4. EXPERIMENTAL DETAILS

4.2.1. Accelerometer Mounting

In order to mount and secure the accelerometers, brackets were made and installed at the measurement positions. Due to space limitations, aluminum brackets were machined and bolted on the top of the McPherson strut and next to the wheel hub both on the driver’s side of the vehicle as shown in the figure 4-5 below.

![Figure 4-5: (Left) top of the McPherson strut; (Center) bracket next to wheel hub; (Right) lower A-arm]

An accelerometer was also attached to the suspension link on a flat portion on the bottom of the lower arm. All of the brackets were installed with the vehicle maintained at the normal riding height. They were also specifically oriented in such that the accelerometer’s positive x-direction was facing front of the car, the positive z-direction was facing the top of the car and the positive y-direction was oriented toward the left side of the vehicle.

4.2.2. Microphone Mounting

Microphones were also located inside the vehicle cabin as well as outside of the car near the front driver side wheel. There were a total of four microphones used in the experiment, two of which were ICP microphones. One microphone was mounted at the left side of driver’s headrest (Fig 4.6 - middle) thru the hole that was made on the side of driver’s headrest facing forward. The second ICP microphone was installed on the
CHAPTER 4. EXPERIMENTAL DETAILS

outside of the cabin next to front wheel on the driver's side (Fig. 4.6 - right). For this case, a microphone windscreen was used to protect the diaphragm and reduce extraneous wind noise. Another two microphones located inside the binaural head were installed at the passenger's seat position (Fig. 4.6 - left). The head assembly was placed on a stand so as to resemble how person would be positioned in the seat.

![Figure 4-6: (Left) passenger's seat with binaural head; (Middle) driver's seat with conventional microphone; (Right) microphone next to the front wheel](image)

A security strap as well as the vehicle's seat belt was used to ensure that the stand and head assembly was secure and prevented from moving. All three microphones were connected to the data acquisition system that was secured in the rear seat during the preliminary testing and next to the vehicle for final round of testing performed on the dynamometer in the hemi-anechoic room. All cabling was secured with tape.

4.3. Pre-testing

A preliminary round of testing was performed halfway through the project to assist students from the University of Sherbrook in their analysis of the vehicle and at the same time to give the Windsor team chance to fine-tune the test procedure. During the entire experiment, the driver, binaural head and data acquisition operator were present in the vehicle. In addition to the OldB Orchestra 12 channel acquisition system, six charge
amplifiers, a laptop and two deep draw batteries with associated cabling were present in
the car. For each separate trial, several runs were performed resulting in 5 satisfactory
data sets. All the windows and doors are shut close to minimize any noise penetration
from outside the cabin. So as to eliminate any vibroacoustic effects generated from the
brakes, no braking was performed while the data was being collected. The equipment was
also calibrated before all tests to ensure proper operation.

4.3.1. Test Track Specifications
All pre-testing trials were done at Ford Motor Company (Windsor Engine Plant) in
Windsor. The 14 foot wide track was approximately 1 kilometre long and constructed of
poured concrete slabs as illustrated in figure 4-7.

![Figure 4-7: Ford Motor Company-Windsor Engine Plant Test Track](image)

4.3.2. Self-propelled vs. Towed Vehicle
Testing was divided into two separate cases (Fig. 4.8), self propelled and towed.
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Data was recorded for 15 seconds while the vehicle operated at a steady speed of 50 km/hr. For the second part of the experiment, the vehicle was towed with the engine off, also at 50 km/hr.

4.4. Final Testing

The final round of testing, where most of the data was obtained, was done at the Brüel & Kjær Application Research Center (ARC) in Canton, Michigan, USA. This was done in a semi-anechoic room, shown in Figure 4-9, equipped with a 4WD dynamometer.
CHAPTER 4. EXPERIMENTAL DETAILS

4.4.1. *Engine Dynamometer Semi-Anechoic Room*

The function of the chassis dynamometer was to replicate the rolling resistance that the vehicle would experience while driven on the road. In order to ensure accurate sound measurement with minimal background noise, testing was done in a hemi-anechoic room where only the floor was reflective. The walls were treated with sound absorbing wedges thus minimizing both ambient noise and reflections and providing a room cut-off frequency of 90 Hz. The dynamometer rollers also had a road surface imprint adhered to them to better replicate a real driving surface. For this case, the surface imprint was of the Ford Testing Ground.

4.4.2. *Test setup and operation conditions*

The vehicle was positioned on the dynamometer and secured using heavy-duty straps. The car doors and windows were secured shut to eliminate any noise generation from outside the cabin. For both cases of self-driven and motored vehicle, the testing speed, engine load, air circulation and exhausts emissions were controlled remotely from the controlling room (Fig. 4-10) located next to the test cell.

![Control Room for remote Load and Speed Control](image)

*Figure 4 - 10: Control Room for remote Load and Speed Control*
CHAPTER 4. EXPERIMENTAL DETAILS

Upon installation of the transducers, the associated cabling was secured. The accelerometers were connected to the preamplifiers and then, together with the microphones, to data acquisition system. A portable computer was used to record, store and monitor the data during acquisition as illustrated in Figure 4-11.

Data acquisition was performed during motored and driven conditions. For both cases, the following operation conditions were considered:

- Idling/Ambient
- Steady speeds:
  - 20 km/hr
  - 40 km/hr
  - 50 km/hr
  - 60 km/hr and
CHAPTER 4. EXPERIMENTAL DETAILS

- 80 km/hr

- Acceleration run-up from 0 to 80 km/hr

For the vibration acquisition, the accelerometer positioned on the wheel hub and was stationary for the entire experiment. The second accelerometer was moved between tests, initially located on the lower A-arm it was later moved to the top of the McPherson strut.

4.5. Data Acquisition

The multichannel data acquisition used - an Orchestra-Stell, shown in figure 4-12 was connected to the host PC.

![Orchestra-Stell](image)

Figure 4-12: *Orchestra-Stell*

Out of 12 available channels, six were connected to the accelerometers and the other four were used for the microphone inputs. Because of the effect of heat generation for the brake calliper, a piezoelectric accelerometer had to be used. Six Brüel & Kjær amplifiers (Figure 4-13) were used to condition the two 3-axis accelerometers.
CHAPTER 4. EXPERIMENTAL DETAILS

Figure 4-13: Preamplifiers: (Left) type 2635(2); (Right) type 2626(4)

For each steady speed run, 15 second data was collected, whereas for the acceleration tests, approximately 30 seconds of acquisition was required due to the maximum possible acceleration rate of the dynamometer.


To validate the measured sound quality results, subjective investigation using a jury was also implemented. For this, a diverse group of people was asked to evaluate a serious of the recorded sounds. Out of 20 subjects, 16 were males and 4 were females with ages ranging from 21 to 53 (Figure 4-14). No specific criterion was used in the selection of the jury subjects. They were instead selected randomly based on availability. Also, no screening for hearing loss was performed to ensure a “real” average jury representation. Jury tests were performed in the NVH lab where subjects listened to the recorded sounds through headphones in order to perceive the stimuli in the same manner as in vehicle acquisition. The use of headphones has the additional benefit of eliminating any room acoustic influences. The test was designed in such a way to be brief and requiring only simple comparisons between two sounds (i.e. “Is sound A louder then sound B?”). After
CHAPTER 4. EXPERIMENTAL DETAILS

receiving the necessary instructions, the jury subjects were left alone to complete the test which was of average 15 minutes duration per person.

Figure 4-14: Summary of subject’s age population ranging from 21 to 53
Chapter 5
5. DATA ANALYSIS

Upon completion of the experimental setup portion of this thesis, as presented in the previous section, the collection and post-processing of the raw data had to be performed next. This chapter will include a description of the different techniques related to the signal processing that was performed in this study. It includes the analysis of specific psychoacoustic metrics, estimation of the frequency response and coherence functions, prediction of pressure levels and verification of the results through jury evaluation.

5.1. Preliminary Considerations

Prior to the discussion of the data analysis, several terms first need to be defined. First, the definition of analog to digital conversion must be discussed. Also specific considerations with respect to sampling frequency and sampling period must be explored.

5.1.1. Analog to Digital Conversion

Most signals in the real world are analog and must be converted into digital form before being post-processed. The first critical step in the transformation from an analog to digital signal output is the signal sampling and quantization stage. The continuous signal must be converted to a discrete signal which is known as "sampling". Following, the discrete signal is converted into a digital signal using the process known as "quantization".
CHAPTER 5. DATA ANALYSIS

5.1.1.1. Sampling Rate & Sampling Period

A critical step in the transformation of a continuous to discrete signal is the selection of the proper sample rate. Here, the sampling frequency must be high enough to capture the highest frequency of interest. There are different sampling techniques and are generally classified as either fixed or variable. According to the Nyquist theorem, in order to recover an input signal without distortion, the signal needs to be sampled at a rate which is at least greater than twice the maximum frequency of interest. If the presented measurement conditions of the Nyquist theorem are not maintained, information contained in the original signal may not be completely recovered. It is often desired to sample the signal at higher than the minimum requirements. In this case, we have a trade-off between finer resolution of the sample vs. computational effort and data storage. The time between samples is referred to as the sampling period and simply put; it is the inverse of the sampling frequency. In the case that the sampling interval is different then the interval of the analog signal, energy leakage may occur in the frequency domain. To avoid errors in the signal processing with respect to points mentioned above, certain precautions need to be taken as discussed in greater detail in the following sections.

5.1.1.1.1. Aliasing

Aliasing occurs when one attempts to record and play back a signal that contains frequencies higher than one-half of the sampling rate. The effect can be seen in both the time and/or frequency domain. To avoid this, the Nyquist frequency has to be greater than the maximum frequency component be found in the signal.
CHAPTER 5. DATA ANALYSIS

5.1.1.1.2. Filtering

In its simplest form, filtering is the process of removal or attenuation of undesirable frequencies from the signal. Depending on the frequency range of interest, the application of either low-pass, high-pass or band-pass filters may be considered. In the case of low pass filters, frequencies above a specified point are removed whereas in the case of high pass filters the lower frequencies are removed below a desired point on the frequency scale. Finally, if interested in a specific range, one can also eliminate certain lower and higher frequency using band pass filters. Efficiency may be improved by reducing the sampling rate if the maximum frequency of interested is significantly lower than the highest frequency contained in the signal. Roll-off characteristics of the filter are another point that needs to be considered, and because of this phenomenon, when the signal is analyzed, individual segments are overlapped to eliminate unreliable data.

5.1.1.1.3. Leakage

Spectral leakage is the term that describes the phenomenon when some of the energy of the original signal spectrum appears to “spilled over” to other frequencies. Those errors are always present, but can be reduced by applying different widowing functions to the signal.

5.1.1.1.4. Window functions

Leakage errors that are present in the signal are caused by the discontinuities at the end of the sampling period. To reduce these, the sampling signal must be made to be periodic by multiplying the sampled data by zero outside of the chosen interval. This alters the
CHAPTER 5. DATA ANALYSIS

energy content of the signal as well as its amplitude, but the information is then restored through application of specific correction factors which are specific for different types of windowing functions. A trade-off between resolution and dynamic range is present when dealing with different windowing functions. The most common window functions include Rectangular, Flat-top, Hanning and Hamming functions. For random signal analysis and narrowband applications, the Hamming window is most commonly applied.

5.2. Software used

Different commercial software packages can be used for the purpose of calculation of psychoacoustic metrics. For this study, the 01 dB software packages of dBFA and dB Sonic were used. For the determination of the frequency response functions and coherence between the pressure and acceleration excitations from outside of the vehicle and the sound pressure obtained inside the cabin, the dBFA software was used. To establish correlation between outside excitations and psychoacoustic metrics, separate Matlab codes had to be developed since the above mentioned software do not support direct evaluation of either the frequency response functions or coherence between the pressure and the psychoacoustic metrics. Separate Matlab codes were also made to estimate pressure levels using the FRFs obtained earlier. Finally, for verification of the results, another commercial software package (Pulse sound quality) was used in addition to the 01dB Jury testing module to look at the agreement between the objective and subjective ratings. Refer to the Table 5-1 for a summary on how the different software programs were used as well as their specific applications.
## Table 5 - 1: Summary of software used in the study and its particular application

| 01 dB STELL |  
|------------------|------------------|
| dB Sonic | [Steady Driving Speeds]  
| | • Loudness vs. Time  
| | • Roughness vs. Time  
| | • Fluctuation Strength vs. Time  
| | • A-Weighted SPL vs. Time  
| | [Accelerations]  
| | • FFT - waterfalls  
| dB FA |  
| | • FRF & Coherence (Pa & m/s²) to (Pa)  
| Matlab |  
| | • FRF & Coherence (Pa & m/s²) to (Psychoacoustic metrics)  
| | • Sound Pressure estimations  
| 01 dB Jury testing |  
| | • Jury verification (Test #1)  
| PULSE |  
| | • Jury verification (Test #2)  

### 5.3. Processing of Psychoacoustic Metrics

The psychoacoustic metrics of Loudness, Roughness and Fluctuation Strength as well as the A-weighted SPL at steady driving speeds were processed. Also, the vibration accelerations were analyzed using FFT waterfalls. Here, the SPL levels, time and frequency were also considered. For this purpose, one of the 01 dB-Stell modules called dB Sonic was used. Selected signals from all three microphones located in the vehicle cabin were considered at all steady speeds as well as the acceleration in both cases of self-driven and motored vehicle. This particular software allows for the selection of the desired sound files and by specifying specific parameters. For example, frequency
CHAPTER 5. DATA ANALYSIS

weighting for SPL, window type or window overlap for FFT spectrograms or type of
sound field and interval between points for psychoacoustic metrics we can obtain desired
results. Figure 5-1 shows a schematic representation of an analysis performed using
dBSonic.

![Schematic representation of analysis performed using dBSonic.](image)

**Figure 5-1:** Schematic representation of analysis performed using dBSonic.

5.4. FRF and Coherence Analysis

Estimation of the relationship between the input and the output of the system was
performed using the two different software programs dBFA and Matlab. This task was a
more involved one given that so many signals needed to be considered and that a separate
testing metric was required to be created. For this process, each of the ten input signals
needed to be correlated to each of the three output signals. Two different trials were also
considered at six different steady speeds and one acceleration run-up.

Additionally, two different driving conditions were considered which resulted in 840
frequency response functions and just as many coherence functions for correlation between the sound pressure and acceleration outside and sound pressure inside the vehicle cabin (Table 5-2).

Table 5 - 2: Summary of testing conditions for estimation of FRF and Coherence

<table>
<thead>
<tr>
<th>Input signals</th>
<th>Outside Microphone</th>
</tr>
</thead>
<tbody>
<tr>
<td>(total 10)</td>
<td>3 3D accelerometers</td>
</tr>
<tr>
<td>(total 3)</td>
<td>Inside Microphones</td>
</tr>
<tr>
<td>(total 2)</td>
<td>Trial #1 &amp; #2</td>
</tr>
<tr>
<td>(total 7)</td>
<td>Steady speeds</td>
</tr>
<tr>
<td>(total 2)</td>
<td>Engine ON</td>
</tr>
<tr>
<td>(total 4)</td>
<td>Loudness</td>
</tr>
<tr>
<td>(total 4)</td>
<td>Roughness</td>
</tr>
<tr>
<td>(total 4)</td>
<td>Fluctuation Strength</td>
</tr>
<tr>
<td>(total 4)</td>
<td>A-Weighted SPL</td>
</tr>
</tbody>
</table>

5.4.1. FRF and Coherence Analysis using dBFA

For the first case the raw signal was loaded into dBFA for post-processing. In order to generate the frequency response and coherence functions between any input and output signal there are few steps that first needed to be completed (Fig. 5-2). First, the two signals of interest need to be selected. The auto-spectrum and cross-spectrum of each of them had to be found using narrow band spectrum analysis. The FFT window type
CHAPTER 5. DATA ANALYSIS

needed to be selected as well as the window overlap and the number of FFT lines. To reduce computational time, the frequency band needed to be specified, in this case, it was limited to 1000 Hz. Since we're dealing with dual signal analysis this can be done using batches where signals are calculated simultaneously. The cross-spectrums were calculated in the similar matter making sure that all of the selected parameters match the ones used for auto-spectrum calculations to be able to compute Transfer Functions (FRFs) and Coherence.

![Figure 5-2: Schematic representation of analysis performed using dBFA.](image)

From the Auto-spectrums $G_{AA}$ (input) and $G_{BB}$ (output) as well as the cross spectrum $G_{AB}$ between the input and the output, analysis produces the transfer function

$$H_1(f) = \frac{G_{AB}}{G_{AA}}$$

and Coherence $\gamma^2(f) = \frac{|G_{AB}|^2}{G_{AA} \cdot G_{BB}}$. Calculations of Transfer functions and
CHAPTER 5. DATA ANALYSIS

Coherence were presented in 3.5.1

5.4.2. FRF and Coherence Analysis using Matlab

Since dBFA does not allow for the calculation of frequency response functions between pressure and/or acceleration or any of the psychoacoustic metrics, Matlab codes had to be developed. Matlab has a built-in function for either the calculation of auto-spectrums or cross-spectrums separately. They can then be combined to calculate the FRFs and coherence according to the procedure given in the section 3.5.1 or using built-in functions for direct estimation of both FRFs and coherence.

<table>
<thead>
<tr>
<th>Matlab Function</th>
<th>Matlab Function Name</th>
<th>For Consistent Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>pwelch</code></td>
<td>Power Spectral Density</td>
<td>Auto-Spectrum</td>
</tr>
<tr>
<td><code>cpsd</code></td>
<td>Cross Power Spectral Density</td>
<td>Cross-Spectrum</td>
</tr>
<tr>
<td><code>tfestimate</code></td>
<td>Transfer Function Estimate</td>
<td>FRF</td>
</tr>
<tr>
<td><code>mscohere</code></td>
<td>Magnitude Squared Coherence</td>
<td>Coherence</td>
</tr>
</tbody>
</table>

Independent, if we calculate the auto-spectrums and cross spectrum first and then use them to find the FRFs and coherence or instead find it directly, give the same results. So for convenience, the built in functions “`tfestimate`” and “`mscohere`” were used.

The built-in function estimates the transfer function of the system with input A and output B using Welch’s averaged periodogram method. Coherence is also estimated in the similar matter. They are both given as:

\[ [T_{xy}, F] = \text{tfestimate}(A, B, \text{WINDOW}, \text{NOVERLAP}, \text{NFFT}, Fs, \text{'whole'}) \]
CHAPTER 5. DATA ANALYSIS

\[ [C_{xy}, F] = \text{mscohere}(A, B, \text{WINDOW}, \text{NOVERLAP}, \text{NFFT}, \text{Fs}, 'whole') \]

Where:

- \( A \) Input Signal (Time Domain)
- \( B \) Output Signal (Time Domain)
- \( \text{WINDOW} \) Specific Window function
- \( \text{NOVERLAP} \) Percentage of overlap between segments
- \( \text{NFFT} \) Number of FFT points
- \( \text{Fs} \) Sampling frequency
- 'whole' / 'half' Whole or half of the Nyquist interval

Since this approach was proven not to be adequate when we compared the estimated and real values, an alternative was required. However, despite the fact that the FRFs and coherence function were proven to be unsatisfactory, they were still able to be used to estimate the sound pressure levels.

Consider for example the case where the vehicle was self driven at the steady speed of 40 km/hr. Given that there were two trials per speed, trial #1 was used to find frequency response functions between input and output signal. The calculated FRF would be then used to estimate the output signal from the second trial. The relationship between the input and the output of the system can be represented as: \( A(f) \cdot H_1(f) = B(f) \) where \( H_1 \) is the FRF of the system. This expression is valid in the frequency domain so once the output has been estimated, it would be given in the frequency domain. As such, the inverse of the FFT of the signal was required to obtain the signal in the time domain. At this point, a comparison is possible between the original and predicted levels to see if the
CHAPTER 5. DATA ANALYSIS

FRFs are valid as well as the resulting confidence levels (Fig. 5-3). Also obtained are the values of sound pressure which can further be analyzed by loading those sound files into dB Sonic for analysis of the psychoacoustic metrics.

5.4.3. Jury Evaluation

Finally to verify if the psychoacoustic metrics are true representation of how real subjects would react to the stimuli, a panel of jurors was used for further evaluation. Two separate tests were performed using two commercially available software: 01dB Jury Testing Module 1.2 and Brüel & Kjær Pulse-Automotive Sound Quality. Since the sounds were
obtained using a binaural head, two separate signals for the left and right passenger's ears had to be merged together. The Automotive Sound Quality program was used to perform this task. From the original 15 second signal, the middle third section was considered. The ends of the signal were faded for 0.5 seconds to give smooth transition between the separate signals resulting in 6 seconds of playing time per sample. For the first part 5 sounds were tested (Engine fired with speeds 20, 40, 50, 60 and 80 km/hr) using a paired strategy. The subjects were asked to indicate which of the two sounds played in the pair were louder. After entering their personal information, the jury members would listen to all 5 sounds and would be given opportunity to do so as many times as they found to be necessary. After listening to the given pair of sounds the jury member would specify which of sounds they found louder (Fig. 5-4).

**Figure 5-4:** Jury test #1 Evaluation screen presented to jurors
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After listening to the pair of sounds they would provide their input by sliding the bar across the given scale based on how they feel about the played pair of sounds.

For the second part of jury testing, a different setup was used. Since a great number of signals were obtained, only a few randomly selected sounds were used. The subjects were asked to give answer to the following questions:

- "Is the sound A LOUDER then the sound B?"
- "Is the sound A more PLEASANT then the sound B?"
- "Can you hear ENGINE noise more in the sample A then in the sample B?"
- "Can you hear ROAD noise more in the sample A then in the sample B?"
- "Do you PREFER A more then B?"
- "Is the sound A ROUGHER then the sound B?"
- "Is the sound A more ANNOYING then the sound B?"

In this particular test they had an option to choose between "YES", "NO" and "SAME". They were also "forced" to give the answer in specified time of 5 seconds since all sounds were played back-to-back with 5 seconds silence between the pairs.
Chapter 6

6. RESULTS & DISCUSSIONS

The following chapter will provide a summary and discussion of the results. To be able to manage the data efficiently, and to keep it within allowed space limitations, most of the post-processed data will not be presented directly in this chapter. However, all remaining results are provided in the appendix. First an analysis of the objective psychoacoustic metrics of Loudness, Roughness, Fluctuation Strength and A-weighted Sound Pressure Level is given. The consideration of this along with microphone performance allows for the elimination of the two inside microphones. Next, the Frequency Response Functions and Coherence between accelerations from three accelerometers and one microphone that were positioned outside (near the wheel) and one of the microphones inside the car is considered. Finally, the Jury test results and how they relate to the objective psychoacoustic metrics will be discussed.

6.1. Microphone Performance & Importance of Binaural Recording

The vehicle interior was equipped with three microphones; two in the binaural head and one positioned on the left side of driver’s headrest. Inspection of the data shows a significant difference between the binaural recording and the data obtained using single microphone. It was also found that the microphone on the manikin’s right side gave higher results than the one on the left due to its proximity to the window. For the same reason, the microphone on the left side of the driver’s headrest was expected to give similar results, however, this was not found to be so for all sound quality metrics as illustrated in the following figures.
6.1.1. Discrepancies between Microphones - Loudness

In the case of driven vehicle with the engine operating it can be seen that when looking at values of loudness obtained from three different microphones there are significant differences as soon as the vehicle develops some speed.

For example, driving at 20 km/hr gives discrepancies of more than 3 Sones for the mean values of loudness between two microphones that are positioned next to the window and this difference grows as the speed is increased to about 5 Sones at 40 km/hr (Fig. 6-1). At this speed, the differences are greatest. At 50 km/hr they become smaller as the speed approaches 60 km/hr (Fig. 6-2) they are minimal. Increasing to 80 km/hr illustrates significant differences again. Based on this, it could be suggested that, depending on the experiment, the use of single point microphone may be appropriate if interested in loudness values for vehicle idling or at the specific speed of approximately 60 km/hr.
For all other cases, the vehicle speed influences significantly the loudness for different microphones types. Testing the motored vehicle with the engine off showed much better agreement for loudness at all speeds between the driver’s left ear and right passenger’s ear. These results can be found in the appendix.

6.1.2. Discrepancies between Microphones - Roughness

Variations were also present for mean roughness values when compared between the different microphones. At lower speeds such as 20km/hr (Fig. 6-3) and idle, significant discrepancy are present. With an increase in speed, considerable variations are also present but are not as severe as for the very low speed cases. This was found to be valid for both cases of self driven and motored vehicle. Additional results can be found in the appendix.
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6.1.3. Discrepancies between Microphones - Fluctuation Strength

For fluctuation strength it can be seen that the right passenger's ear provided more conservative results but with no significant difference between microphones due to the fact that the values are so low. To illustrate, consider Fig. 6-4.
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6.1.4. Discrepancies between Microphones - A-weighted Sound Level

No noticeable variation is observed for A-weighted sound levels for either case of motored or self-driven vehicle. A fraction of a dB is not sufficient enough for an observer to notice a difference between two signals. As such, no differences are realized between the uses of either microphone type. To illustrate this point, consider the measured A-weighted SPL levels for self-driven vehicle at 50 km/hr given in Figure 6-5.

![Figure 6-5: Illustration of A-weighted SPL vs. Time for Self-Driven Car on the Dynamometer at 50 km/hr where Blue, Red and Black represent Passenger's Left, Passenger's Right & Driver's Left Ears respectively](image)

This observation should raise some concern given that Sound Pressure Level or A-weighted Sound Level are the most widely used metric and, as can be seen here, may not be adequate given that some of the stimuli may be lost by this evaluation approach.

Based on the observations above, it was decided to continue the analysis using the microphone positioned at passenger’s right ear only. All microphones provided comparable results, but with the use of a conventional microphone, a loss of real signal meaning may be present. The head, torso, shoulders and ears can attenuate or amplify the
CHAPTER 6. RESULTS & DISCUSSIONS

signal and are much better representation on how humans perceive the sound. Another advantage is that when jury testing is performed, it is done with data that’s acquired with binaural recording. Binaural replay can give sensation of directivity on top of better illustration of some of sound quality attributes which were shown previously.

6.2. Loudness with Respect to Different Driving Conditions

The following section will provide insight into how loudness values are affected between the cases of the driven and motored vehicle at different speeds. Testing the car at six speeds and examining the results, it can seen that the engine plays a more important role when vehicle operates at lower speeds as oppose to driving at higher speeds. The influence of the road-tire-suspension interactions have a much greater effect at the higher speeds when above 40 km/hr. Inspection of the mean values of loudness for the cases of idling, 20 and 40 km/hr (Fig. 6-6) it is seen the loudness is roughly twice as high for the case with the driven vehicle when compared with the motored car.

Figure 6-6: Illustration of Loudness vs. Time for Self-Driven (Blue) and Motored (Red) Car on the Dynamometer at 40 km/hr for Passenger’s Right Ear
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On the other hand, for speeds greater than 50 km/hr (Fig 6-7) this difference is much smaller. The fired and motored vehicle at higher speeds differs roughly by a factor of 1.3 in the favour of fired automobile. It’s important to note that the tests performed on the driven car were done in second gear with engine running at wide open throttle. This is the industry standard for vehicle’s interior testing on a dynamometer. By being consistent, it removes the variability between makes and models.

![Graph showing loudness vs. time for self-driven (blue) and motored (red) car on the dynamometer at 50 km/hr for passenger's right ear.](image)

**Figure 6-7: Illustration of Loudness vs. Time for Self-Driven (Blue) and Motored (Red) Car on the Dynamometer at 50 km/hr for Passenger's Right Ear**

It’s important to note that in the previous figure the mean value of loudness differed by less then 5 Sones for the self driven and dynamometer driven vehicle, even under those extreme driving conditions. To illustrate how “small” those variations were, one must remember that similar discrepancies were seen when using different microphones as was discussed in the previous section and illustrated in Figure 6-4. Given that the test conditions are not like normal driving conditions, it would be expected that the values found at higher speeds would be much closer. To support this statement, one can look at the preliminary results that were obtained driving and towing the vehicle at 50 km/hr on
CHAPTER 6. RESULTS & DISCUSSIONS

the testing track. For this case, the engine was running at approximately 2000 rpm and we can see that at the tested road speed, the engine noise contributed little to the overall loudness (Fig. 6-8) within vehicle's cabin since the "driving curve" is only marginally greater than the "towing curve" (mean 16.92 Sones compared to mean 16.51 Sones). This shows that as far as loudness is concerned at the higher speeds, the influence of the engine lessens and the influence of road-tire-suspension interactions increases.

Figure 6-8: Illustration of Loudness vs. Time for Self-Driven (Black) and Towed (Blue) Car on the Testing Track at 50 km/hr for Passenger's Right Ear
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Figure 6 - 9: Illustration of Loudness vs. Time for Motored Car on the Dynamometer at all speeds (Ambient, 20, 40, 50, 60 & 80 km/hr) for Passenger’s Right Ear

Figure 6 - 10: Illustration of Loudness vs. Time for Self-Driven Car on the Dynamometer at all speeds (Idle, 20, 40, 50, 60 & 80 km/hr) for Passenger’s Right Ear
CHAPTER 6. RESULTS & DISCUSSIONS

For the case of the motored car (Fig. 6-9) it can seen that as the vehicle speed is increased, so does the loudness value. There is nothing out of ordinary here. On the other hand, when we look at the loudness at different speeds while the engine is running (Fig. 6-10) quite diverse results were obtained. With an increase in speed up to 40 km/hr, the loudness levels increased as well. However, at 50 km/hr the levels drop significantly. Values of loudness at both 50 and 60 km/hr for this case are much lower than the loudness values at 40 km/hr. It would appear that the engine and/or some other drivetrain components may be affected by the running engine and are resonating at the speed of 40 km/hr. It is suggested that the natural frequency of the cabin interior may be matching the operating frequency of the engine to produce these results. To verify that this is not a case of interpreting the data incorrectly, four independent trials were compared and all provided the same results.

6.3. Roughness with Respect to Different Driving Conditions

In consideration of roughness, it was found that the engine had very little effect. As soon as speed was developed, the major contributors were the tire-surface-suspension interactions. As discussed above, at 40 km/hr there appears to be that “magic speed” where something unusual occurred (Fig. 6-11). At this position, the loudness values varied significantly but not so for the case of roughness, this engine speed had no affect.
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For this case, the values for roughness were even higher for the case of the motored vehicle as oppose to the self-driven car. As the speed increased only slight variations are present. They appear to be higher for the case of the self propelled vehicle for higher speeds but we need to consider the fact that engine was running at extreme operating conditions (second gear with wide open throttle). The presence of resonances is evident since roughness is greatest during conditions of shaking and rattling. Inspection of the preliminary tests (Fig. 6-12) performed on the towed and self driven vehicle also showed that the towed vehicle had higher mean levels indicating the presence of engine noise contributed to the masking of the modulated signal from the road noise.
6.4. Fluctuation Strength with Respect to Different Driving Conditions

Very little contribution to fluctuation strength can be seen from the engine being on, particularly at higher speeds. Low modulations are masked by the engine at speeds above 40 km/hr and up to 80 km/hr (Fig. 6-13). At these high speeds, the fluctuation strength levels are observed can be twice as high for the case of the motored vehicle. However, the levels are very low and as such, very little importance should be given to this metric for this particular study.
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Figure 6-13: Illustration of Fluctuation Strength vs. Time for Self-Driven (Blue) and Motored (Red) Car on the Dynamometer at 80 km/hr for Passenger's Right Ear

6.5. A-weighted Sound Level with Respect to Different Driving Conditions

For the speeds up to 40 km/hr (Fig. 6-14) the engine was a significant contributor to the A-weighted sound level along with the tire-road-suspension interactions. As soon as the speed was increased, the influence of engine lessens. At higher speeds such as 60 km/hr (Fig. 6-15), the difference is less then 3 dB.

Figure 6-14: Illustration of A-weighted SPL vs. Time for Self-Driven (Blue) and Motored (Red) Car on the Dynamometer at 40 km/hr for Passenger's Right Ear
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In this case, an observer is not able to distinguish between the two signals since the difference is so small.

![Illustration of A-weighted SPL vs. Time for Self-Driven (Blue) and Motored (Red) Car on the Dynamometer at 60 km/hr for Passenger's Right Ear](image)

This is also seen when looking at the acceleration curves between the two cases of self-driven and motored vehicle. Since loudness calculations are not valid for unsteady signals, and both roughness and fluctuation strength are derived from loudness, we cannot look at the acceleration data from a psychoacoustic metric perspective. However, dBA levels (Fig. 6-16) can be analyzed for this case. The same conclusions are drawn that at higher speeds, the engine has less effect on the A-weighted sound level.
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As was the case with the other sound quality metrics analyzed, when we look at all speeds at the same time with the engine running (Fig. 6-17), at 40 km/hr resonance appears to occur with the values highest at this point for the case of the steady signal. With inspection of the acceleration data, at this speed small dips and valleys are present. However, these they are not as evident since the vehicle speed approaches resonance much quicker and also moves away from it faster as well.
6.6. FFT-Waterfalls for Acceleration Sweeps

While little additional information is provided by the FFT spectrogram (Fig: 6-18 to 6-21), confirmation of some of the previous observations is given. Specifically, the predominant frequency of the measured noise is in the lower portion of the frequency spectrum. This again is indicative of the road-tire-suspension mechanism being the primary noise contributors. The lack of the high frequency signal again indicates the absence of any aero-acoustic noise generation. This was proven to be valid for both cases of self driven (second gear - WOT) and motored car that was driven from 0 to 80 km/hr. It is also interesting to see the differences between the dB and dBA levels. If one were to base the analysis on SPL (dB) information, misleading results can be experienced from a perceived perspective. In other words, the importance of frequency content is significant, especially at the lower end of the spectrum. Applying weighting filter to the data results
are much better representation on how humans perceive sound levels.

Figure 6 - 18: Illustration of SPL (dB) vs. Time vs. Frequency (0 - 7.5 kHz) for Self-Driven Car for 0-80 Acceleration Sweep for Passenger's Right Ear

Figure 6 - 19: Illustration of A-weighted SPL (dBA) vs. Time vs. Frequency (0-7.5 kHz) for Self-Driven Car for 0-80 Acceleration Sweep for Passenger's Right Ear
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Figure 6-20: Illustration of SPL (dB) vs. Time vs. Frequency (0 - 7.5 kHz) for Motored Car for 0-80 Acceleration Sweep for Passenger’s Right Ear

Figure 6-21: Illustration of A-weighted SPL (dBA) vs. Time vs. Frequency (0 - 7.5 kHz) for Motored Car for 0-80 Acceleration Sweep for Passenger’s Right Ear
6.7. Frequency Response and Coherence Functions

The following section provides some examples of the calculated frequency response functions obtained in order to present a relationship between the system inputs and outputs as well as how they relate to each other. The ten input signals (all at front driver's side) are as follows:

<table>
<thead>
<tr>
<th>Table 6 - 1: List of input transducers used in the experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
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<td>4</td>
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<td>6</td>
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<td>7</td>
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<tr>
<td>8</td>
</tr>
<tr>
<td>9</td>
</tr>
<tr>
<td>10</td>
</tr>
</tbody>
</table>

The system consisted of three microphone outputs from inside of the vehicle:

<table>
<thead>
<tr>
<th>Table 6 - 2: List of output transducers used in the experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
</tbody>
</table>

Testing was done at six different steady speeds as well as an acceleration test from 0 to 80 km/hr. these were all performed with the conditions of the vehicle being driven and
motored. As this provided hundreds of different FRFs and Coherence functions, discussions in this section will be limited to only provide few of the examples to illustrate the main points. The remaining data can be found in the appendix. To be consistent with the results presented in the previous sections, only the right passenger’s ear microphone was used for this evaluation. Typical results for two microphone signals would be similar to Figure 6-22 where the top graph represents the frequency response function and the bottom one shows the coherence function which corresponds to the degree of linearity between the two signals in the frequency domain.

Figure 6-22: Illustration of Frequency Response Function (Top) and Coherence (Bottom) between Outside Microphone and Passenger’s Right Ear for Self-Driven Car at 40 km/hr

Figure 6-23 illustrates the FRFs and coherence of the vibration data signal that is correlated to the pressure inside the vehicle. The blue line represents the longitudinal vibration direction, the red line the lateral and the green line represents the vertical direction of the vibration. All three directions generally follow the same trend; however, the vertical direction usually provides slightly higher results then the other two. This is also the most important direction since humans are most sensitive to vibration in vertical direction. However, this can not be taken as a general rule since at different speeds and at
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different accelerometer positions, variations are present. When inspecting all of the
different inputs (Fig 6-24) one can also see that they are all relatively comparable to each
other and that only slight variations are present. It is difficult to make any kind of general
statement that applies to all the different inputs as well as all the different speeds simply
because there are so many of them.

Figure 6 - 23: Illustration of Frequency Response Functions (Top) and Coherence
(Bottom) between Acc #3 (All three directions and Passenger's Right Ear for Self-Driven
Car at 50 km/hr
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Figure 6 - 24: Illustration of Frequency Response Functions between All 10 inputs and Passenger's Right Ear for Self-Driven Car at 40 km/hr

Figure 6 - 25: Illustration of Coherence levels between All 10 inputs and Passenger's Right Ear for Self-Driven Car at 40 km/hr

Coherence levels should ideally be equal to one or very close to one but unfortunately that is not seen here. The levels are much lower and vary between different trials depending on the speed, accelerometer position, specific direction of excitation and
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different operating conditions. Given the fact that the system is so complex, consisting of
different materials, structural nonlinearities as well as the fact that there are high levels of
damping present, especially for suspension induced vibrations, it is not unexpected that
the coherence levels between the vibro-acoustic inputs and outputs are so low. Looking at
all of the 10 inputs, they all agree at about 400 Hz, but for the remainder of the scale, the
microphone gives better result.

![Illustration of Frequency Response Functions (Top) and Coherence (Bottom) between Acc #1 in Vertical Direction and Passenger's Right Ear for Self-Driven (Blue) and Motored (Red) Car at 20 km/hr](image)

At lower speeds, such as 20 km/hr (Fig. 6-26), it can be seen that there are visible
differences between the FRFs and Coherence functions between the self driven and
motored car. For this particular study, focus was given to the frequency from 0 to 1000
Hz. Thus based on the available scale; at lower speeds the frequency response functions
varied across the entire scale, but especially between 450 to 1000 Hz. On the other hand,
if looking at the higher speeds around 60 km/hr (Fig. 6-27), both cases are almost
identical. Again, this further indicates that the engine and noise sources affected by operating engine do not contribute significantly to the overall vibro-acoustic effects at speeds higher than 40 km/hr. These results are consistent with the findings from the psychoacoustic section was presented earlier.

To verify the quality of the FRFs, especially with the poor coherence levels, one needs to look at how they can be used to predict pressure levels. Obtained frequency response functions were used to calculate and predict pressure values inside the vehicle based on one of the inputs from outside. One of the trials can be used to calculate the FRF from the input and output signals and that FRF would later be applied to one of the input signals from another trial to predict a new value. If one were to look at the original and predicted levels for the case of the motored vehicle at 60 km/hr (Fig 6-28 & 6-29), one could see that the predicted pressure levels are very similar. Both microphone and accelerometer
stimuli can be used to obtain pressure inside the car; however, we need to be aware that different acceleration directions can give better results when compared to others. This section was used to quickly check the validity of predicted results and not to examine all of them.

![Illustration of Original (Top) and Predicted (Bottom) Pressure Levels for Motored Car at 60 km/hr between Outside Microphone and Passenger's Right Ear](image)

**Figure 6-28:** Illustration of Original (Top) and Predicted (Bottom) Pressure Levels for Motored Car at 60 km/hr between Outside Microphone and Passenger's Right Ear
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Figure 6-29: Illustration of Original (Top) and Predicted (Bottom) Pressure Levels for Motored Car at 60 km/hr between Acc #2 in Longitudinal Direction and Passenger's Right Ear

Inspection of the frequency response functions between different inputs and all psychoacoustic metrics of interest is necessary. These were obtained in the same manner as previously during the determination of pressure as an output. The outside microphone was used to illustrate the results given in Figure 6-30. For the FRF calculations, two signals of equal length are required. Given that the data for loudness, roughness, fluctuation strength, and A-weighted pressure levels was represented by a significantly less number of points, input signal needed to be reduced. Because of this fact, we need to look at the predicted levels of all of the metrics before any conclusions can be drawn. By just examining the FRFs in Figure 6-30 and coherence levels in Figure 6-31, one can not really be sure if the results have any meaning. The general shapes of the FRFs look satisfactory even though the coherence levels are not as promising, but it was proven in the previous section that this was not a significant problem as we got quite comparable
results between the original and predicted pressure levels.

Figure 6-30: Illustration of Frequency Response Functions between Sound Quality Metrics and Pressure Levels for Self-Driven Car at 60 km/hr between Outside Microphone and Passenger's Right Ear

Figure 6-31: Illustration of Coherence between Sound Quality Metrics and Pressure Levels for Self-Driven Car at 60 km/hr between Outside Microphone and Passenger's Right Ear
CHAPTER 6. RESULTS & DISCUSSIONS

Unfortunately, for this case, it was proven that the prediction any of sound quality metrics in this manner was unsatisfactory. There are major discrepancies between the original and expected levels for all of the metrics (loudness, roughness, fluctuation strength and A-weighted sound levels) as can be seen in Figures 6-32 thru 6-35.

Figure 6-32: Illustration of Original (Blue) and Predicted (Red) Loudness for Self-Driven Car at 60 km/hr between Outside Microphone and Passenger's Right Ear
CHAPTER 6. RESULTS & DISCUSSIONS

Figure 6-33: Illustration of Original (Blue) and Predicted (Red) Roughness for Self-Driven Car at 60 km/hr between Outside Microphone and Passenger’s Right Ear

Figure 6-34: Illustration of Original (Blue) and Predicted (Red) Fluctuation Strength for Self-Driven Car at 60 km/hr between Outside Microphone and Passenger’s Right Ear
Based on the observations above, one can see that the use of FRFs for the prediction of sound quality metrics is not appropriate given that the predicted results do not even remotely represent expected values. However, one can use already predicted values of pressure obtained earlier in order to calculate the psychoacoustic metrics. The following Figures 6-36 to 6-39 show agreement between the original and calculated levels for all metrics. At this point, the 60 km/hr motored vehicle is taken arbitrary simply to illustrate this point. At this particular speed, the predicted mean levels of A-weighted sound level are within 2 dB with respect to the original data. This represents a variation that can not be distinguished by human perception. Roughness and fluctuation strength showed excellent agreement as well.
CHAPTER 6. RESULTS & DISCUSSIONS

Figure 6-36: Illustration of Original (Red) and Predicted (Green) A-weighted SPL for Motored Car at 60 km/hr found at Passenger’s Right Ear

Figure 6-37: Illustration of Original (Red) and Predicted (Green) Loudness for Motored Car at 60 km/hr found at Passenger’s Right Ear

Jury evaluation consisted of two separate tests. For the first test, the goal was to validate the results given in the Figure 6-10 where the mean loudness values were greatest at the speed of 40km/hr.
CHAPTER 6. RESULTS & DISCUSSIONS

Which sound is LOUDER?

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<th>ENGINE ON 50kph</th>
<th>ENGINE ON 60kph</th>
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<td>22</td>
<td>24</td>
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<td>STAND. DEV.:</td>
<td></td>
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</tbody>
</table>

Figure 6-40: Jury evaluation results for 5 different driving speeds

Inspection of the jury test results given in figure 6-40, similar conclusions as before can be made. All 20 subjects agreed that the sound got louder as the vehicle’s speed increased to 40 km/hr. Passing this point a major drop was observed at the speed of 50 km/hr. Subjective analysis and psychoacoustic observations showed very good agreement. For the second test, random signals were used trying to get a general understanding of the already calculated psychoacoustic metrics. Looking at Figure 6-41, it can be seen again that 18 out of 20 subjects found the signal to be louder for the case of vehicle running at 40 km/hr as opposed to 50 km/hr.
CHAPTER 6. RESULTS & DISCUSSIONS

Q1-Which sound is Louder?

Consider Figure 6-16 where the A-weighted SPLs were compared for both cases of the self driven and motored vehicle and Figure 6-42 where the subjects were asked to choose the more pleasant sound for the acceleration from 0 to 80 km/hr. It was demonstrated earlier that at higher speeds, the engine did not have any effect on the A-weighted SPL. However, by now looking at the responses from jurors, it is also seen that approximately an equal number of subjects chose either the first signal or the second to be the more pleasant, whereas for 25% of the jurors, the stimuli was same.

Figure 6 - 41: Illustration of subject's response for Vehicle running at 40 and 50km/hr

Figure 6 - 42: Illustration of subject's response for acceleration from 0 to 80km/hr

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CHAPTER 6. RESULTS & DISCUSSIONS

One must be careful not to extract any wrong conclusions from some of the subject's responses. For the most part, agreement with the objective observation exist, however, if we were to look at Figure 6-43, it can be seen that since subjects are not trained, approximately half of them indicated that they could hear road noise more so for the case of where the engine was running. For the results for the remaining questions, please refer to appendix C.

![Diagram](image)

**Figure 6 - 43:** Illustration of subject's response for the speed of 20 km/hr for self driven and motored vehicle
Chapter 7

7. CONCLUSIONS & FUTURE WORK

Presently one of the major development issues for the automotive industry is automotive cabin noise. As a result, significant effort is being done to both reduce sound levels as well as improve the sound quality in order to give the consumer a more enjoyable driving environment. Having said this, it is critical to gain an understanding about the different noise sources and their relationship with the receiver points of interest.

7.1. Conclusions

Upon conducting a thorough analysis in addition to reviewing the initial objectives of the study, the following conclusions have been reached:

1. NVH experiments were performed on a vehicle equipped with a passive suspension system in order to benchmark it for future development of an active suspension system. Collected data is now available and may be used in the future for before and after comparison between an active and passive suspension system.

2. Automotive cabin noise was evaluated and compared qualitatively by measuring the road induced noise and vibration of a self-driven and motored vehicle at different driving speeds. Analyses were done using numerical sound quality metrics and were later verified using jury testing evaluation. It was shown that the road-tire-suspension interactions played a significant role on the psychoacoustic perception of the sounds, especially at higher driving speeds. The engine was found to contribute to masking of certain unpleasant components of the sounds.
CHAPTER 7. CONCLUSIONS & FUTURE WORK

These may become more audible if a reduction in engine noise is seen in the future.

3. The transmission paths of the excitation energy experienced in the vehicle cabin from road induced noise and vibration were evaluated using frequency response functions. It was shown that both airborne and structure borne excitations contributed significantly to the overall sound pressure experienced in the cabin. However, not one of the paths can be classified as particularly important given that at different driving conditions, variations were present.

4. An attempt was made to establish a correlation between the noise and vibration measurements from the outside of the vehicle to the noise and psychoacoustic observations inside the vehicle. This was proven to be possible with some inherent limitations. Direct prediction of the sound quality metrics inside the vehicle from both acceleration and sound pressure observed outside of the vehicle cabin did not show compatible results to the measured data. However, it was proven possible to predict the sound pressure for which the psychoacoustic metrics could be calculated indirectly.

7.2. Possible Future Work

The following are suggestions for future work to expand on the presented work.

1. Before and after comparison between active and passive suspension systems.

2. Vibration that can be felt inside the vehicle cabin can influence interior comfort of the occupants. Additional vibration measuring points such as on the steering
CHAPTER 7. CONCLUSIONS & FUTURE WORK

wheel, controlling pedals and the seat should be performed in order to gain a better understanding of this phenomenon.

3. With the available data, it is possible to employ additional sound quality metrics and look at the different aspects of human sound perception within the vehicle (e.g. speech intelligibility).

4. Perform a more comprehensive Jury evaluation focusing on different demographic groups.

5. Collect additional data at more engine speeds and different driving speeds.
REFERENCES


APPENDICES
APPENDIX A - Psychoacoustic Observations

ENGINE ON / OFF

Driver's Left Ear and Passenger's Left and Right Ears

Loudness vs. Time
Roughness vs. Time
Fluctuation Strength vs. Time
dBA vs. Time
Loudness vs. Time - Driver's Left Ear

Figure A1 & A2: Engine ON - Idle (left) & 20 km/hr (right)-Trial 1

Figure A3 & A4: Engine ON - 40 km/hr (left) & 50 km/hr (right)-Trial 1

Figure A5 & A6: Engine ON - 60 km/hr (left) & 80 km/hr (right)-Trial 1

Loudness vs. Time - Passenger's Left Ear

Figure A7 & A8: Engine ON - Idle (left) & 20 km/hr (right)-Trial 1

Figure A9 & A10: Engine ON - 40 km/hr (left) & 50 km/hr (right)-Trial 1
Loudness vs. Time – Passenger’s Left Ear

Figure A11 & A12: Engine ON – 60 km/hr (left) & 80 km/hr (right)-Trial 1

Loudness vs. Time – Passenger’s Right Ear

Figure A13 & A14: Engine ON – Idle (left) & 20 km/hr (right)-Trial 1

Figure A15 & A16: Engine ON – 40 km/hr (left) & 50 km/hr (right)-Trial 1

Figure A17 & A18: Engine ON – 60 km/hr (left) & 80 km/hr (right)-Trial 1
Roughness vs. Time - Driver’s Left Ear

Figure A19 & A20: Engine ON - Idle (left) & 20 km/hr (right)-Trial 1

Figure A21 & A22: Engine ON - 40 km/hr (left) & 50 km/hr (right)-Trial 1

Figure A23 & A24: Engine ON - 60 km/hr (left) & 80 km/hr (right)-Trial 1

Roughness vs. Time - Passenger’s Left Ear

Figure A25 & A26: Engine ON - Idle (left) & 20 km/hr (right)-Trial 1

Figure A27 & A28: Engine ON - 40 km/hr (left) & 50 km/hr (right)-Trial 1
Roughness vs. Time – Passenger’s Left Ear

Figure A29 & A30: Engine ON – 60 km/hr (left) & 80 km/hr (right)-Trial 1

Roughness vs. Time – Passenger’s Right Ear

Figure A31 & A32: Engine ON – Idle (left) & 20 km/hr (right)-Trial 1

Figure A33 & A34: Engine ON – 40 km/hr (left) & 50 km/hr (right)-Trial 1

Figure A35 & A36: Engine ON – 60 km/hr (left) & 80 km/hr (right)-Trial 1
Fluctuation Strength vs. Time - Driver's Left Ear

Figure A37 & A38: Engine ON – Idle (left) & 20 km/hr (right) - Trial 1

Figure A39 & A40: Engine ON – 40 km/hr (left) & 50 km/hr (right) - Trial 1

Figure A41 & A42: Engine ON – 60 km/hr (left) & 80 km/hr (right) - Trial 1

Fluctuation Strength vs. Time – Passenger’s Left Ear

Figure A43 & A44: Engine ON – Idle (left) & 20 km/hr (right) - Trial 1

Figure A45 & A46: Engine ON – 40 km/hr (left) & 50 km/hr (right) - Trial 1
Fluctuation Strength vs. Time – Passenger’s Left Ear

Figure A47 & A48: Engine ON – 60 km/hr (left) & 80 km/hr (right)-Trial 1

Fluctuation Strength vs. Time – Passenger’s Right Ear

Figure A49 & A50: Engine ON – Idle (left) & 20 km/hr (right)-Trial 1

Figure A51 & A52: Engine ON – 40 km/hr (left) & 50 km/hr (right)-Trial 1

Figure A53 & A54: Engine ON – 60 km/hr (left) & 80 km/hr (right)-Trial 1
**dBA vs. Time - Driver's Left Ear**

Figure A55 & A56: Engine ON - Idle (left) & 20 km/hr (right) - Trial 1

Figure A57 & A58: Engine ON - 40 km/hr (left) & 50 km/hr (right) - Trial 1

Figure A59 & A60: Engine ON - 60 km/hr (left) & 80 km/hr (right) - Trial 1

Figure A61: Engine ON - 0-80 km/hr - Trial 1

**dBA vs. Time - Passenger's Left Ear**

Figure A62 & A63: Engine ON - Idle (left) & 20 km/hr (right) - Trial 1

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dBA vs. Time – Passenger’s Left Ear

Figure A64 & A65: Engine ON – 40 km/hr (left) & 50 km/hr (right)-Trial 1

Figure A66 & A67: Engine ON – 60 km/hr (left) & 80 km/hr (right)-Trial 1

Figure A68: Engine ON – 0-80 km/hr-Trial 1

dBA vs. Time – Passenger’s Right Ear

Figure A69 & A70: Engine ON – Idle (left) & 20 km/hr (right)-Trial 1

Figure A71 & A72: Engine ON – 40 km/hr (left) & 50 km/hr (right)-Trial 1
dBA vs. Time – Passenger’s Right Ear

Figure A73 & A74: Engine ON – 60 km/hr (left) & 80 km/hr (right) – Trial 1

Figure A75: Engine ON – 0-80 km/hr – Trial 1
Loudness vs. Time - Driver's Left Ear

Figure A76 & A77: Engine OFF - Idle (left) & 20 km/hr (right) - Trial 1

Figure A78 & A79: Engine OFF - 40 km/hr (left) & 50 km/hr (right) - Trial 1

Figure A80 & A81: Engine OFF - 60 km/hr (left) & 80 km/hr (right) - Trial 1

Loudness vs. Time - Passenger's Left Ear

Figure A82 & A83: Engine OFF - Idle (left) & 20 km/hr (right) - Trial 1

Figure A84 & A85: Engine OFF - 40 km/hr (left) & 50 km/hr (right) - Trial 1
Loudness vs. Time – Passenger’s Left Ear

Figure A86 & A87: Engine OFF – 60 km/hr (left) & 80 km/hr (right)-Trial 1

Loudness vs. Time – Passenger’s Right Ear

Figure A88 & A89: Engine OFF – Idle (left) & 20 km/hr (right)-Trial 1

Figure A90 & A91: Engine OFF – 40 km/hr (left) & 50 km/hr (right)-Trial 1

Figure A92 & A93: Engine OFF – 60 km/hr (left) & 80 km/hr (right)-Trial 1
Roughness vs. Time - Driver’s Left Ear

Figure A94 & A95: Engine OFF - Idle (left) & 20 km/hr (right)-Trial 1

Figure A96 & A97: Engine OFF - 40 km/hr (left) & 50 km/hr (right)-Trial 1

Figure A98 & A99: Engine OFF - 60 km/hr (left) & 80 km/hr (right)-Trial 1

Roughness vs. Time - Passenger’s Left Ear

Figure A100 & A101: Engine OFF - Idle (left) & 20 km/hr (right)-Trial 1

Figure A102 & A103: Engine OFF - 40 km/hr (left) & 50 km/hr (right)-Trial 1
Roughness vs. Time - Passenger's Left Ear

Figure A104 & A105: Engine OFF – 60 km/hr (left) & 80 km/hr (right)-Trial 1

Roughness vs. Time - Passenger's Right Ear

Figure A106 & A107: Engine OFF – Idle (left) & 20 km/hr (right)-Trial 1

Figure A108 & A109: Engine OFF – 40 km/hr (left) & 50 km/hr (right)-Trial 1

Figure A110 & A111: Engine OFF – 60 km/hr (left) & 80 km/hr (right)-Trial 1
Fluctuation Strength vs. Time - Driver’s Left Ear

Figure A112 & A113: Engine OFF - Idle (left) & 20 km/hr (right)-Trial 1

Figure A114 & A115: Engine OFF - 40 km/hr (left) & 50 km/hr (right)-Trial 1

Figure A116 & A117: Engine OFF - 60 km/hr (left) & 80 km/hr (right)-Trial 1

Fluctuation Strength vs. Time – Passenger’s Left Ear

Figure A118 & A119: Engine OFF - Idle (left) & 20 km/hr (right)-Trial 1

Figure A120 & A121: Engine OFF - 40 km/hr (left) & 50 km/hr (right)-Trial 1
Fluctuation Strength vs. Time – Passenger's Left Ear

Figure A122 & A123: Engine OFF – 60 km/hr (left) & 80 km/hr (right)-Trial 1

Fluctuation Strength vs. Time – Passenger's Right Ear

Figure A124 & A125: Engine OFF – Idle (left) & 20 km/hr (right)-Trial 1

Figure A126 & A127: Engine OFF – 40 km/hr (left) & 50 km/hr (right)-Trial 1

Figure A128 & A129: Engine OFF – 60 km/hr (left) & 80 km/hr (right)-Trial 1
dBA vs. Time - Driver's Left Ear

Figure A130 & A131: Engine OFF - Idle (left) & 20 km/hr (right)-Trial 1

Figure A132 & A133: Engine OFF - 40 km/hr (left) & 50 km/hr (right)-Trial 1

Figure A134 & A135: Engine OFF - 60 km/hr (left) & 80 km/hr (right)-Trial 1

Figure A136: Engine OFF - 0-80 km/hr-Trial 1

dBA vs. Time - Passenger's Left Ear

Figure A137 & A138: Engine OFF - Idle (left) & 20 km/hr (right)-Trial 1
dBA vs. Time – Passenger’s Left Ear

Figure A139 & A140: Engine OFF -40 km/hr (left) & 50 km/hr (right)-Trial 1

Figure A141 & A142: Engine OFF -60 km/hr (left) & 80 km/hr (right)-Trial 1

Figure A143: Engine OFF -0-80 km/hr-Trial 1

dBA vs. Time – Passenger’s Right Ear

Figure A144 & A145: Engine OFF -Idle (left) & 20 km/hr (right)-Trial 1

Figure A146 & A147: Engine OFF -40 km/hr (left) & 50 km/hr (right)-Trial 1
dBA vs. Time – Passenger’s Right Ear

Figure A148 & A149: Engine OFF – 60 km/hr (left) & 80 km/hr (right)-Trial 1

Figure A150: Engine OFF – 0-80 km/hr-Trial 1
APPENDIX B - Frequency Response Functions & Coherence
Outside Microphone & Driver's Left Ear

Figure B1 & B2: (Engine ON-Idle)-Trial 1

Outside Microphone & Driver's Left Ear

Figure B3 & B4: (Engine ON-20 km/hr)-Trial 1

Outside Microphone & Driver's Left Ear

Figure B5 & B6: (Engine ON-40 km/hr)-Trial 1
Figure B7 & B8: (Engine ON-50 km/hr)-Trial 1

Figure B9 & B10: (Engine ON-60 km/hr)-Trial 1

Figure B11 & B12: (Engine ON-80 km/hr)-Trial 1
Figure B13 & B14: (Engine ON-0 to 80 km/hr)-Trial 1
Outside Microphone & Passenger's Left Ear

Figure B15 & B16: (Engine ON-Idle)-Trial 1

Outside Microphone & Passenger's Left Ear

Figure B17 & B18: (Engine ON-20 km/hr)-Trial 1

Outside Microphone & Passenger's Left Ear

Figure B19 & B20: (Engine ON-40 km/hr)-Trial 1
### Figure B21 & B22: (Engine ON-50 km/hr)-Trial 1

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### Figure B23 & B24: (Engine ON-60 km/hr)-Trial 1

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### Figure B25 & B26: (Engine ON-80 km/hr)-Trial 1

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Figure B27 & B28: (Engine ON-0 to 80 km/hr)-Trial 1
Figure B29 & B30: (Engine ON-Idle)-Trial 1

Figure B31 & B32: (Engine ON-20 km/hr)-Trial 1

Figure B33 & B34: (Engine ON-40 km/hr)-Trial 1
Outside Microphone & Passenger’s Right Ear

Figure B35 & B36: Ear (Engine ON-50 km/hr)-Trial 1

Figure B37 & B38: (Engine ON-60 km/hr)-Trial 1

Figure B39 & B40: (Engine ON-80 km/hr)-Trial 1
Outside Microphone & Passenger’s Right Ear

Figure B41 & B42: (Engine ON-0-80 km/hr)-Trial 1
Figure B43 & B44: (Engine ON-Idle)-Trial 1

Figure B45 & B46: (Engine ON-20 km/hr)-Trial 1

Figure B47 & B48: (Engine ON-40 km/hr)-Trial 1
### Acc #1 (wheel hub) (longitudinal, lateral, vertical) & Driver’s Left Ear

#### Figure B49 & B50: (Engine ON-50 km/hr)-Trial 1

#### Figure B51 & B52: (Engine ON-60 km/hr)-Trial 1

#### Figure B53 & B54: (Engine ON-80 km/hr)-Trial 1
Ace #1 (wheel hub) (longitudinal, lateral, vertical) & Driver's Left Ear

Figure B55 & B56: (Engine ON-0-80 km/hr)-Trial 1
Figure B57 & B58: (Engine ON-Idle)-Trial 1

Figure B59 & B60: (Engine ON-20 km/hr)-Trial 1

Figure B61 & B62: (Engine ON-40 km/hr)-Trial 1
Ace #1 (wheel hub) (longitudinal, lateral, vertical) & Passenger’s Left Ear

Figure B63 & B64: (Engine ON-50 km/hr)-Trial 1

Ace #1 (wheel hub) (longitudinal, lateral, vertical) & Passenger’s Left Ear

Figure B65 & B66: (Engine ON-60 km/hr)-Trial 1

Ace #1 (wheel hub) (longitudinal, lateral, vertical) & Passenger’s Left Ear

Figure B67 & B68: (Engine ON-80 km/hr)-Trial 1
Figure B69 & B70: (Engine ON-0-80 km/hr)-Trial 1
Ace #1 (wheel hub) (longitudinal, lateral, vertical) & Passenger’s Right Ear

Figure B71 & B72: (Engine ON-Idle)-Trial 1

Ace #1 (wheel hub) (longitudinal, lateral, vertical) & Passenger’s Right Ear

Figure B73 & B74: (Engine ON-20 km/hr)-Trial 1

Ace #1 (wheel hub) (longitudinal, lateral, vertical) & Passenger’s Right Ear

Figure B75 & B76: (Engine ON-40 km/hr)-Trial 1
Ace #1 (wheel hub) (longitudinal, lateral, vertical) & Passenger's Right Ear

Figure B77 & B78: (Engine ON-50 km/hr)-Trial 1

Ace #1 (wheel hub) (longitudinal, lateral, vertical) & Passenger's Right Ear

Figure B79 & B80: (Engine ON-60 km/hr)-Trial 1

Ace #1 (wheel hub) (longitudinal, lateral, vertical) & Passenger's Right Ear

Figure B81 & B82: (Engine ON-80 km/hr)-Trial 1
Figure B83 & B84: (Engine ON-0-80 km/hr)-Trial 1
Figure B85 & B86: (Engine ON-Idle)-Trial 1

Figure B87 & B88: (Engine ON-20 km/hr)-Trial 1

Figure B89 & B90: (Engine ON-40 km/hr)-Trial 1
Figure B91 & B92: (Engine ON-50 km/hr)-Trial 1

Figure B93 & B94: (Engine ON-60 km/hr)-Trial 1

Figure B95 & B96: (Engine ON-80 km/hr)-Trial 1
Ace #2 (lower A-arm) (longitudinal, lateral, vertical) & Driver's Left Ear

Figure B97 & B98: (Engine ON-0-80 km/hr)-Trial 1
Figure B99 & B100: (Engine ON-Idle)-Trial 1

Figure B101 & B102: (Engine ON-20 km/hr)-Trial 1

Figure B103 & B104: (Engine ON-40 km/hr)-Trial 1
Figure B105 & B106: (Engine ON-50 km/hr)-Trial 1

Figure B107 & B108: (Engine ON-60 km/hr)-Trial 1

Figure B109 & B110: (Engine ON-80 km/hr)-Trial 1
Figure B111 & B112: (Engine ON-0-80 km/hr)-Trial 1
Acc #2 (lower A-arm) (longitudinal, lateral, vertical) & Passenger’s Right Ear

Figure B113 & B114: (Engine ON-Idle)-Trial 1

Acc #2 (lower A-arm) (longitudinal, lateral, vertical) & Passenger’s Right Ear

Figure B115 & B116: (Engine ON-20 km/hr)-Trial 1

Acc #2 (lower A-arm) (longitudinal, lateral, vertical) & Passenger’s Right Ear

Figure B117 & B118: (Engine ON-40 km/hr)-Trial 1
Figure B119 & B120: (Engine ON-50 km/hr)-Trial 1

Figure B121 & B122: (Engine ON-60 km/hr)-Trial 1

Figure B123 & B124: (Engine ON-80 km/hr)-Trial 1
Figure B125 & B126: (Engine ON-0-80 km/hr)-Trial 1
Figure B133 & B134: (Engine ON-50 km/hr)-Trial 1

Figure B135 & B136: (Engine ON-60 km/hr)-Trial 1

Figure B137 & B138: (Engine ON-80 km/hr)-Trial 1
Figure B139 & B140: (Engine ON-0-80 km/hr)-Trial 1
Figure B141 & B142: (Engine ON-Idle)-Trial 1

Figure B143 & B144: (Engine ON-20 km/hr)-Trial 1

Figure B145 & B146: (Engine ON-40 km/hr)-Trial 1
Figure B147 & B148: (Engine ON-50 km/hr)-Trial 1

Figure B149 & B150: (Engine ON-60 km/hr)-Trial 1

Figure B151 & B152: (Engine ON-80 km/hr)-Trial 1
Acc #3 (strut-top) (longitudinal, lateral, vertical) & Passenger's Left Ear

Figure B153 & B154: (Engine ON-0-80 km/hr)-Trial 1
Figure B155 & B156: (Engine ON-Idle)-Trial 1

Figure B157 & B158: (Engine ON-20 km/hr)-Trial 1

Figure B159 & B160: (Engine ON-40 km/hr)-Trial 1
Figure B161 & B162: (Engine ON-50 km/hr)-Trial 1

Figure B163 & B164: (Engine ON-60 km/hr)-Trial 1

Figure B165 & B166: (Engine ON-80 km/hr)-Trial 1
Ace #3 (strut-top) (longitudinal, lateral, vertical) & Passenger’s Right Ear

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Figure B167 & B168: (Engine ON-0-80 km/hr)-Trial 1
Outside Microphone & Driver's Left Ear

Figure B169 & B170: (Engine OFF-Ambient)-Trial 1

Outside Microphone & Driver's Left Ear

Figure B171 & B172: (Engine OFF-20 km/hr)-Trial 1

Outside Microphone & Driver's Left Ear

Figure B173 & B174: (Engine OFF-40 km/hr)-Trial 1
Figure B175 & B176: (Engine OFF -50 km/hr)-Trial 1

Figure B177 & B178: (Engine OFF -60 km/hr)-Trial 1

Figure B179 & B180: (Engine OFF -80 km/hr)-Trial 1
Outside Microphone & Driver's Left Ear

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Figure B181 & B182: (Engine OFF -0 to 80 km/hr)-Trial 1
Outside Microphone & Passenger’s Left Ear

Figure B183 & B184: (Engine OFF - Ambient)-Trial 1

Outside Microphone & Passenger’s Left Ear

Figure B185 & B186: (Engine OFF -20 km/hr)-Trial 1

Outside Microphone & Passenger’s Left Ear

Figure B187 & B188: (Engine OFF -40 km/hr)-Trial 1
Outside Microphone & Passenger's Left Ear

Figure B189 & B190: (Engine OFF -50 km/hr)-Trial 1

Outside Microphone & Passenger's Left Ear

Figure B191 & B192: (Engine OFF -60 km/hr)-Trial 1

Outside Microphone & Passenger's Left Ear

Figure B193 & B194: (Engine OFF -80 km/hr)-Trial 1

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Outside Microphone & Passenger’s Left Ear

Figure B195 & B196: (Engine OFF -0 to 80 km/hr)-Trial 1
Outside Microphone & Passenger's Right Ear

Figure B197 & B198: (Engine OFF - Ambient)-Trial 1

Outside Microphone & Passenger's Right Ear

Figure B199 & B200: (Engine OFF -20 km/hr)-Trial 1

Outside Microphone & Passenger's Right Ear

Figure B201 & B202: (Engine OFF -40 km/hr)-Trial 1
Figure B203 & B204: Ear (Engine OFF -50 km/hr)-Trial 1

Figure B205 & B206: (Engine OFF -60 km/hr)-Trial 1

Figure B207 & B208: (Engine OFF -80 km/hr)-Trial 1
Figure B209 & B210: (Engine OFF -0-80 km/hr)-Trial 1
Figure B211 & B212: (Engine OFF - Ambient)-Trial 1

Figure B213 & B214: (Engine OFF - 20 km/hr)-Trial 1

Figure B215 & B216: (Engine OFF - 40 km/hr)-Trial 1
Figure B217 & B218: (Engine OFF -50 km/hr)-Trial 1

Figure B219 & B220: (Engine OFF -60 km/hr)-Trial 1

Figure B221 & B222: (Engine OFF -80 km/hr)-Trial 1
### Acc #1 (wheel hub) (longitudinal, lateral, vertical) & Driver's Left Ear

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<th>Average [0-60 Trial 1]</th>
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<th>-20.0</th>
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<td>Average [0-60 Trial 1]</td>
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<td>-20.0</td>
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Figure B223 & B224: (Engine OFF -0-80 km/hr) - Trial 1

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Ace #1 (wheel hub) (longitudinal, lateral, vertical) & Passenger's Left Ear

Figure B225 & B226: (Engine OFF - Ambient)-Trial 1

Figure B227 & B228: (Engine OFF -20 km/hr)-Trial 1

Figure B229 & B230: (Engine OFF -40 km/hr)-Trial 1
Figure B231 & B232: (Engine OFF -50 km/hr)-Trial 1

Figure B233 & B234: (Engine OFF -60 km/hr)-Trial 1

Figure B235 & B236: (Engine OFF -80 km/hr)-Trial 1
Acc #1 (wheel hub) (longitudinal, lateral, vertical) & Passenger’s Left Ear

Figure B237 & B238: (Engine OFF -0-80 km/hr)-Trial 1
**Figure B239 & B240: (Engine OFF - Ambient)-Trial 1**

**Figure B241 & B242: (Engine OFF -20 km/hr)-Trial 1**

**Figure B243 & B244: (Engine OFF -40 km/hr)-Trial 1**
Ace #1 (wheel hub) (longitudinal, lateral, vertical) & Passenger’s Right Ear

Figure B245 & B246: (Engine OFF -50 km/hr)-Trial 1

Ace #1 (wheel hub) (longitudinal, lateral, vertical) & Passenger’s Right Ear

Figure B247 & B248: (Engine OFF -60 km/hr)-Trial 1

Ace #1 (wheel hub) (longitudinal, lateral, vertical) & Passenger’s Right Ear

Figure B249 & B250: (Engine OFF -80 km/hr)-Trial 1
Figure B251 & B252: (Engine OFF -0-80 km/hr)-Trial 1
Figure B253 & B254: (Engine OFF - Ambient) - Trial 1

Figure B255 & B256: (Engine OFF - 20 km/hr) - Trial 1

Figure B257 & B258: (Engine OFF - 40 km/hr) - Trial 1
Ace #2 (lower A-arm) (longitudinal, lateral, vertical) & Driver's Left Ear

![Graph of Engine OFF -50 km/hr](image)

Figure B259 & B260: (Engine OFF -50 km/hr)-Trial 1

Ace #2 (lower A-arm) (longitudinal, lateral, vertical) & Driver's Left Ear

![Graph of Engine OFF -60 km/hr](image)

Figure B261 & B262: (Engine OFF -60 km/hr)-Trial 1

Ace #2 (lower A-arm) (longitudinal, lateral, vertical) & Driver's Left Ear

![Graph of Engine OFF -80 km/hr](image)

Figure B263 & B264: (Engine OFF -80 km/hr)-Trial 1

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Figure B265 & B266: (Engine OFF -0-80 km/hr)-Trial 1
Acc #2 (lower A-arm) (longitudinal, lateral, vertical) & Passenger’s Left Ear

Figure B267 & B268: (Engine OFF - Ambient)-Trial 1

Acc #2 (lower A-arm) (longitudinal, lateral, vertical) & Passenger’s Left Ear

Figure B269 & B270: (Engine OFF - 20 km/hr)-Trial 1

Acc #2 (lower A-arm) (longitudinal, lateral, vertical) & Passenger’s Left Ear

Figure B271 & B272: (Engine OFF - 40 km/hr)-Trial 1
Figure B273 & B274: (Engine OFF -50 km/hr)-Trial 1

Figure B275 & B276: (Engine OFF -60 km/hr)-Trial 1

Figure B277 & B278: (Engine OFF -80 km/hr)-Trial 1
Ace #2 (lower A-arm) (longitudinal, lateral, vertical) & Passenger’s Left Ear

| ID | Average Ht (0-1) - Motoried 0-80 Trial Position 1 - 2X | 0.05 | -54.3 |
| ID-1 | Average Ht (0-1) - Motoried 0-80 Trial Position 1 - 2Y | 0.05 | -56.1 |
| ID-1 | Average Ht (0-1) - Motoried 0-80 Trial Position 1 - 2Z | 0.05 | -52.1 |

Figure B279 & B280: (Engine OFF -0-80 km/hr)-Trial 1
Figure B281 & B282: (Engine OFF - Ambient)-Trial 1

Figure B283 & B284: (Engine OFF - 20 km/hr)-Trial 1

Figure B285 & B286: (Engine OFF - 40 km/hr)-Trial 1
### Acc #2 (lower A-arm) (longitudinal, lateral, vertical) & Passenger's Right Ear

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<th>Mirrored 50° Thre Position1 - ZZ</th>
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<td>229</td>
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<td>230</td>
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Figure B287 & B288: (Engine OFF -50 km/hr)-Trial 1

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<tr>
<td>230</td>
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<td>0.13%</td>
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Figure B289 & B290: (Engine OFF -60 km/hr)-Trial 1

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<td>-81%</td>
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<td>229</td>
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Figure B291 & B292: (Engine OFF -80 km/hr)-Trial 1

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Ace #2 (lower A-arm) (longitudinal, lateral, vertical) & Passenger’s Right Ear

Figure B293 & B294: (Engine OFF -0-80 km/hr)-Trial 1
Acc #3 (strut-top) (longitudinal, lateral, vertical) & Driver’s Left Ear

Figure B295 & B296: (Engine OFF -Idle)-Trial 1

Acc #3 (strut-top) (longitudinal, lateral, vertical) & Driver’s Left Ear

Figure B297 & B298: (Engine OFF -20 km/hr)-Trial 1

Acc #3 (strut-top) (longitudinal, lateral, vertical) & Driver’s Left Ear

Figure B299 & B300: (Engine OFF -40 km/hr)-Trial 1
Figure B301 & B302: (Engine OFF -50 km/hr)-Trial 1

Figure B303 & B304: (Engine OFF -60 km/hr)-Trial 1

Figure B305 & B306: (Engine OFF -80 km/hr)-Trial 1
Figure B307 & B308: (Engine OFF -0-80 km/hr)-Trial 1
Ace #3 (strut-top) (longitudinal, lateral, vertical) & Passenger's Left Ear

Figure B309 & B310: (Engine OFF -Idle)-Trial 1

Ace #3 (strut-top) (longitudinal, lateral, vertical) & Passenger's Left Ear

Figure B311 & B312: (Engine OFF -20 km/hr)-Trial 1

Ace #3 (strut-top) (longitudinal, lateral, vertical) & Passenger's Left Ear

Figure B313 & B314: (Engine OFF -40 km/hr)-Trial 1
Figure B315 & B316: (Engine OFF -50 km/hr)-Trial 1

Figure B317 & B318: (Engine OFF -60 km/hr)-Trial 1

Figure B319 & B320: (Engine OFF -80 km/hr)-Trial 1
Ace #3 (strut-top) (longitudinal, lateral, vertical) & Passenger’s Left Ear

Figure B321 & B322: (Engine OFF -0-80 km/hr) - Trial 1

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Ace #3 (strut-top) (longitudinal, lateral, vertical) & Passenger’s Right Ear

Figure B323 & B324: (Engine OFF -Idle)-Trial 1

Ace #3 (strut-top) (longitudinal, lateral, vertical) & Passenger’s Right Ear

Figure B325 & B326: (Engine OFF -20 km/hr)-Trial 1

Ace #3 (strut-top) (longitudinal, lateral, vertical) & Passenger’s Right Ear

Figure B327 & B328: (Engine OFF -40 km/hr)-Trial 1
Figure B329 & B330: (Engine OFF -50 km/hr)-Trial 1

Figure B331 & B332: (Engine OFF -60 km/hr)-Trial 1

Figure B333 & B334: (Engine OFF -80 km/hr)-Trial 1
Figure B335 & B336: (Engine OFF - 0-80 km/hr) - Trial 1
APPENDIX C - Jury Testing Responses
Q1-Which sound is Louder?

Figure C1: Subjects' responses on the question which sound is LOUDER between Engine ON-50 km/hr and Engine ON-40km/hr

Q2-Which sound is Louder?

Figure C2: Subjects' responses on the question which sound is LOUDER between Engine OFF-60 km/hr and Engine ON-60km/hr
Figure C3: Subjects’ responses on the question which sound is more PLEASANT between Engine OFF-80 km/hr and Engine ON-80km/hr

Figure C4: Subjects’ responses on the question which sound is more PLEASANT between Engine OFF-0-80 km/hr and Engine ON-0-80km/hr
Q5-Which sound is ENGINE dominant?

![Graph showing responses]

Figure C5: Subjects' responses on the question which sound is more ENGINE dominant between Engine ON-40 km/hr and Engine OFF-40 km/hr

Q6-Which sound is ENGINE dominant?

![Graph showing responses]

Figure C6: Subjects' responses on the question which sound is more ENGINE dominant between Engine ON-80 km/hr and Engine ON-50 km/hr
Q7-Which sound is ROAD dominant?

Figure C7: Subjects' responses on the question which sound is more ROAD dominant between Engine OFF-40 km/hr and Engine OFF-60km/hr

Q8-Which sound is ROAD dominant?

Figure C8: Subjects' responses on the question which sound is more ROAD dominant between Engine ON-20 km/hr and Engine OFF-20km/hr
Q9-Which sound do you PREFERE?

Figure C9: Subjects' responses on the question which sound do they PREFERE between Engine OFF-60 km/hr and Engine ON-60 km/hr

Q10-Which sound do you PREFERE?

Figure C10: Subjects' responses on the question which sound do they PREFERE between Engine OFF-80 km/hr and Engine OFF-40 km/hr
Q11-Which sound is ROUGHER?

Figure C11: Subject's responses on the question which sound is ROUGHER between Engine OFF-50 km/hr and Engine OFF-80 km/hr

Q12-Which sound is ROUGHER?

Figure C12: Subject's responses on the question which sound is ROUGHER between Engine OFF-40 km/hr and Engine OFF-40 km/hr
Q13-Which sound is more ANNOYING?

Figure C13: Subjects' responses on the question which sound is more ANNOYING between Engine ON-Idle and Engine ON-60km/hr

Q14-Which sound is more ANNOYING?

Figure C14: Subjects' responses on the question which sound is more ANNOYING between Engine ON-0-80km/hr and Engine OFF-0-80km/hr
VITA AUCTORIS

Nebojša Radić was born in 1979 in Sarajevo, Yugoslavia. He graduated from Petar Kocic High School in Zvornik, Republika Srpska in 1997. In 2002 he graduated from St. Clair College in Windsor, Ontario with a Mechanical Engineering Technology Diploma - Automotive Design Option. Soon after, he attended the University of Windsor where he gets B.A.Sc. in Mechanical Engineering/Automotive Option in 2005. He is currently a candidate for the Master's degree in Mechanical Engineering at the University of Windsor. He presented following work in non-refereed conference proceedings:
