The psychoacoustics of electric vehicle signature sound.

by

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Supervisor: Dr. A. Bekker

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Abstract

The psychoacoustics of electric vehicle signature sound.

D.J. Swart

Dissertation: PhD (Engineering)

March 2018

The automotive industry is currently exploring the global sound sphere to identify a pleasant, safe and unique electric vehicle signature sound. Drive-train acoustics contribute to the performance benchmark of vehicles in the marketplace. Electric vehicle sound signatures differ vastly from those of internal combustion engines. Questions arise as to how these signature sounds relate to consumer experiences, and how the positive attributes of these sounds can be extracted and enhanced. The presented work aimed to investigate the objectively and subjectively evaluated attributes of electric vehicle signature sound, and the associated consumer satisfaction. A subjective evaluation procedure for the classification of the noise produced by electric vehicles was adapted from existing methodologies for internal combustions engines. It was found that ‘Calm’, ‘Deep’, ‘Rumbling’,‘Creative’ and ‘Futuristic’ semantics should be added to existing tests to typically describe electric vehicle sound character. The sound signatures of six standard production electric vehicles and one hybrid electric vehicle were benchmarked through constant speed and Wide Open Throttle drives. Time and frequency domain analyses were used to compare the different vehicles, and results revealed that electric vehicles contain substantial sound energy in the upper frequency bands due to the tonal components. Lower sound pressure levels

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were achieved in a multi-stage gearbox, with regards to the high frequency content associated with electric motors. High Prominence Ratio levels, in excess of 10 dB, were found for electric vehicles and current literature points to diminished consumer satisfaction as a result. Furthermore, standard production electric vehicle sound signatures were evaluated against enhanced sound stimuli, based on subjective semantics and objective metrics, to determine the dimensions of electric vehicle sound quality that can lead to improved consumer satisfaction. The methodology was to undertake two independent subjective evaluations, performed by a jury of 32 and 52 members respectively, to determine the perceived electric vehicle sound experience. Results showed that Sharpness is fundamental to governing the electric vehicle sound experience. Secondly, the underlying dimensions of electric vehicle sound quality are sparsely described in literature and was therefore investigated. A factor analysis found that additional to the dimensions of refinement and powerfulness of internal combustion vehicle sound, electric vehicles also have a third dimension associated with a 'Futuristic' factor. Lastly, a consumer satisfaction model was proposed through multiple linear regression and the 95^{th} percentile Sharpness value. The model yielded promising results for both interior and motorbay sound signatures and is proposed as a means of gauging consumer satisfaction for electric vehicle sound quality. The complexity of electric vehicle sound character was discussed and recommendations were offered with respect to the design considerations of future electric vehicle sound signatures. A holistic approach regarding both subjective and objective evaluation methods is recommended for future electric vehicle research, in order to fully understand the attributes that govern electric vehicle sound quality.

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Uittreksel

Die psigo-akoestiek van die handelsmerk-klank van elektriese voertuie.

D.J. Swart

Proefskrif: PhD (Ingenieurswese)

Maart 2018

Die voertuig industrie is huidiglik op soek na ’n unieke elektriese voertuigklank binne die globale klankruimte, wat uniek is en ‘n gevoel van genot en veiligheid oordra. Die akoestiek van die aandryfstelsel dra by tot die prestasie-maatstaf van voertuie binne die mark. Elektriese voertuig handelsmerk-klank verskil baie van dié van binnebrandenjins. Vrae ontstaan oor hoe hierdie handelsmerk-klanke verband hou met verbruikerservarings, en hoe die positiewe eienskappe van hierdie klanke onthul en verbeter kan word. Die uiteengesette werk het ten doel om die objektiewe en subjektiewe geëvalueerde eienskappe van elektriese voertuig handelsmerk-klank, en die gepaardgaande verbruikersbevrediging, te ondersoek. ‘n Subjektiewe evalueringsprosedure vir die klassifikasie van die geraas wat deur elektriese voertuie weergegee word, is aangepas uit bestaande metodologieë vir binnebrandenjins. Daar is bevind dat die ‘Rustige’, ‘Diep ’, ‘ Dreunende’, ‘Kreatiewe’ en‘ Futuristiese’ semantiek by bestaande toetse gevoeg moet word om die tipiese elektriese voertuigklankkarakter te beskryf. Die handelsmerk-klank van ses standaard produksie elektriese voertuie en een hibriede elektriese voertuig is deur middel van ritte teen konstante spoed en volle versnelling getoets. Tyd en frekwensie domein analise is gebruik om die verskillende voertuie te eva-

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lueer. Bevindings het getoon dat elektriese voertuie merkwaardige klankenergie in die hoë frekwensie bande vertoon, as gevolg van die tonale klankkomponente. Laer klankpeilvlakke is bevind in die veelvuldige ratkasstelsel met inaggenome die hoë frekwensie geraas wat met elektriese motors geassosieër word. Hoë vlakke (>10 dB) van prominente tone is ondervind op elektriese voertuie en bestaande literatuur koppel dit aan verlaagde verbruiker-tevredenheid. Voorts is standaard produksie handelsmerk-klanke geëvalueer teenoor verbeterde klank stimulasies, gebaseer op subjektiewe semantiek en objektiewe metrieke, om die dimensies van die elektriese voertuigklankgehalte te bepaal, wat tot beter verbruikersbevrediging kan lei. Die metodologie was om twee onafhanklike, subjektiewe evaluerings te onderneem wat deur 'n paneel van 32 en 52 lede respektiewelik onderneem is, om die waargenome elektriese voertuigklankervaring te bepaal. Resultate het getoon dat Skerpheid 'n fundamentele rol speel in die elektriese voertuig klankervaring. Tweedens word die onderliggende dimensies van die klankgehalte van elektriese voertuie ondersoek, aangesien dit weinig in die literatuur beskryf word. 'n Faktor-analise het bevind dat die 'Futuristiese' semantiek dimensie, aangevul moet word, by die huidige 'kragtige' en 'gesuiwerde' semantiek, wat reeds vir binnebrandenjin voertuie bestaan. Laastens is 'n verbruikersbevredigingsmodel voorgestel deur middel van meervoudige lineêre regressie en die 95ste persentasie Skerpheidswaarde. Die model het belowende resultate opgelewer vir beide kajuit- en motorkompartement handelsmerk-klank. Hierdie model word voorgestel as 'n metode om verbruikersbevrediging van elektriese voertuigklankgehalte te bepaal. Die kompleksiteit van die elektriese voertuigklankkarakter is bespreek en aanbevelings is voorgestel met betrekking tot die ontwerpskonsepte van toekomstige handelsmerk-klank van elektriese voertuie. 'n Holistiese benadering rakende beide subjektiewe en objektiewe evalueringsmetodes word aanbeveel vir toekomstige elektriese voertuignavorsing, ten einde die eienskappe wat elektriese voertuigklankkwaliteit reguleer, ten volle te verstaan.

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Chapter 1

Introduction

The automotive industry is currently progressing toward the advancement and market expansion of electric and hybrid vehicles. Several conventional internal combustion engine (ICE) car manufacturers, such as BMW, Volkswagen, Volvo, Toyota and Nissan, all currently have either hybrid or electric vehicles in production. However, the vision of a complete transformation of the automotive industry from conventional ICE vehicles to a zero-emission mobility future is hindered by several obstacles. Limited battery technology and the cost of the required public infrastructure are restraining the popularity of these vehicles, especially in the South African context. In recent years another concern has surfaced, that of the sound signatures of these vehicles.

Both electric and hybrid vehicles are extremely silent at vehicle speeds below 25 km/h [1]. This poses a problem for both electric/hybrid vehicle drivers and pedestrians. While pedestrian safety is of great concern, the focus of this dissertation will be the driver-related aspects of an electric vehicle. ICE vehicles stimulate driving comfort and safety cues through engine noises audible to the driver. The audible engine noise from ICE vehicles provides feedback to the driver regarding change in speed, and perceived driving comfort [2]. Further, different vehicle brands have unique sound signatures and it is possible to identify a specific car through the audible signature sound only. Sports cars like Ferrari and Porsche are renowned for stimulating driving pleasure through their unique sound signatures. These stimuli are found wanting in electric vehicles (EVs) and thus the

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need exists to investigate the possibility of developing a unique sound signature [3].

1.1 Research Objectives and Structure

The general objectives of this dissertation are to investigate the sound signatures of EVs currently in production, considering the unfiltered, authentic and inherent sound signature at the source (motorbay) as well as the filtered interior sound signatures as experienced by consumer; and to determine the perceived consumer satisfaction of these sound signatures through subjective jury evaluations. Jennings *et al.* [4] and Von Gosler & Van Niekerk [5] have produced studies on the sound quality evaluation of ICE vehicles and the correlation between the objective and subjective metrics for ICE vehicles, respectively. However, current literature on the sound quality of EVs and the various metrics that influence the sound quality are sparse [6]. Lennström *et al.* [6] presented a study on the influence of the testing environment on jury testing for sound evaluation of EVs, while Giudice *et al.* [7] investigated the underlying dimensions of EV sound quality. Several other studies have investigated isolated sound characteristics, such as perceived annoyance [8] or unpleasantness [9], of EV sound signatures. However, the full extent of parameters that influence consumer satisfaction of EV sound signatures is still unknown. Genuit & Fiebig [10] have investigated the sound design and synthesis of EV signature sound. The study found that the consumer acceptance of modified sounds is unclear, and suggests that additional research should focus on modifiers that evoke positive emotions and are capable of masking the undesirable components that are inherent to EV signature sound.

Current literature shows that several aspects of EV signature sound are still unknown; the following research questions could provide some insight to filling the knowledge gaps:

- What are the established sound signatures for EVs in current production and how do they relate to consumer satisfaction requirements?
- What are the appropriate semantics that can be used to sufficiently describe the perceived sound from EVs, and do the underlying sound dimen-

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sions align with current findings in the literature?

- How can sound modifiers be applied in order to improve perceived consumer satisfaction?
- Can perceived consumer satisfaction of EV signature sound be predicted using known metrics?

To this end, a literature review is conducted on the fundamentals of vehicle sound and the techniques used to evaluate and measure vehicle sound signatures. The EV sound signature in the South African context was investigated [11], followed by the comparison of the drive-train noise of commercial EVs that are available internationally [12]. Furthermore, the subjective sound quality of EVs was investigated through enhancements applied to the signature sound of EVs in current production [13]. Lastly, EV sound quality was investigated using current psychoacoustic metrics [14], and the link between these metrics and consumer satisfaction was established [15]. A consumer satisfaction metric was proposed to gauge the perceived consumer satisfaction for electric vehicle sound signatures. The main findings were concluded and recommendations for future work is provided.

1.2 Significant Research Contribution

This research aims to investigate the sound sphere that governs EV signature sound with respect to consumer satisfaction. The research provides a significant contribution through the holistic investigation of EV sound quality, from the determination of appropriate semantics to the investigation of motorbay and interior sound quality, using both subjective and objective methods. Finally, a link between the subjective semantics and objective metrics was established for EVs in terms of consumer satisfaction. To our knowledge, this link has not yet been investigated and thus provides a unique and significant contribution to the field of EV sound quality.

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Chapter 2

Literature Review

2.1 Sound Theory

Sound is a familiar concept that is present in almost every sphere of life. The fundamentals of sound such as magnitude, frequency (pitch) and phase govern our basic understanding of the concept. However, the interpretation and evaluation of sound is far more complex and intricate than expected. This chapter covers some fundamentals of the human perception of sound, as well as advanced analysis techniques.

2.1.1 The Auditory System

Sound is one of the primary senses through which most living creatures communicate and receive information. A human can detect and distinguish between different sounds by means of the ear. The human ear is a complex and intricate organ, by which we as humans are able to translate physical sound waves into an audible perception of sound. A basic understanding of the human auditory system aids us in understanding how these sound waves are quantified, known as human hearing. A schematic diagram of the ear is provided in Figure 2.1.

Sound waves generate a fluctuation in pressure as they pass through a medium. This fluctuation in pressure can be measured by using a pressure transducer or

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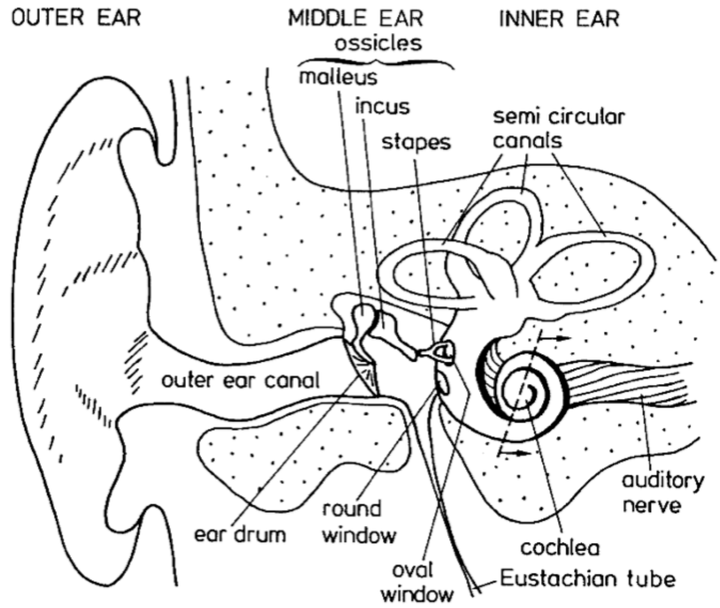

Figure 2.1: Schematic drawing of the outer, middle and inner ear [16].

a microphone, and the human ear functions in a similar manner. From Figure 2.1, we can see that the human ear consists of three sections: the outer ear, middle ear and inner ear. Sound waves are collected by the outer ear and funneled through the ear canal towards the tympanic membrane, more commonly known as the ear drum. The ear drum vibrates and sends a signal through the middle ear to the inner ear, in a process where this vibration is transmitted to the auditory nerve and is eventually perceived as sound. The middle ear consists of very dense bones which function as a lever mechanism to transport and amplify the vibration of the ear drum to the oval window membrane. The oval window then vibrates and transmits the vibrations through fluid in the cochlea. Within the cochlea, small hairs detect the vibration and emit neurological pulses to the brain through the auditory nerve [16]. This neural process is defined as the concept of hearing.

The human auditory system only responds to hearing sensations within the frequency range of approximately 20 Hz to 20 kHz. The human ear is not equally sensitive to all frequencies due to the behavior of the cochlea and the coupling from the middle ear to the inner ear, which acts as a type of filter. There exists a specific amplitude at each individual frequency within the audible range

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of sound waves, where the auditory system can no longer detect a sound sensation. This is called the threshold of hearing or threshold in quiet, as indicated in Figure 2.2. The dotted line deviation in the threshold in quiet represents the typical hearing of subjects whose hearing is damaged due to frequent exposure to very loud music or sounds. Similarly, there exists a specific amplitude at each frequency where the magnitude of the sound sensation is overpowering for the auditory system and thus induces pain. This is called the threshold of pain. Typical, standard hearing tests are conducted through the range of audible frequencies to determine if a subject's hearing corresponds to the standardised threshold of hearing.

The threshold of hearing curve illustrates the perceived loudness as experienced by the human ear within the audible frequency range. This simply means that the sound at every frequency on the threshold of hearing curve is perceived to be equally loud compared to the remaining set of audible frequencies, and thus it can also be described as an equal-loudness curve. Several sets of equal-loudness curves exist between the threshold of hearing and the threshold of pain and are referred to as phon curves, where the zero phon curve coincides with the threshold of hearing curve.

2.1.2 Sound Quantification

Sound is measured as a variation in pressure, for which the standard unit is Pascal. However significant differences in pressure variation, to the order of 10^7, can be found between audible low and high frequency waves, and thus a more appropriate decibel scale has been defined [16]. The Sound Pressure Level (SPL) is defined as,

$$L_P = 20\log_{10}\frac{p}{p_0}, \tag{2.1}$$

where

$$\begin{aligned} p =& \text{Measured RMS Pressure} \\ p_0 =& \text{Reference Pressure} = 20\ \mu Pa \end{aligned}$$

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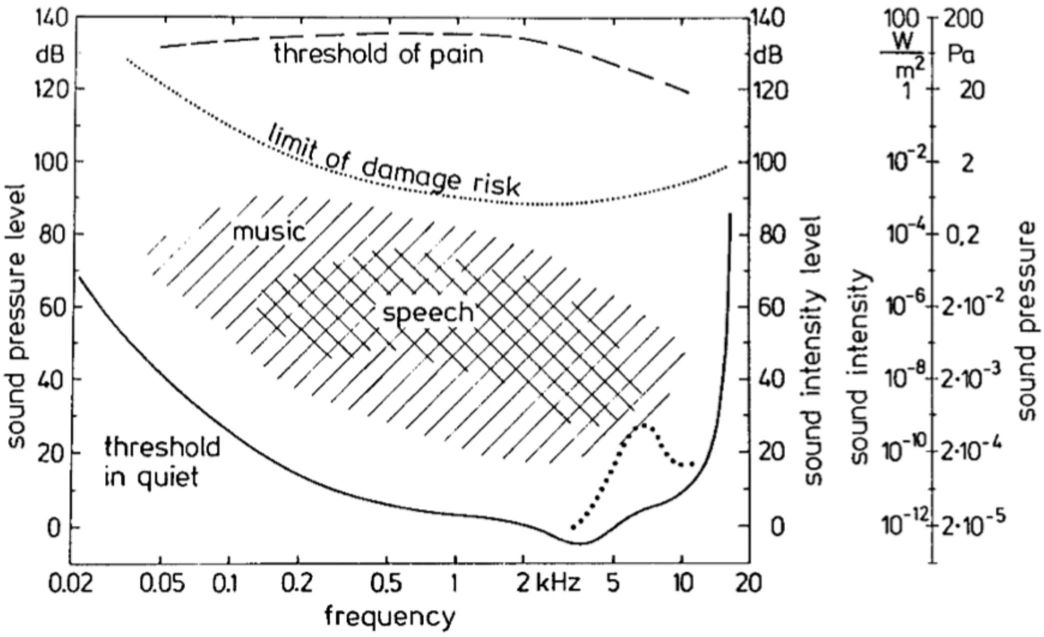

Figure 2.2: The hearing area of the human auditory system [16].

and is measured in decibels. The reference pressure corresponds to a single tone sound at 1 kHz producing an SPL value of 0 dB on the 0 phon line. In the field of acoustics, two common weighting scales can also be applied, namely the 'A-weighted' and 'C-weighted' scales. Additionally a 'B-weighted' scale also exists, however it is used less frequently. The 'A-weighted' and 'C-weighted' scales correspond to the 40 and 60 phon lines respectively. The 'C-weighted' scale is used particularly when measuring very loud noise, or noise in the low frequency range, whereas the 'A-weighted' scale is the common frequency weighting curve used to determine annoyance caused by noise and perceived loudness, denoted as dB(A), which conforms approximately to the typical response of the human ear [17].

2.1.3 Masking

Masking occurs when a tone can no longer be heard due to the level of other noise sources [18]. Wind and tyre noise observed during driving conditions are categorised as a broadband noise. *White noise* is a broadband noise which has a

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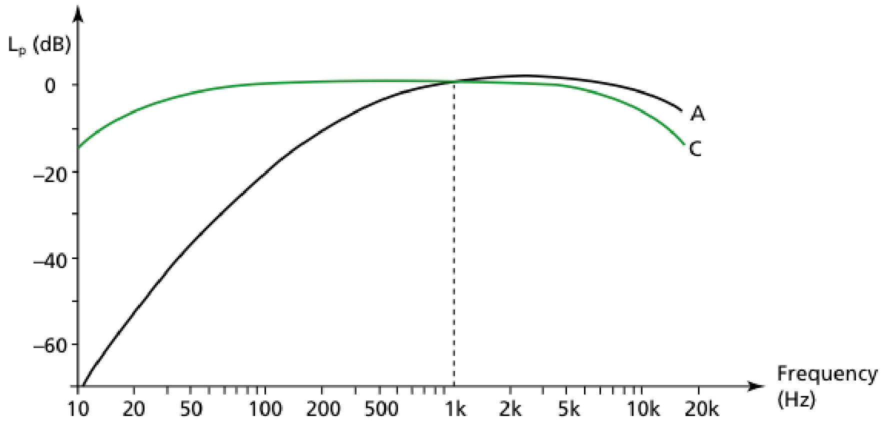

Figure 2.3: A- and C-weighted scales [17].

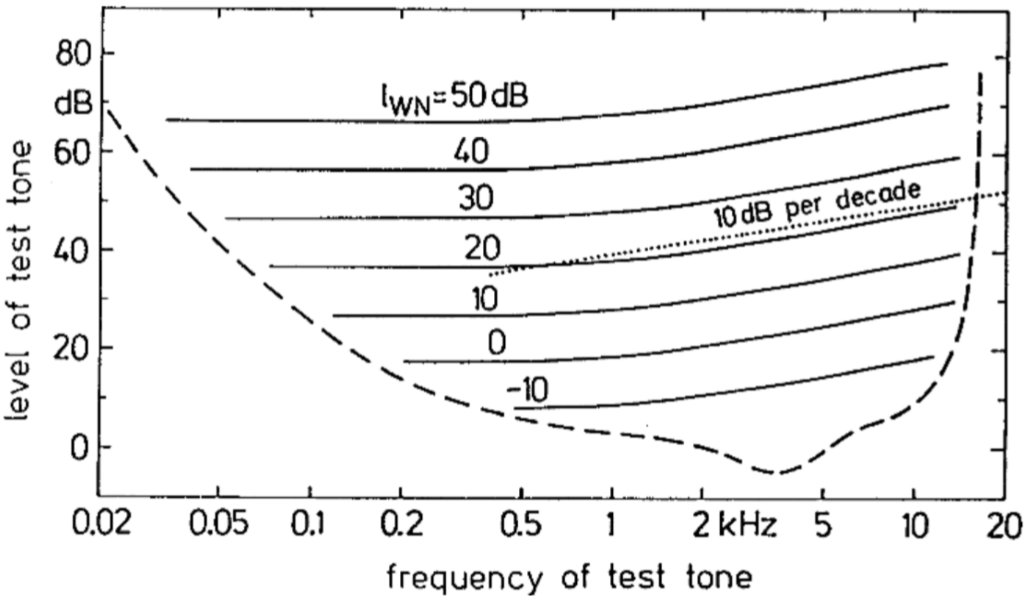

Figure 2.4: Level of test tone just masked by white noise of the given density level l_{WN}, as a function of the test tone frequency [16].

constant spectral density level [16] and is a very effective masker, as illustrated in Figure 2.4. The figure illustrates the level of a single frequency test tone which is required to be audible above a specific intensity level of white noise. The masking effects of broadband noise is of great interest to electric vehicles as wind and road noise can be categorized as a broadband noise.

Another type of masking that is of interest to this research is *single tone* masking. Single tone masking is illustrated in Figure 2.5, and the resulting effects dif-

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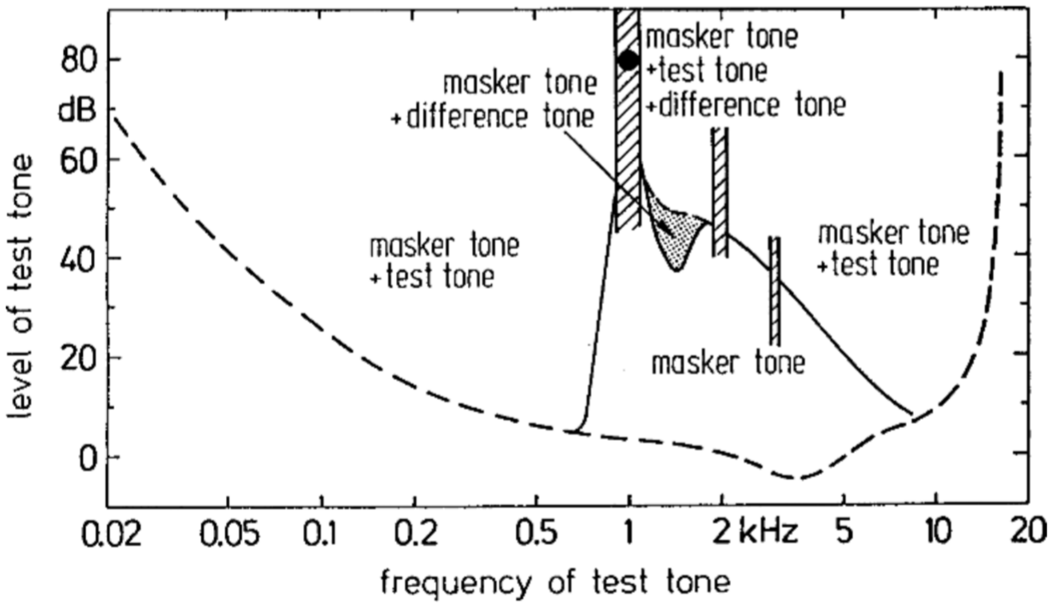

Figure 2.5: Level of test tone just masked by a masking tone (1 kHz, 80 dB) as a function of the test-tone frequency [16].

fer to that of broadband masking. Single tone masking effects are similar to the threshold of quiet for frequencies distant from the masker tone. The masking effects increase substantially as the test tone approaches the masker tone frequency. When the test tone frequency is in close proximity to the masker tone frequency, the required level of test tone is infinite as the test tone is completely masked and cannot be distinguished from the masker tone. Two similar cases of absolute masking occur after the masking frequency has been exceeded at two separate frequencies. These frequencies appear to be at 2 and 3 kHz which coincides with harmonics of the 1 kHz masker, but additional analysis is required to prove this. This is an interesting phenomenon as it shows that it is possible to mask a specific frequency by means of a lower frequency single tone masker. The question arises whether it is possible to mask higher frequencies of electric motor sounds with lower frequency masker tones? The potential of this masking capability will be investigated. Additionally, single tone masking produces difference tones within the vicinity of the masker tone. The difference tones could alter the sound character and thus a need for further research exists.

A combination of multiple single tone masking is referred to as *multi-tone* masking. Multiple tones or complex tones can be used to approximate the masking

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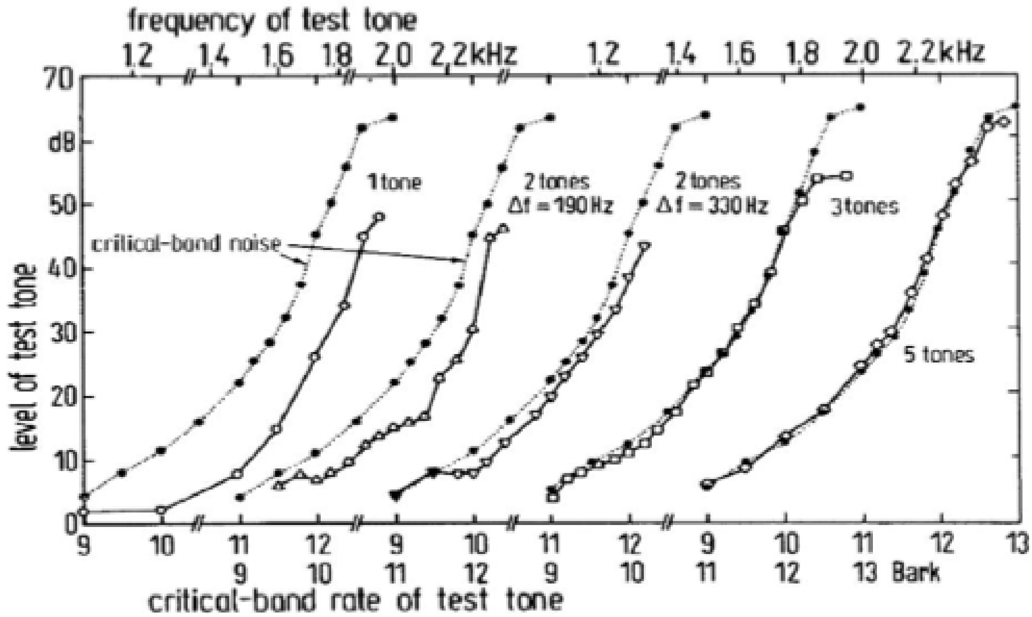

Figure 2.6: Level of test tone just masked by a number of tones within the critical band around 2 kHz as a function of the frequency (upper scale) and critical-band rate (lower scale) of the test tone [16].

effect of broadband noise, as illustrated in Figure 2.6. The masking properties of multi-tone masking migrates from single tone to broadband masking as the number of masking tones increases. The figure shows that a good approximation for broadband noise can be achieved by only five masker tones. The possibility of generating masking effects that simulate broadband noise and, in turn, possibly road noise exists, and needs to be investigated further. The transition between single tone masking and broadband masking is not well documented.

2.2 Sound Evaluation

The evaluation of vehicle sound is categorised by two distinct approaches. The subjective approach is subjective of nature and is primarily focussed on the perceived sound experiences of a jury through the evaluation of different stimuli. Subjective evaluations can be performed using different methods and evaluation environments, and offer a result that is relevant and true to specific jury or context. The second approach is driven by objective metrics, which are calcu-

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lated through mathematical models or equations, and provide consistent results that are irrelevant of specific context or evaluation environments. In this study the subjective approach refers to perceptual investigation of the sound, whereas the objective approach refers to the technical evaluation of the sound. The respective sound evaluation approaches are explained in greater detail below.

2.2.1 Subjective Evaluation

A *tracking method* allows a subject to vary the test tone in one dimension to establish a threshold. For example, the subject is allowed to vary the loudness of the sound to establish the threshold between audible and inaudible sounds. The true hearing threshold can then be found by averaging the results. This method is of great practical use for establishing thresholds, such as the threshold of hearing in hearing tests. The method of tracking could also be used to determine the threshold of annoyance which is a key element for sound quality and overall consumer satisfaction [8; 16]. A number of subjective evaluations methods are used to analyse and categorise different sounds. These are described below.

Forced Choice Paired Comparison

The subject is presented with two sound stimuli and is forced to choose a preference along one dimension. For example, the subject should state which sound stimulus, A or B, appears to be sharper. A sufficient reflection time (>4s) is also required between the presented stimuli, to allow the brain to compare the stimuli on a deeper level than just a simple loudness comparison. The advantage of using forced pair comparison is that it produces a clear indication of the winning result. However, one disadvantage is that forced pair comparison does not signify the margin or magnitude by which the one stimuli dominates the other [5; 19].

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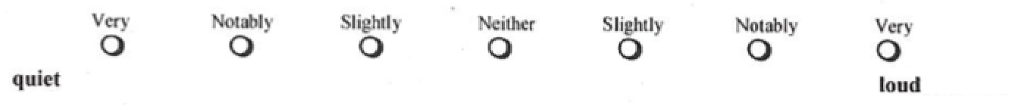

Figure 2.7: Example of a semantic bi-polar pair [6].

Comparison of Stimulus Pairs

The subject is presented with pair combinations of sound stimuli, for example stimuli A and B, and stimuli C and D. Sound stimuli A and B vary only along one dimension, for example loudness, whereas sound stimuli C and D vary along a different dimension, such as pitch. The subject is then required to state if the perceived difference between stimulus pairs A and B is larger than the perceived difference between C and D, or vice versa. One advantage of using this method is that it can indicate the importance of certain psychoacoustic parameters, such as loudness or sharpness, as perceived by the human ear. Knowing the influence of these parameters can help to improve overall customer satisfaction [16].

Bi-polar Semantic Differential Scales

The subject is provided with a stimulus which must be described using a set of bi-polar semantic pairs. The bi-polar pairs are usually accompanied by a fixed point scale as shown in Figure 2.7. The bi-polar pairs are a set of words with opposite meanings, e.g. the subject is required to differentiate if the stimulus is loud or quiet using a 7 point scale. The use of bi-polar semantic pairs has been well documented for sound quality evaluations on internal combustion engines (ICE), but sparsely documented for electric vehicles. This method will be considered as one of the main sound evaluation procedures to be used in this study, due to its extensive use in the automotive industry. However appropriate bi-polar adjectives for electric vehicles are still to be determined. The correlation between the subjective and objective evaluation for electric vehicles is also absent in current literature [6; 19].

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2.2.2 Objective Evaluation

Conventional methods of evaluating vehicle sound are usually centered around SPL measurements and analysis. Frequency weighting curves, such as A-weighting for SPL measurements, provide some insight with regards to the human perception of sound. Is the level of sound pressure, with respect to time or frequency content, sufficient to describe the full array of sound experienced by the listener? In some cases, yes - the level of sound pressure is sufficient to distinguish between different sounds. However, more complex sound quality attributes cannot be quantified with sound pressure alone. Several psychoacoustic metrics are available to identify and encapsulate a broad range of sound quality effects. The fundamental theory that governs the metrics of Loudness, Sharpness, Roughness, Fluctuation Strength, Impulsiveness, Prominence Ratio, Speech Interference Level, and Speech Intelligibility Index is briefly described.

Loudness is a sensation of the intensity and magnitude of sound experienced by the human ear. Loudness is not dependent on amplitude alone. Factors such as bandwidth, waveform, frequency and exposure time can influence the loudness perceived by humans. Zwicker proposed a relation (Eq.2.2) to objectively quantify loudness which incorporates the factors that influence loudness. In the succeeding chapters, Zwicker Loudness shall be referred to simply as Loudness, and is calculated according to the DIN 45631/A1 standard, which is the only standard applicable for both stationary and transient Loudness [20].

$$N = \int_0^{24Bark} N' dz \qquad \text{[Sone]} \tag{2.2}$$

The Bark was proposed by Zwicker as a division of the frequency spectra, similar to third octave bands. A pure tone producing 40 dB at 1 kHz would produce 1 Sone, which is the reference value for Zwicker Loudness [16].

Noise which contains high frequency content has been shown to be annoying [5], and in objective evaluation metric terms, this is referred to as *Sharpness*. A means of measuring the average pitch of a sound was proposed by Aure. Aure's Sharpness is shown by Equation 2.3 and is defined as the specific loudness N' divided by the total loudness N over a certain exposure time [5]. The weighting

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function $g_A(z)$ is dependent on loudness [21].

$$Sh = 0.11 \frac{\int_0^{24Bark} N'(z) \cdot g_A(z) \cdot z/Bark\, dz}{\int_0^{24Bark} N'(z)\, dz} \qquad [acum]$$
$$\text{where} \qquad g_A(z) = 0.078 \cdot \frac{e^{0.171 \cdot z/Bark}}{z/Bark} \cdot \frac{N/sone}{\ln(0.05N/sone + 1)} \tag{2.3}$$

Research has shown that Zwicker Loudness and Aure's Sharpness correspond well with subjective evaluations for ICE vehicles [5], however little is known about the correlation for electric vehicles. The Aure's method is also preferred when evaluating sound with varying degrees of loudness [22]. In the succeeding chapters, Aure's Sharpness shall be referred to simply as Sharpness, and be calculated using the DIN 45631/A1 Specific Loudness and Aure's algorithm for Sharpness.

Sounds that produce a significant change in level over a short period of time are considered to be impulsive. The psychoacoustic measure of *Impulsiveness* determines the perceived sensation of human hearing, as experienced for highly impulsive sounds [23]. The impulsiveness is calculated using an excitation function through the Hearing Model proposed by [24]. A nonlinear comprehensive function is applied to the excitation function to account for the presence of background noise, which reduces the significance of the impulsive event. Impulsiveness is highly dependent on the mean frequency of the impulsive events [23], especially for frequencies below 10 Hz. As compensation, the calculated impulse values are summed, after a 4^{th} order highpass filter (10 Hz) is applied. Additional scaling factors are also applied to match the metric calculations to the perceived impulsiveness found through audiometry testing [25].

The sensation of *Roughness* is induced in acoustic stimuli through modulation, either in frequency or amplitude. More specifically, the roughness in the sound is dependent on the variation of the temporal envelope, particularly in the frequency range between 20 and 300 Hz. Lower frequencies outside this range tend to produce a beating sensation, whereas for the higher frequencies, the tonal character becomes more evident. The roughness metric used by Artemis software from Head Acoustics is based on a hearing model developed by Sottek & Genuit [26], where the full calculation procedure is explained. The roughness

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metric is determined through the combination of the specific roughness for each critical band, and is also dependent on the modulation depth and frequency. Roughness is measured in the unit *asper*. One asper of roughness is defined as a tone of 1 kHz at 60 dB, with 100% modulation at a modulation frequency of 70 Hz. The objective roughness of a sound is not highly dependent on the magnitude of the sound, and thus sounds with similar level or loudness can be characterized by different roughness values [16].

Fluctuation Strength is an objective metric that is influenced by modulation of sound, similarly to roughness, however, more specific to sounds with low modulation frequencies (<20 Hz). Fluctuation strength is measured in *vacil* and the reference value is defined by a tone of 1 kHz at 60 dB, with 100% modulation at a modulation frequency of 4 Hz [16]. The maximum fluctuation strength is achieved at a modulation frequency of 4 Hz, and the metric is also not influenced substantially by changes in magnitude, but is rather highly susceptible to change in the modulation, depth and frequency.

The Speech Interference Level (SIL) is a psychoacoustic metric that determines the influence of background noise on the clarity of speech. The metric is calculated by averaging the SPL of specific octave bands which are known to govern speech intelligibility [27], as shown by Equation 2.4. Several other methods for calculating SIL exist, however this approach was selected due to its increased bandwidth.

$$SIL = \frac{L_{p500} + L_{p1000} + L_{p2000} + L_{p4000}}{4} \quad \text{[dB]} \tag{2.4}$$

The *Speech Intelligibility Index* (SII) measures the level of background noise with respect to the speech spectrum. The SII is calculated by first performing a broad band analysis (3^{rd} Octave) on the signal, whereafter the level differences between the noise level and speech spectrum are calculated per frequency band. The resulting data is then weighted using a band importance function, according to the relevant speech dependent frequency bands. Finally, a summation is preformed across all frequency bands to produce a percentage value representative of the SII [28]. The SII is a measure of the degree of interference caused by the signal (stimuli dependent) compared to the known speech spectrum (fixed), and is calculated according to the ANSI S3.5-1997 standard [29].

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Prominence ratio (PR) is a method designed to detect prominent tonal components in a given noise sample [30]. The prominence ratio classifies a tone as prominent, based on the difference in the level of the critical band of the tonal frequency and the level of the critical band of the neighbouring frequencies. The prominence ratio thus gives an indication of the level of a tone, based on the level of the surrounding frequencies. The prominence ratio is governed by Equation 2.5 as documented by the ECMA-74 standard [31].

$$\begin{gathered}\Delta L_P = 10\log\left(10^{0,1L_M}\right) - 10\log\left[\left(10^{0,1L_L} + 10^{0,1L_U}\right)x0,5\right]\text{dB} \\ \text{for} f_t > 171{,}4\ \text{Hz}\end{gathered} \tag{2.5}$$

The prominence ratio criterion [31] specifies that a sound with tonal frequencies above 1 kHz is prominent, when the difference in critical band level is greater than 9 dB. The required level difference for tonal components below 1 kHz, increases by 3 dB per octave as the tonal frequency decreases. The theory provided presents the simplest form of the metrics as used for stationary signals, however similar procedures are followed for transient or time-varying signals, where these metrics are calculated over shorter time increments to produce a temporal indication of the progression of the sound character.

2.3 Signal Processing

Various techniques and tools are currently available that simplify sound analysis and improve the understanding of sound generation and sound interaction with various surroundings. Some of these tools are highlighted in this section and the relevance to this research is emphasized.

2.3.1 Fast Fourier Transform

Jean Baptiste Joseph Fourier stated that any periodic function or signal could be expressed as a sum of a set of sinusoidal functions [32]. This theorem is the ba-

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sis of the Fourier transform, which is used to transform a signal from the time domain to the frequency domain. The data from the signal is not changed or altered in any way during this transformation; it is simply transformed into another form, which allows the Fourier transformation to be reversible [33]. With the help of modern day computers, it is possible to measure a large variety of signals if using the right equipment. Fast Fourier Transform (FFT) is used to analyze measurement signals by converting the time domain signal to the frequency domain. However, to accomplish this, the continuous signal needs to be sampled at a discrete number of points. A sampler and an analog-to-digital (A/D) converter are used to sample the signal at a specific sample rate and convert it to a digital signal. The FFT analysis is an invaluable tool for assessing the frequency content of signals and is widely used in the automotive industry. Care should be taken to avoid known effects such as aliasing, leakage and misrepresentative spacial and temporal resolutions.

2.3.2 Order Analysis

Order analysis is a technique that has become very popular in the automotive industry in recent times. Order analysis performs a spectral analysis (FFT, Power Spectral Density (PSD) or Auto Power Spectra (APS)) with respect to measurement time or as a function of revolutions per minute (rpm), which enables the researcher to track specific sound frequencies with respect to vehicle speed. Relationships between frequency and rpm are visible from order analysis and these relationships are called orders, as illustrated in Figure 2.8. The first order is defined as the rotation speed of the shaft, the second, third and nth order are components which rotate, or occur at twice, three times and n times the shaft speed respectively. The order plot illustrates the frequency bandwidth of each order, as well as the varying degrees of magnitude. The order plot can illuminate components that deliver the greatest contribution towards the overall characteristic sound of the motor. The relationships between change in speed and the change in sound magnitude with regard to the frequency domain are of great interest in the automotive industry [18]. Parameters such as block size, sample rate and number of sample points influence the resolution of the order plot in terms of the amplitude, as well as the bandwidth of each order.

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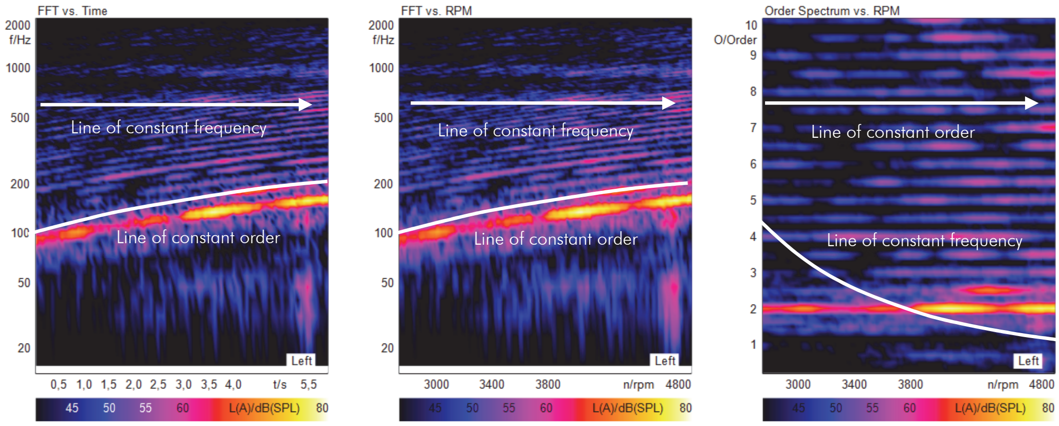

Figure 2.8: FFT vs Time, FFT vs RPM and Order vs RPM [34].

2.4 Vehicle Acoustics

In modern times, the quality of a vehicle is not only determined by its performance, but also the vehicle acoustics as experienced both inside and outside the vehicle. The acoustic characteristics of a vehicle are closely related to the perceived satisfaction of driving the vehicle, and thus the refinement of vehicle acoustics plays a vital role in prevailing vehicle development [2]. The vehicle industry's two broad classes, namely vehicles powered by internal combustion engines and vehicles powered by electric motors or a combination of both, are distinguished acoustically by the unique sound signatures they produce, and the sound quality challenges they pose are significantly different for each class [4; 18]. Different acoustic characteristics include those of the drive-train, wind and tyre noise, and a range of procedures exist to benchmark different vehicles.

2.4.1 Drive-train

Wang [2] describes the noise sources linked with an ICE vehicle drive-train and the typical frequency ranges in which they occur. Wang [2] describes the mid frequency range (20 - 400 Hz) of noise sources to be associated with sensations such as booming and roughness, which are linked with the firing frequencies. The high frequency range (>400 Hz) of noise sources is associated with sensations such as whine or whistle and is linked with the super-firing frequencies. Jennings

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et al. [4] found that the enhancement of precieved sportiness and powerfulness in ICE vehicle sounds can be linked to the presence of half-engine orders. In comparison, EV drive-train noise is found to be extremely quiet at low speeds [35], posing a safety risk to unaware pedestrians. Furthermore, the low drive-train noise increases the detectability of other noise sources, such as pumps, fans and power electronics, in the vehicle's interior due to the lack of masking. The electric motor's tonal characteristics are prominent and potentially annoying to the driver, reducing vehicle satisfaction [8].

2.4.2 Wind and Tyre Noise

The wind and tyre noise affects both electric and ICE vehicles, and is the dominant noise source at higher vehicle speeds [18]. Cerrato [18] stated that wind and tyre noise can increase annoyance, and reduce speech intelligibility. The reduced masking effect of electric vehicle drive-train noise increases the audibility of wind and tyre noise in the interior of the vehicle [4; 18].

2.4.3 Benchmarking

Benchmarking procedures for ICE vehicle sound quality is well documented in literature [2; 4; 5]. Three frequently used procedures are constant speed drives, Part Throttle (PT) drives, and Wide Open Throttle (WOT) drives. Constant speed drives provide a platform to benchmark vehicles at specific speeds, for example the known vehicle speeds that induce maximum wind and tyre noise contributions [18]. PT drives assess gradual vehicle acceleration [36] and can be used to simulate daily driving conditions. WOT drives provoke the maximum response of the vehicle drive-train as a result of the full throttle acceleration, and thus it is a preferred method for vehicle benchmarking [2; 4].

This literature review provides a broad background and understanding of the research that was covered in this study. A comprehensive and in-depth discussion of the relevant literature will be provided in the respective subsequent chapters.

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Chapter 3

Subjective Evaluation of Interior Noise produced by Electric Vehicles

The work presented is a collaboration effort of the author of this PhD dissertation with Dr. Annie Bekker of the Department of Mechanical and Mechatronic Engineering at Stellenbosch University, Stellenbosch, South Africa. This peer-reviewed paper was presented at the 9th South African Conference on Computational and Applied Mechanics (SACAM) in January 2014 [11] Dr. Bekker is the co-author of this paper as the supervisor of the PhD candidate. A signed declaration to this effect is in the possession of both the candidate and the supervisor. The paper investigated the subjective evaluation procedure for EVs, based on current procedures for ICE vehicles documented in literature. The specific semantics required to describe the EV sound character were investigated and the sound signatures of an electric vehicle, two ICE vehicles and one concept sound stimulus were evaluated through jury testing. This paper achieves one of the main objectives of this dissertation by developing a subjective evaluation procedure with suitable semantics for the interior sound of EVs. Furthermore, it contributes to the investigation of the perceived consumer satisfaction of the vehicles through the subjective jury evaluations. The subjective evaluation procedure used for the jury testing can be found in Appendix B.1. The evaluated sound stimuli can be found in Appendix C.

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3.1 Introduction

The current trend in the automotive industry is towards developing electric and hybrid vehicles. Both electric and hybrid vehicles are notoriously silent for vehicle speeds below 25 km/h [1]. Historically, auto manufacturers have been using the interior sound of internal combustion engine (ICE) vehicles to stimulate a positive driving experience through audible cues perceived by the driver. These stimuli are found wanting in electric vehicles and are raising questions as to customer preferences and expectations with regard to the interior sound character of the vehicle [4]. This gives rise to the need to investigate the attributes of a positive sound signature for electric cars.

Subjective evaluation procedures have been well documented for ICE vehicles but are still under development for electric vehicles [4; 5]. Traditionally, consumer satisfaction ratings of vehicle interior sounds are determined through subjective evaluations with jury testing. These evaluations can be carried out on a test track or in the laboratory environment such as a listening room or sophisticated sound-car simulators. It has been shown that similar results can be obtained in all three environments [4; 6].

Jennings *et al.* [4] showed that two underlying dimensions govern ICE vehicle sound quality. The first is the perceived power or strength dimension of the vehicle, and the second is a comfort-related dimension. The presence and contribution of these dimensions to the electric vehicle sound character will be investigated.

The resulting data from the jury testing is illustrated using polar plots, which provide a fast yet effective way of comparing different sound characters [4]. Proven subjective evaluation procedures from ICE cars, as posed by Jennings *et al.* [4] will be used as a baseline for this research. Additional semantics are investigated in order to adjust the model posed by Jennings *et al.* [4] to be better suited to the evaluation of electric vehicle sound characteristics.

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3.2 Investigative Approach

South Africans are relatively new to the idea of electric cars. To date, the only commercially available electric vehicle in South Africa is the Nissan LEAF, which was first launched in October, 2013 [37]. As a result the Nissan LEAF was selected as the electric test vehicle for the recording of sound stimuli for subjective evaluations. Tests on the Nissan LEAF were conducted with the courtesy of Nissan South Africa in July 2013 on the N4 Highway outside Rosslyn, Pretoria. Microphones were placed in the cabin and under the hood of the vehicle to measure the interior and underhood sound produced by the Nissan drive-train as shown in Figure 3.1 and Figure 3.2. Data was acquired with a LMS SCADAS data acquisition system. The sample rate of the recordings was set at 44 100 Hz. The recorded data was analysed in LMS Test.Xpress software for all the runs in order to select the best sound clips.

Wide-open-throttle (WOT) accelerations were performed on a straight section of smooth tar road on the N4 highway. This test protocol is relied on by the automotive industry to elicit the character of the drive-train sound for subjective evaluations [4]. For these experiments, the vehicle was accelerated at full throttle to 120 km/h from stand-still. In the WOT drives, the motor is operated at its maximum capacity which provokes the most significant sound and vibration excitation of the vehicle drive-train.

The sound recordings from the WOT tests were analysed in LMS Test.Express 6A in order to select the best sound clip for the subjective evaluations. The sound clips were carefully selected to ensure a smooth run without pass-by noise. The sound clips were also trimmed at the beginning and end to remove audible cues from the researcher to the driver. The files were then exported as .wav audio files to be used in the subjective evaluations.

Different subjective evaluation methods are outlined by Fastl & Zwicker [16] in order to determine sound quality characteristics as perceived by human listeners. Methods such as forced paired comparison and comparison of stimulus pairs indicate a preferred stimulus over another. However these methods do not provide an indication of the magnitude of the winning performance margin. Bipolar semantic differential scales also provide information on the preferred psy-

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Figure 3.1: Placement of underhood microphone of the Nissan LEAF.

Figure 3.2: Placement of a microphone for interior sound measurement at the middle headrest of the rear passenger seat of the Nissan LEAF.

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Table 3.1: Sources of sound stimuli used

Sound A	Sound B	Sound C	Sound D	Sound E
Motor Vibration	LEAF Interior	F14 Startup	LEAF Underhood	Washing Machine
Sound AA	Sound BB	Sound CC	Sound DD	Sound EE
LEAF Interior	LEAF Underhood	Concept Sound	Mercedes Interior	Porsche Interior

choacoustic metric whilst yielding a degree of magnitude for the winner as well. Bi-polar semantic differential scales are thus very useful and are used in industry for subjective noise, vibration and harshness (NVH) testing [4; 5; 38]. It was therefore decided to use these tests as the basis for the present evaluations. Jury testing was selected as the preferred methodology to perform subjective evaluations due to the shortage of electric vehicles and the unavailability of a vehicle for in-car evaluations. Lennström *et al.* [6] have historically proved that the difference between jury testing and in-car evaluation is not significant.

Two different assessment environments were created within the subjective evaluation tests in order to achieve the objectives at hand. The first environment was designed to determine appropriate semantics that could be used in bi-polar semantic tests to evaluate the attributes of an electric vehicle sound signature. The second environment was designed to rate the semantic attributes of electric and ICE vehicle sound signatures, as well the perceived consumer satisfaction. The different sound stimuli and their origins as used in the subjective evaluation are listed in Table 3.1.

The first environment required the juror to listen to five sound stimuli. The juror was tasked to select three appropriate adjectives from a dropdown list of words. An example of the first environment is shown in Figure 3.3. Dropdown menus were selected to improve the user-interface and test efficiency. The pool of words was obtained from a subjective evaluation of machinery noise by Kuwano & Namba [38]. Three of the five test stimuli were produced by electric vehicles but measured at different locations, namely the interior, underhood and fore-aft motor vibration as measured on the motor casing. The remaining two sounds were cho-

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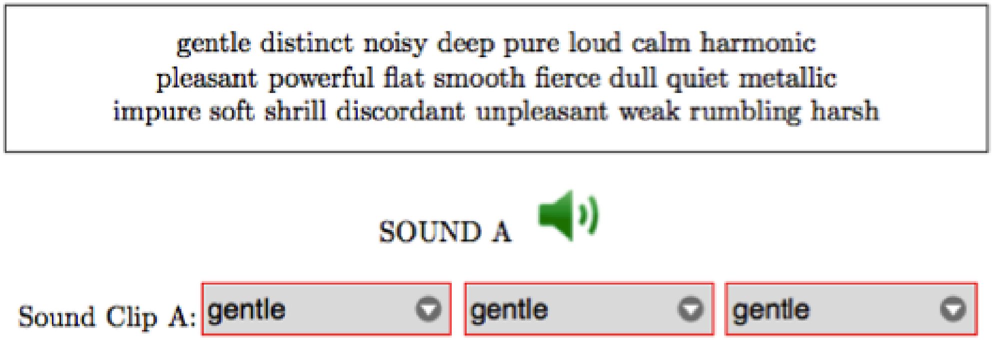

Figure 3.3: First environment for subjective evaluation.

sen from sounds commonly associated with electric motors [6]. The first is the start-up of an F-14 jet aircraft and the second, that of a washing machine during its spin cycle. These sounds were chosen specifically to broaden the word association search for electric vehicles. On completion of the first set of tests, the juror was required to select their preferred sound and provide two of their own words to describe the preferred sound. This was done in order to hopefully obtain an additional sound characteristic from the user's perspective that could possibly describe the sound produced by electric vehicles.

The second testing environment was a bi-polar semantic differential evaluation as posed by Jennings *et al.* [4]. Jennings performed this specific test on 72 luxury ICE vehicles. The second testing environment was used to determine the difference in perception of the interior and underhood sounds from an electric vehicle. In addition, the general perception of the sound signature of an EV as opposed to an ICE vehicle was investigated. The two EV sounds were accompanied by the interior sounds from a Mercedes B180 CDI and a Porsche 911 Turbo. These two ICE sounds are different in sound character to provide variation in the data. A computer generated sound was also evaluated in an attempt to find a link between the ICE and EV sounds. The sound in question was generated by means of frequency and amplitude modulation in combination with order filtering of the lower motor orders. Finally, the juror was required to assess the satisfaction of each sound clip in the second environment in order to establish a link between subjective sound metrics and perceived consumer satisfaction. The bi-polar semantics that were used in the second testing environment are illustrated

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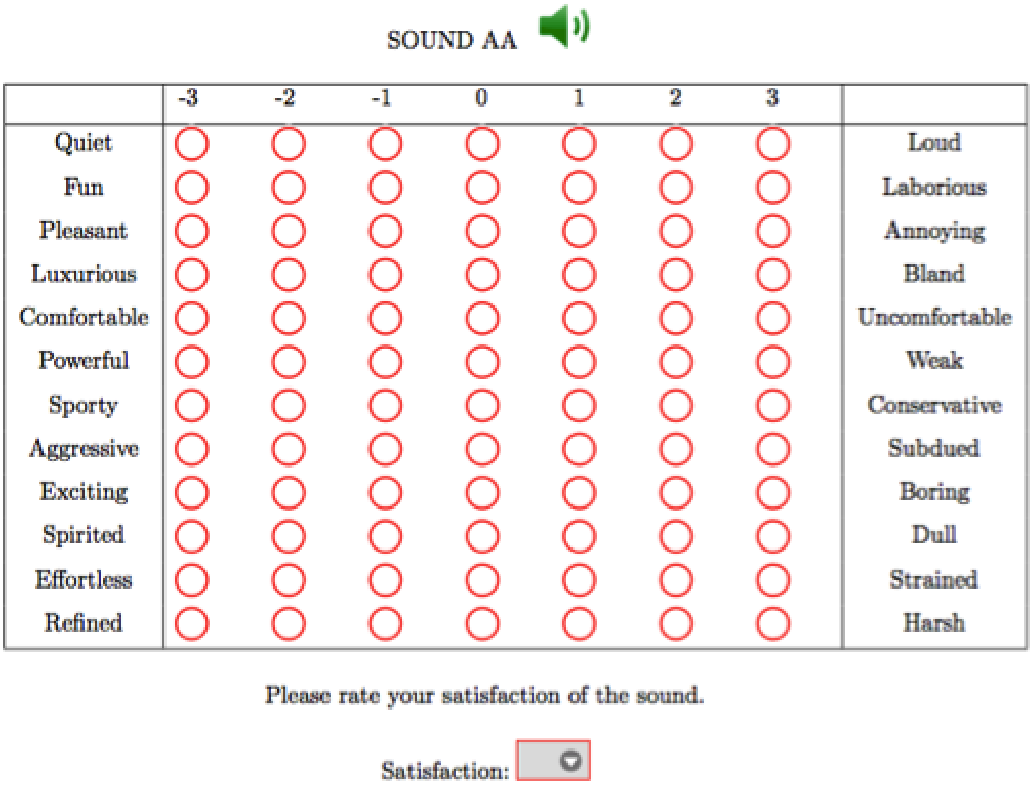
SOUND AA

	-3	-2	-1	0	1	2	3	
Quiet								Loud
Fun								Laborious
Pleasant								Annoying
Luxurious								Bland
Comfortable								Uncomfortable
Powerful								Weak
Sporty								Conservative
Aggressive								Subdued
Exciting								Boring
Spirited								Dull
Effortless								Strained
Refined								Harsh

Please rate your satisfaction of the sound.

Satisfaction:

Figure 3.4: Second environment for subjective evaluation.

in Figure 3.4.

The subjective evaluation form was generated using Latex, creating a fillable pdf form. The sound stimuli were embedded into the pdf to improve the ergonomics of the test and enable the form to be filled in electronically as illustrated in Figure 3.3 and 3.4. Upon completion, the form was submitted and directly sent to the author's email account. It was decided to exercise all the tests at one specific location with the exact same equipment, over the course of 3 days. The subjective evaluation tests were conducted in a silent room on the 6th floor of the Mechanical and Mechatronic Engineering building at Stellenbosch University. The lights were switched off to eliminate any visual distraction in the room, and the sound was played through a VLC media player on a standard Dell Intel Core Duo Desktop with a SoundMAX Integrated HD Digital Audio sound card. The sound was played to each juror through a Sennheiser HD 380 Pro over-ear headphones.

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Table 3.2: The different modes for the word association test

Mode	Sound B	Sound D	All Sounds
1st	Deep	Powerful	Powerful
2nd	Rumbling	Rumbling	Noisy
3rd	Powerful	Deep	Shrill/Deep

3.3 Important Findings

The data from each juror was saved and exported to Microsoft Excel for further analysis. Nine males and eight females took part in the subjective evaluation. The average age of the jurors was 23, with a maximum and minimum age of 34 and 20 respectively. The home language of jurors was predominantly Afrikaans, followed by English and German.

The word association completed in the first environment was analysed to determine the most frequently selected word, or the mode of the data set. It was found that 70.6% of the jurors preferred sound clip B while 23.5% preferred sound clip D. Interestingly these stimuli correspond to the interior and underhood recorded sounds of the Nissan LEAF. The different modes for the entire data set as well as the preferred sounds are shown in Table 3.2. Results show that the words 'powerful', 'deep' and 'rumbling' are associated with electric vehicle sound. The strong character of these words suggests that the aspects relating to vehicle power, as discussed by Jennings *et al.* [4] is significant in electric vehicles. The data also shows that the words 'noisy' and 'shrill' are used to describe sounds similar to that of an electric vehicle. The words 'pleasant' and 'quiet' were not selected once by any of the jurors, illustrating that these were words are not commonly associated with the sound of electric vehicles.

The bi-polar semantics data was averaged across all participating jurors. The data was averaged for each semantic characteristic corresponding to the specific sound stimulus. The averaged data was then graphed using polar plots, which can plot multiple axes on a single graph. The polar plots are graphed according to the same 7-point scale as for the bi-polar semantics, i.e. from the centre to the outer ring. The resulting graph can be seen as a type of sound map with refer-

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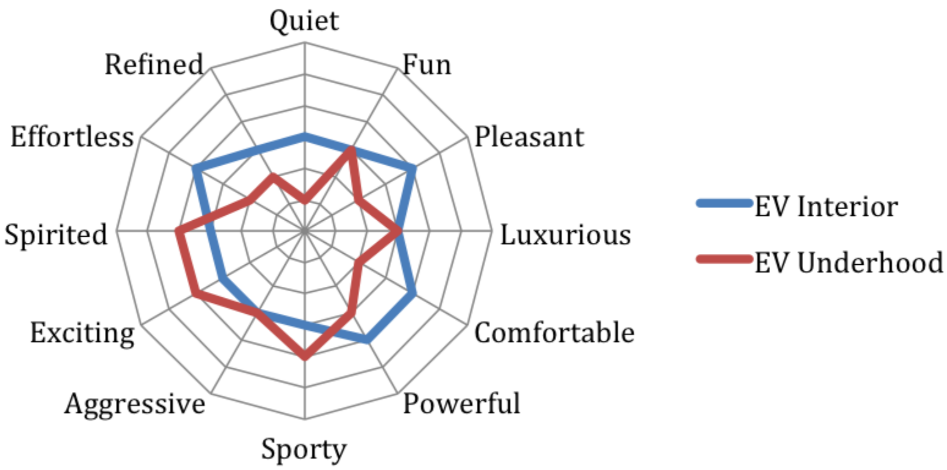

Figure 3.5: EV semantic characteristics comparison between interior and underhood sounds.

ence to the specific semantics used. These sound maps can then be compared to determine the characteristics that drive the perception of the superiority of one sound over another. The resulting polar plots from the bi-polar semantic evaluation are illustrated in Figures 3.5-3.7.

The interior sound of the Nissan LEAF is considerably more quiet, effortless, comfortable and pleasant than the sound produced under the hood of the vehicle. It is clear that the overall sound character of the Nissan LEAF has been refined substantially from the exterior to the interior of the vehicle, and that it has a similar interior sound character to a luxury commercial vehicle such as the Mercedes Benz B180CDI. According to results from the perceived consumer satisfaction in Table 3.3, this EV interior sound appears to provide greater satisfaction than its ICE counterpart. The EV sound signature appears to be more comfortable than that of the Mercedes, which could result in a greater satisfaction rating, but further analysis is required to find the principal components which can account for this result.

The highest satisfaction score was achieved by the Porsche interior sound. Porsche

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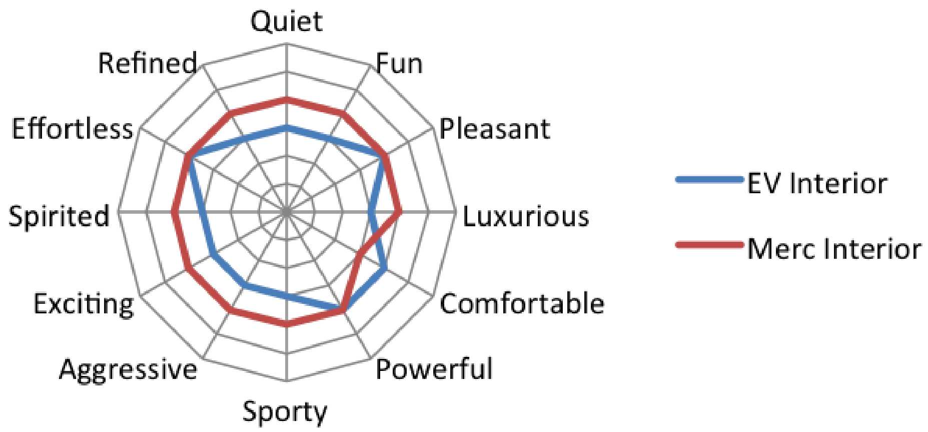

Figure 3.6: EV and Mercedes interior sound comparison of semantic characteristics.

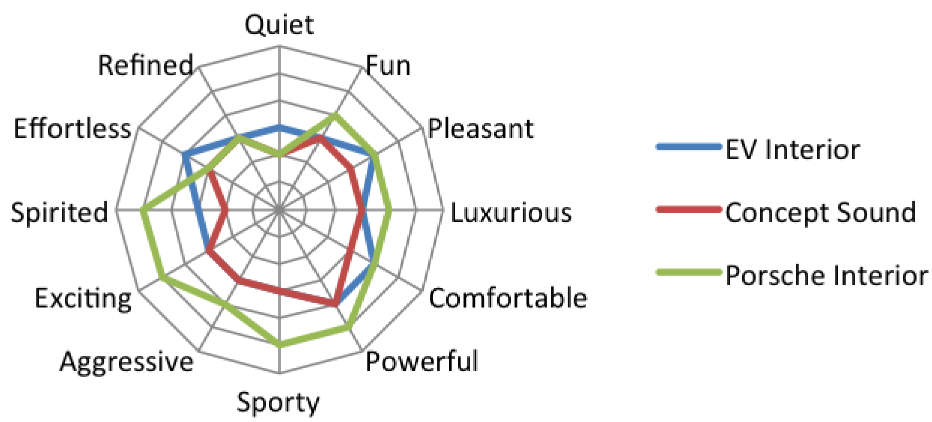

Figure 3.7: EV interior, Concept sound and Porsche interior sound comparison.

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Table 3.3: Vehicle sound comparison with respect to perceived consumer satisfaction.

Vehicle Sound	Overall Satisfaction
EV Interior	64%
EV Underhood	55%
Concept Sound	58%
Mercedes Interior	60%
Porsche Interior	65%

sound is superior to the EV sound signature in terms of perceived luxuriousness, powerfulness, fun and aggressiveness to name a few. However the greatest difference in sound character is found in the spirited, exciting and sporty categories. These sound characteristics are most likely the factors that contributed to the increased satisfaction of the Porsche sound. The concept sound has similar characteristics to the EV interior sound but falls short in a few categories, such as comfort, pleasantness and effortlessness. Improving these areas could result in a higher consumer satisfaction and will be considered in the next concept sound stimulus. The EV interior sound is perceived to be more effortless and quiet than the Porsche sound signature, which is expected since electric vehicles are known to be quieter than ICE vehicles. An interesting result however is that the Porsche sound is perceived to be more luxurious than the EV sound. This is surprising since Porsche is considered a sport vehicle rather than a luxury vehicle brand such as BMW or Mercedes. The high luxuriousness in the Porsche sound might be attributed to the build quality of the vehicle which is reflected in the higher retail price.

3.4 Conclusion

The subjective evaluations of noise produced by electric vehicles were investigated through jury testing and a subjective evaluation form. The form utilised word association and a bi-polar semantic differential scale in order to evaluate the subjective response of the jury to a variety of sound stimuli. Electric vehicle sounds from the Nissan LEAF were recorded and used as stimuli for the tests. Additional sounds from an airplane and washing machine were also used

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to broaden the possible list of descriptive sounds. Seventeen subjects participated in the evaluation. The results showed that 'powerful', 'rumbling' and 'deep' are words commonly associated with the sound of electric vehicles, and thus illustrates the strong presence of the power or strength aspects of electric vehicle sound. A significant difference in perceived loudness and pleasantness exists between the interior sound and underhood measured sounds. The subjective characteristic of sportiness is inferior in electric vehicle sounds. It was also found that the sound of a Porsche 911 Turbo is perceived to be the most satisfying with the interior sound of the Nissan LEAF following closely. It is concluded that semantic bi-polar scales can be used as one of the methods to effectively determine the subjective evaluation of sound signatures for electric vehicles.

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Chapter 4

The Comparison and Analysis of Standard Production Electric Vehicle Drive-Train Noise

The exposition presented in this chapter is a collaboration effort with Dr. Annie Bekker of the Department of Mechanical and Mechatronic Engineering at Stellenbosch University, Stellenbosch, South Africa, and Prof. Jörg Bienert of the Department of Mechanical Engineering at the University of Applied Sciences, Ingolstadt, Germany. The work was published in the International Journal of Vehicle Noise and Vibration in 2016. Dr. Bekker is the co-author of this paper as the supervisor of the PhD candidate, and Prof. Bienert acted as host supervisor during an exchange semester in Germany, and provided measuring equipment and guidance regarding NVH measurement protocols. A signed declaration to this effect is in the possession of both the candidate and supervisor. The paper investigates the sound signatures of electric vehicles currently found in industry [12]. This paper achieves one of the main objectives of this dissertation by investigating the established sound signatures of EVs currently in production, and accentuates the key differences and characteristic between EV signature sounds.

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4.1 Introduction

The automotive industry is expanding and evolving daily to satisfy the needs of technology driven consumers, those seeking faster, safer and cheaper vehicles. Due to high fuel prices and the inevitable decrease of oil reserves around the world, the demand in technological advances has recently shifted towards more energy efficient vehicles [39]. The automotive industry is thus compelled to explore transportation methods that are less reliant on, or even independent of, conventional Internal Combustion Engine (ICE) technology [40]. This is evident by the increased number of Electric Vehicles (EV) and Hybrid Electric Vehicles (HEV) that are found on the roads today, in addition to a projected sales growth rate of 20% for electric vehicles [41].

The demand for EVs and HEVs is propelled even more by increasingly stringent emission legislation and the reduction of greenhouse gasses produced in cities, the largest contributors to energy-related global greenhouse gases [42]. Automotive vehicle emissions in the Netherlands have been linked to respiratory death and diseases [43]. Although the EVs and HEVs pose significant advantages in terms of emissions, they do present some other challenges. The low levels of sound emitted by electric motors offer benefits in terms of a quieter cityscape [44], although these reduced noise emissions tend to be problematic for drivers and pedestrians at vehicle speeds below 25 km/h [1]. The need for safer EVs and HEVs is evident through resulting legislation changes: legislation in the US, EU and guidelines posed by Japan requires EVs to produce exterior warning sounds at lower vehicle speeds [45], [46] and [47]. At higher speeds, both the interior and exterior sound of EVs is dominated by wind and tyre noise [48] and therefore warning sounds at higher speeds are redundant. Relevant questions remain - do EVs only require sound modifications at lower vehicle speeds? How does this affect the driver's perception? Studies by Cocron *et al.* [35] and Hoogeveen [49] found that continuous sound is important to a driver's perception, as it provides stimulus to the driver through audible sound cues, suggesting that a continuous sound signature should be audible to the driver as well. EVs are linked to a bland sound character which reduces the thrill and satisfaction of driving [50] and consequently influences the uptake and acceptance of EVs in the automotive indus-

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try. Considering this background, a series of questions arises with regards to the diversity and suitability of the sound character of EVs.

What is the benchmark sound signature currently found in the automotive industry regarding standard production EVs? Do these sound signatures fulfil drivers' needs with respect to sufficient warning attributes to pedestrians, driver sound quality, and driver feedback? How do these sound signatures compare with known positive aspects regarding customer sound satisfaction?

4.2 Experimental Procedure

Interior (passenger cabin) and Motorbay sound recordings were obtained from six commercial electric vehicles. The Motorbay sound in this context refers to sound measured inside the motorbay compartment of the vehicle. The sound was measured in close proximity to the electric motor, either under the hood or towards the rear of the vehicle, depending on where the motor was positioned. Two Head Acoustic SQuadriga [51] portable recording devices were used as the recording platform for both interior and motorbay measurements. A total of 5 channels were recorded across the two devices at a sample frequency of 44.1 kHz. The interior sound was recorded with two SQuadriga Binaural headsets. The headsets were positioned on researchers in the driver seat and the rear right passenger seat respectively. During the testing of 2-seater vehicles, the second researcher was positioned in the front right passenger seat instead, alongside the driver. All interior measurements refer to the passenger microphone position unless specified as the interior(driver) position. The motorbay sound was recorded using a half-inch 40AE G.R.A.S pre-polarised free field microphone, which was placed in close proximity to the electric motor and inverter. The motorbay microphone was secured using heavy duty duct tape and encapsulated in a foam casing to prevent vibrational disturbances. Test runs were performed before the commencement of the actual measurements to ensure that the interior microphones were at an optimal measurement level and that the motorbay microphone did not have any substantial wind noise disturbances. It was found that the suitable microphone ranges were -16 dB(V) and +4 dB(V) for interior and

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motorbay sound respectively [51]. The recording sound pressure level range for both interior and motorbay measurements was set at 114 dB as to avoid clipping of the sound. The motor rpm could not be obtained as the Controller Area Network (CAN) bus configuration for the various vehicles was not known.

4.2.1 Test Vehicles

Various standard production electric vehicles were tested in Bavaria, Germany over a period of six months. The vehicles were acquired from local vehicle dealerships and assessed through standard industry test protocols. Five electric vehicles were assessed one hybrid-electric vehicle (HEV) with a full electric drive option. The electric vehicles were all selected from the same vehicle class so as to provide a better comparison for inner vehicle acoustics. The HEV falls in a larger vehicle class but was selected due to the full electric drive option that it provides. The full range of left-hand drive testing vehicles is listed below in Table 4.1. In addition, the specific tyres used for each vehicle are specified in Table 4.2. However, the tyre specifications of the HEV could not be disclosed.

Table 4.1: Test vehicles description

Vehicle	Seater	Gearbox	Propulsion
Renault ZOE	4	Direct Drive	Electric Vehicle
Volkswagen e-Up!	4	Direct Drive	Electric Vehicle
Smart Electric	2	Direct Drive	Electric Vehicle
Citroën C-Zero	2	Direct Drive	Electric Vehicle
BMW i3	4	Direct Drive	Electric Vehicle
Porsche Panamera	4	Multi-Stage Gearbox	Hybrid Electric Vehicle

The Porsche Panamera has a different gearbox setup to the full electric vehicles as presented in Table 4.1. Multi-stage gearbox systems require several gear changes during an acceleration run up, whereas direct drive systems do not. This in turn leads to a higher maximum rpm for direct drive systems, which also corresponds to larger motor excitation. The Porsche Panamera Hybrid was considered for selected acceleration test only, so as to show the difference between electric vehicles with and without multi-stage gearboxes. Additional variation in the data was

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Table 4.2: Test vehicle tyres

Vehicle	Tyre Make	Tyre Model
Renault ZOE	Michelin Green X	195/55R16 91Q
Volkswagen e-Up!	Vredestein SNOWTRAC 3	165/70R14 81T
Smart Electric	Kumho ECSTA KH11	175/55R15 77T
Citroën C-Zero	Dunlop ENSAVE 2030	175/55R15 77V
BMW i3	Bridgestone Ecopia EP500	175/60R19 86Q
Porsche Panamera Hybrid	Unknown	Unknown

offered by the Smart Electric and Citroën C-Zero, which are two-seater vehicles, chosen to add variation to the interior acoustic sound signature data.

4.2.2 Test Conditions

The vehicles were tested on secluded roads within close proximity of the vehicle dealership. The secluded roads were selected to provide a smooth and straight testing strip without any bends, and negligible to no vehicle traffic. All vehicles were tested on a smooth and consistent tarred surface with a road gradient of less than 5%. The tests were all conducted on a dry road surface, with fair weather conditions and negligible wind speed. The air temperature of the tests varied between 18 and 23 degrees Celsius.

4.2.3 Test Protocol

A test protocol was designed to evaluate electric vehicle sound and ensure test consistency and repeatability. The test location, road surface, weather conditions, test vehicle and tyre specifications were all recorded. The protocol consisted of two standard tests that are well documented in the automotive industry, namely constant speed drives and Wide Open Throttle (WOT) drives [4; 18; 52]. Constant speed tests were conducted to gather information that simulates everyday driving. Two common speed limits in and around cities and towns are 60 and 80 km/h [53] and were thus selected for testing to represent frequently driven constant vehicle speeds. In addition to constant speed and WOT drives, there is a third test called Part Throttle (PT) drive, which is also frequently dis-

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cussed in literature. PT drive tests focus on the aspects of gradual acceleration of a vehicle, whereas WOT drive tests measure the fastest acceleration possible by a vehicle [36]. The latter was the preferred method for this research as it provides the maximum excitation of the electric motor and drive train. The test protocol is listed below with a short description of each test.

Test 1: Constant Speed Drive (60 km/h) - The test vehicle was accelerated from rest to a speed of 60 km/h and then driven at constant speed. The measurement was started two seconds after the constant speed phase was reached in order to ensure that a sound equilibrium had been reached and that the driver's foot has stabilised on the accelerator pedal. The measurement was recorded for a period of 20 seconds.

Test 2: Constant Speed Drive (80 km/h) - As for Test 1, however with a target speed of 80 km/h.

Test 3: Wide Open Throttle (WOT) - The test vehicle was accelerated from rest to a top speed of 120 km/h in the shortest time possible and then decelerated back to zero. The vehicle was decelerated with a combination of free coasting and regenerative braking, depending on the allowable deceleration distance of the specific test track. Regenerative braking transforms the kinetic energy from the braking cycle into electricity in order to charge the batteries of the vehicle [54]. In some cases however, regeneration does not only apply for the braking cycle but also occurs during the coasting phase. The measurement was started two seconds before the acceleration run was initiated and was allowed to continue until the vehicle came to a complete stop. The measurement period varied between the different vehicles as it depended on the acceleration and deceleration performance of the vehicle.

Each test was repeated several times to ensure a minimum of at least three acceptable recordings; the driving direction, amount of vehicle pass-byes, general impression and comments were recorded.

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4.3 Results

4.3.1 Constant Speed Drives

Two independent analyses were performed to provide information on the sound generated in both the motorbay and in the passenger cabin.

Time Domain Sound Pressure Levels

Time domain Sound Pressure Level (SPL) analysis is used to investigate and compare noise levels of machinery and vehicles in industry. The SPL calculations are guided by Equation 2.1, and is the basis for all SPL analyses. Additionally, SPL weightings exist which can be applied to conform to sound suited for human hearing (A-weighting) or heavy machinery (C-weighting) [17]. A-weighted SPL was used to provide better insight regarding the interior sound as experienced by vehicle occupants. The motorbay SPL sound was also A-weighted in order to establish how occupants would experience the unfiltered sound from the source. The time domain SPL analysis for the electric vehicles is displayed in Figure 4.1. The best measurement run was selected according to the smallest standard deviation and lowest peak values. The selected run was then averaged over the measurement time for further comparison. The average and peak A-weighted SPL values are tabulated in Table 4.3, along with the standard deviation for the selected test runs. The standard deviation for all selected vehicle recordings does not exceed 2% of the measured value, which indicates minimal variation in the data and thus can be considered as an acceptable recording.

The difference in the interior SPL between driver and passenger for both vehicle speeds is noted to be at most 2.8 dB. This is negligible since it does not exceed the perceivable sound pressure level difference barrier of 3 dB [16]. It is of interest to note that the highest SPLs are recorded for the two-seater vehicles, i.e. the Smart and Citroën, for both interior and motorbay measurements. A possible explanation for this finding could be due to the smaller acoustic capacity of the vehicle cabin, which could intensify the sound. Additional research is required

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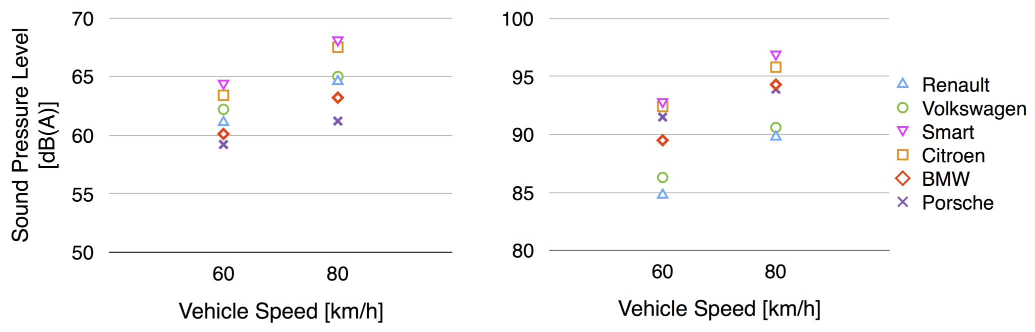

(a) Interior (b) Motorbay

Figure 4.1: Interior and motorbay electric vehicle sound pressure level comparison at constant speed drives.

Table 4.3: A-weighted time-domain SPL for the six test vehicles

Vehicle	60 km/h	Peak	80 km/h	Peak
	dB(A)	dB(A)	dB(A)	dB(A)
Interior				
Renault ZOE	61.1 ± 0.9	65.0	64.6 ± 0.8	67.2
Volkswagen e-Up!	62.2 ± 0.7	64.5	64.6 ± 0.9	69.0
Smart Electric	64.3 ± 0.9	67.4	67.1 ± 0.7	69.8
Citroën C-Zero	63.4 ± 0.6	66.0	67.5 ± 1.2	70.4
BMW i3	60.1 ± 0.9	63.7	63.2 ± 0.9	66.8
Porsche Panamera Hybrid	59.2 ± 0.4	60.1	61.2 ± 0.7	62.7
Motorbay				
Renault ZOE	84.8 ± 0.4	85.9	89.8 ± 0.7	92.1
Volkswagen e-Up!	86.3 ± 0.6	87.8	90.6 ± 0.7	92.1
Smart Electric	92.7 ± 0.6	93.8	96.8 ± 0.4	97.8
Citroën C-Zero	92.4 ± 0.7	94.0	95.8 ± 1.1	98.9
BMW i3	89.5 ± 0.6	90.8	94.3 ± 0.5	95.8
Porsche Panamera Hybrid	91.5 ± 0.6	93.1	94.3 ± 0.8	96.1

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to confirm this. A second discovery of interest is that the vehicle with the lowest interior SPL, the Porsche, does not exhibit the lowest motorbay SPL. Instead the Renault and Volkswagen are found to have the lowest motorbay SPL for both vehicle speeds. A substantial difference of more than 3 dB can be noted between these two vehicles and the other test vehicles. This difference can possibly be accounted for by factors such as acoustic insulation of the motor and inverter cover or casing, as well as the topology of the motor. The largest SPL difference between interior and motorbay recorded sound is found for the Porsche Panamera. This attests to a vehicle with good sound insulation and sound proofing, as the sound propagating from the motorbay to the interior of the vehicle is minimised.

Third Octave Evaluation

Octave analysis is used when aspects regarding the frequency domain are of more interest than the time domain. Two popular techniques found in the industry are normal or standard octave, and third octave analysis. The latter performs an octave analysis in segments of 1/3 octaves instead of whole octaves and thus provides a better resolution with regards to the frequency content of the measured data. A third octave analysis was performed on the electric test vehicles for both sets of constant speed drives, to compare the frequency character of the different vehicles. The motorbay recorded sounds were used in order to avoid any filtering or damping resulting from the motorbay to interior transfer path. No weighting was applied to the data to provide the true frequency response information. When computing and comparing octave analyses of different vehicle speeds, one expects that the majority of the octave envelope will remain the same and only increase in magnitude, since the same e-motor is being measured. However, changes in the envelope may occur due to resonant frequencies or prominent vehicle orders appearing at specific vehicle speeds.

With a few exceptions, the frequency envelope of all vehicles exhibits a constant increase in magnitude with regards to speed change. The BMW illustrates a prominent 4 kHz band at the 60 km/h, which shifts toward the 5 kHz band at 80 km/h. This octave band movement with respect to speed appears to be the presence of a prominent motor order, however this can later be confirmed with

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a spectrogram. The second instance of non-constant envelope rise is found in the 16 kHz band of the Citroën's sound analysis. This specific frequency band decreases in magnitude with an increase in speed. A possible explanation for this counter-intuitive behaviour could be accounted for by the masking effects caused by the magnitude increase of the surrounding frequency bands.

The Smart and Citroën demonstrate significantly higher levels in the high frequency range (>5 kHz) compared to the remainder of the vehicles, with the Citroën being superior. The extreme high levels recorded for the Citroën in the 10 kHz to 20 kHz range is unusual, as no other vehicles display comparable values in this frequency range. The minimum SPL difference found amongst the vehicle pool, in this frequency range, is in the order of 10 dB. A perceivable doubling in sound can be experienced with a magnitude difference of 10 dB and an actual doubling of SPL is recorded at 6 dB [55], which is well exceeded in this case. Although this frequency range is unlikely to be audible for human beings, it can potentially pose problems for animals with enhanced hearing such as dogs, or with vehicle electronics. Further analysis is required to determine the cause of this extreme SPL difference. The Renault illustrates a diminished sound pressure level in the extreme low frequency range (<20 Hz) when compared to the other electric vehicles.

Lastly, when analysing the vehicle pool as a whole, certain trends were identified. The BMW, Citroën and Smart all display local minima, with respect to the envelope, between 200 and 500 Hz, whereas the Renault and Volkswagen display similar minima centered at 500 Hz. The reason for this difference in the specific local minima is unclear and requires additional investigation, possibly indicating a different motor topology or inverter switching scheme. All vehicles demonstrate a local maxima in the 1 kHz band.

4.3.2 Wide Open Throttle Drives

Constant speed drive tests are useful to gather information regarding characteristics at a specific speed, however everyday driving does not only consist of con-

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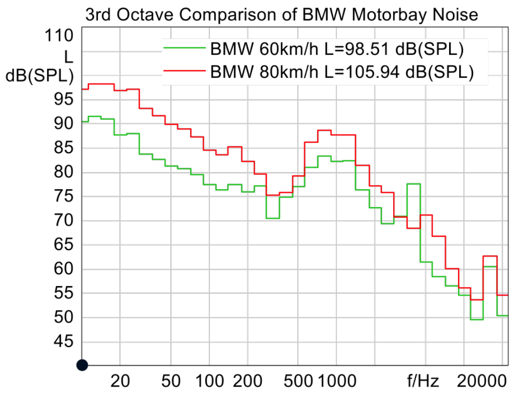
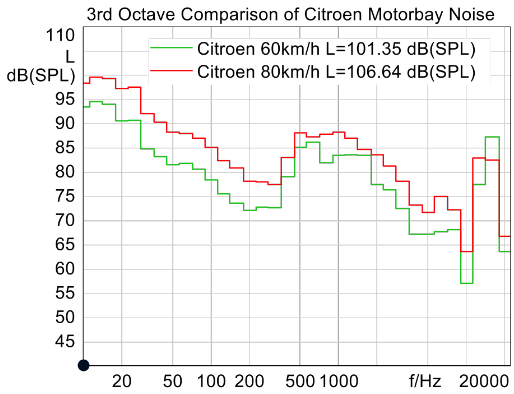
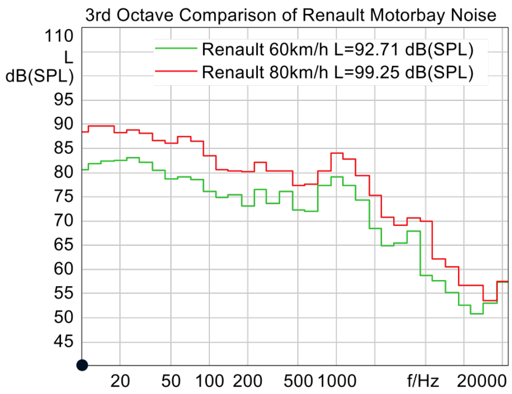


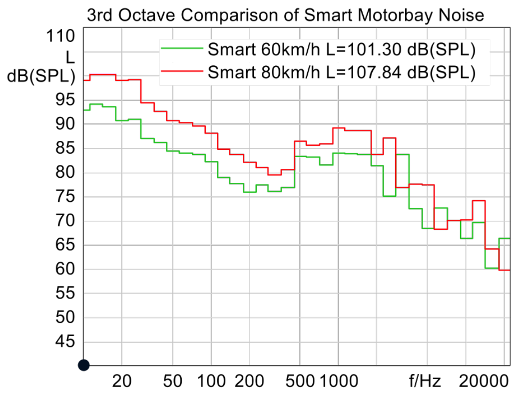
(a) BMW



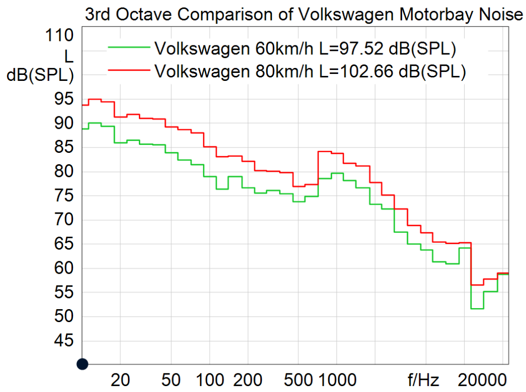
(b) Citroën



(c) Renault



(d) Smart



(e) Volkswagen

Figure 4.2: 3rd Octave comparison of electric vehicle motorbay noise at constant speed drives.

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stant speed driving. A different procedure is therefore required in order to encapsulate the data that emerges from the non-steady state driving phases. Part Throttle (PT) drive and Wide-Open Throttle (WOT) drive tests are used to measure sound for non-steady state driving conditions. As described in Section 4.2.3, WOT was selected as the preferred method since it generates maximum motor excitation. This in turn provides a stronger measured frequency response which allows for easier identification and detection of motor orders and modes. An order can be observed as a linear relationship between the spectral content of the drive train noise and vehicle speed/rpm [18]. Motor orders of a vehicle can best be viewed through the use of spectrograms and analyses such as Auto Power Spectra (APS), Power Spectral Density (PSD) or Fast Fourier Transform (FFT) with respect to vehicle speed or rpm. These analyses can also be illustrated with respect to time, which generate non-linear order lines but provide additional temporal information such as run-up time.

Time Domain Sound Pressure Levels

The interior and motorbay sound SPL during the WOT drive was recorded and the results for the vehicle run-up is illustrated in Figure 4.3. The interior driver noise was selected for comparison rather than the interior passenger noise as it had a constant measurement reference point. The interior passenger noise was recorded at two different interior measurement locations depending on the vehicle passenger capacity as described in Section 4.2. The BMW has the fastest run-up time, just over 10 seconds, with the Smart following in close second place with 14.6 seconds. The Renault, Volkswagen and Citroën have similar run-up times to one another. Results indicate that the Porsche has the slowest run-up, however this is not entirely correct. The full-electric drive option of the Porsche does not accommodate complete WOT drive, but rather a midway between PT and WOT drive. However the results were still included for comparison, in order to illustrate the difference in speed-varying SPL for multi-stage gearbox vehicles and direct drive vehicles. The gear changes for the Porsche can be seen at 3.5 and 8 seconds for both interior and motorbay sound. The gear changes are more prominent in the interior sound since the broadband masking effect from tyre and wind noise is less.

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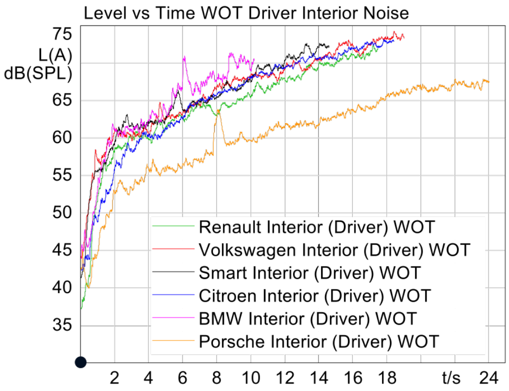
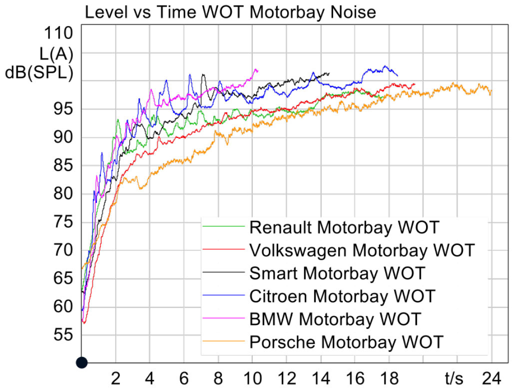


(a) Interior (Driver)



(b) Motorbay

Figure 4.3: A comparison of (a) passenger cabin and (b) motorbay sound pressure levels during WOT acceleration.

The interior vehicle sound comparison indicates that the Porsche and BMW have the lowest SPL during run-up, with the Porsche being significantly lower than the other vehicles. The Citroën, Renault, Smart and Volkswagen converge within a 3 dB difference towards the end of their individual run-ups. The motorbay measured sound portrays a slightly different picture. The Porsche, Renault and Volkswagen have the lowest SPL during run-up, whereas the BMW, Citroën and Smart have the highest.

Lastly, comparing the motorbay to the interior, it can be seen that large changes occur in some vehicles. The BMW, for example, has one of the highest motorbay WOT SPLs, but also the second lowest interior SPL. This indicates that the interior cabin is well insulated for vehicle sound. The Porsche on the other hand displays diminished SPL for both interior and motorbay sound; this signifies that the complete vehicle has an inherently lower SPL, in addition to the good sound insulation found between motorbay and interior noise. The milder WOT drive of the Porsche could also contribute to the lower SPL.

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Spectrograms

Spectrograms present spectral and temporal data with respect to magnitude. The spectral data is represented in Hertz, while the temporal data usually represents a measurement of time. The temporal axis can also illustrate vehicle or motor speed, if the vehicle's rpm data can be obtained. The dominant motor orders of the EV drive-train form frequency peaks that relate to multiples of the motor rpm. These orders appear as non-linear lines, as seen in Figure 4.4, that increase and decrease as the vehicle accelerates and decelerates during a WOT run. Distinct linear lines can be observed in the higher frequency range (>5 kHz). These lines fan out from the same origin and converge again as the vehicle decelerates. These lines are a result of the switching frequencies from the electric motor inverter [56]. The switching frequencies are unique to each electric motor as it depends on the motor topology and inverter. Upon careful examination, it can be seen that the switching frequency lines are repeated in an even higher frequency range as is especially visible in Figure 4.4b. The repetition of higher multiples of the switching frequency is merely a harmonic of the primary trace, as one can see in all cases that it is the exact doubling of the first occurrence. The large yellow areas that appear smudged or grated are caused by broadband noise, such as wind and tyre noise, which induces roughness in the sound [56] through amplitude modulation. It can be observed that these areas are concentrated around the middle of the vehicle run-up and run-down, which corresponds to the vehicle approaching the maximum run-up speed and thus results in the largest wind and tyre noise contribution.

4.4 Discussion

Figure 4.4a shows that the BMW has substantially less noise in the high frequency range (>10 kHz) in comparison to the other EVs. The Volkswagen and BMW have the least number of prominent orders, with 10 and 12 visible prominent orders respectively. An unexpected discovery is that the Volkswagen is the only full electric vehicle that has no orders that exceed the 90 dB range. The most prominent orders of the Volkswagen can be found between 2 kHz and 5 kHz at full run-up.

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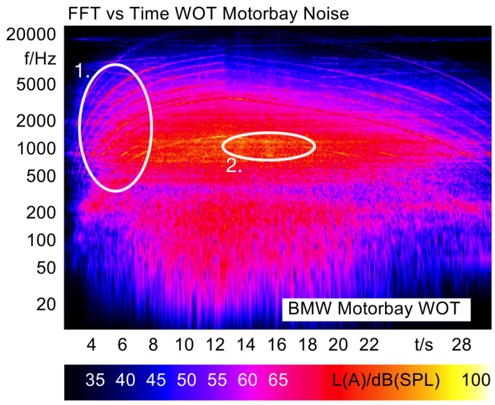
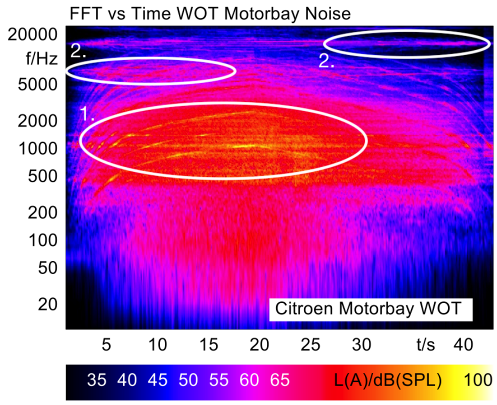
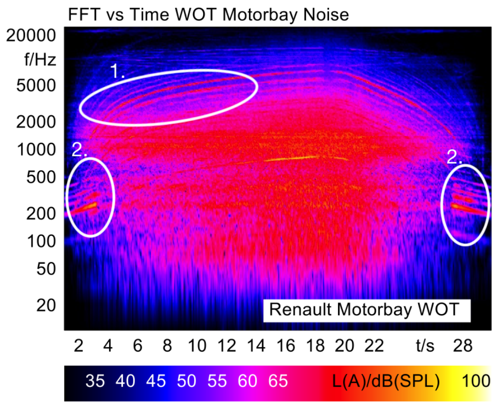


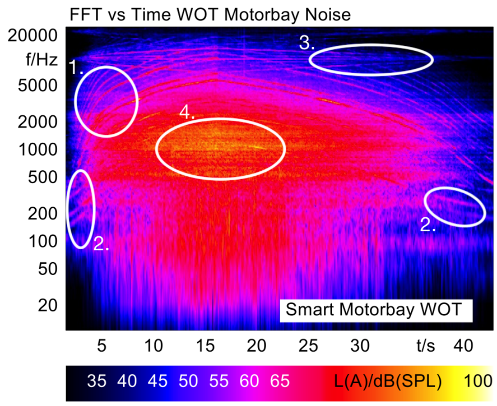
(a) BMW i3



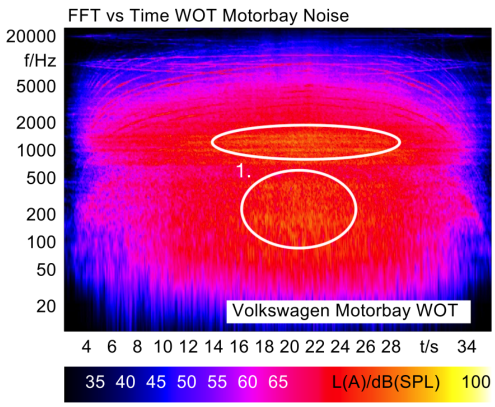
(b) Citroën C-Zero



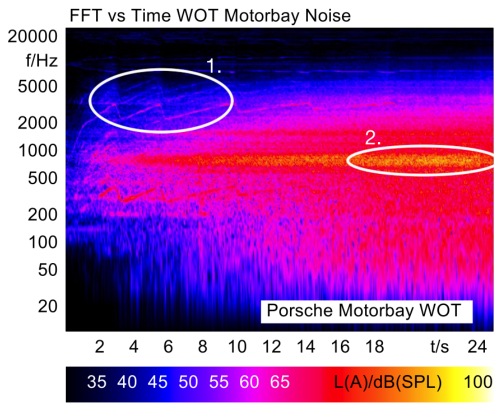
(c) Renault ZOE



(d) Smart Electric



(e) Volkswagen e-Up!



(f) Porsche Panamera Hybrid

Figure 4.4: FFT vs time comparison of electric vehicle motorbay noise during run-up and run-down. The circled areas in figure 4.4a illustrating motor orders (1) and roughness (2) for BMW i3. Figure 4.4b illustrating motor orders (1) and inverter switching frequencies (2) for Citroën C-Zero. Figure 4.4c illustrating motor orders (1) and additional warning sound (2) for Renault ZOE. Figure 4.4d illustrating motor orders (1), additional warning sound (2), inverter switching frequency (3) and roughness (4) for Smart Electric. Figure 4e illustrating roughness (1) for Volkswagen e-Up!. Figure 4.4f illustrating motor orders with gear changes (1) and roughness (2) for Porsche Panamera Hybrid.

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This region is considered to be the most sensitive interval of human hearing [16]. Therefore prominent orders in this region should be more visible, which is not the case. A possible explanation for the decreased magnitude of the prominent orders as well as low overall SPL could be the frequency shielding material, such as the motor cover. It is noted that the Citroën has the most significant prominent orders with regards to magnitude, which are concentrated mostly in the 1 kHz to 2 kHz region. The BMW has three prominent orders that pass through the 2 kHz to 5 kHz region at higher speeds. This confirms the observation of a possible prominent order that was found through third octave analysis in Section 4.3.1. The most prominent order of the Renault approaches 1 kHz at top WOT speed. Additionally there are 5 prominent orders found at the start and end of the Renault WOT, however these orders are not continuous, as they are not visible throughout the whole run. This is typical of an additional warning sound at low speeds as confirmed by Renault [3]. Similar although faint traces can be detected for the Smart as well, which confirms the presence of an artificial warning sound [57]. The most significant orders of the Smart are subtle and are spread through a large frequency range. These orders can be detected from 1 kHz and extending slightly past 5 kHz, with reference to maximum WOT speed. The prominent orders of the Porsche are significantly different from the EV prominent orders. Figure 4.4e illustrates 'spikes' in the motor orders during the WOT run up, which are caused by the gear changes of the MSG for the HEV.

Considering the switching frequencies of the vehicles, these are unique depending on the inner workings of the motors, and are clearly visible on the spectrograms. The spectral lines extruding from the switching frequency origin differ in number and band width of the spread for each vehicle. The switching frequency trace for the Renault and BMW is significantly duller than the remainder of vehicles with the Citroën portraying the most vivid response for the primary trace and the first harmonic. The evident second harmonic trace of the Citroën's switching frequency provides an explanation for the extreme magnitude levels found in Section 4.3.1 in the 10 kHz to 20 kHz range. The origin of the primary trace for all vehicles is found between 5 kHz and 10 kHz, with those of the Renault and Smart situated exactly at 10 kHz. The Citroën has the lowest switching frequency at 8 kHz. This is in close proximity to the frequency interval of human

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hearing that is most sensitive to sound [16]. The audibility of the switching frequency could cause annoyance and in turn diminish the overall sound quality and character.

The results from the EV evaluation show that commercial electric vehicles are quiet and have similar sound character, based on the frequency content. Electric vehicles have a diminished SPL in the frequency range from 200 to 500 Hz. This frequency range is of interest as it approaches the most sensitive hearing range, and research has linked this frequency range to sound quality satisfaction [6]. Lennström *et al.* [6] found that prominent orders in this frequency range improve satisfaction with regards to sound quality. This mid-frequency range is synonymous with prominent lower engine orders of internal combustion engine vehicles [2; 18]. The evaluated vehicles have no prominent orders in this frequency range, as shown in Figure 4.4. This could be a possible reason that affords those vehicles with the neutral and bland sound character as described by [6; 50]. Roughness in the mid-frequency range has been linked to increase sportiness and powerfulness of sound [4; 18]. Figure 4.4 illustrates that all test vehicles, except the Volkswagen, do not present inherent roughness in the mid-frequency range, but rather in the high frequency range (>500 Hz), which indicates the lack of 'sporty' and 'powerful' sound characteristics for EVs. Roughness in this frequency range can be attributed to wind and tyre noise [18]. Does this insinuate that electric vehicles provide lower satisfaction compared to ICE vehicle with regards to sound quality? Is there additional information that can support this theory?

A study on mainstream consumers driving EVs and HEVs [58] found many drivers complained about the lack of engine noise. The lack of driving noise did not only lead to consumer dissatisfaction but also posed a safety risk. Additionally the study indicated that drivers found it challenging and confusing to adapt to the low levels of driver feedback from the e-motor. A study by Jennings *et al.* [4] stated that drivers change their driving style in an unnatural manner in order to avoid adverse sound effects such as noisy or harsh engine sounds. The lack of driver feedback does not only decrease customer satisfaction but also influences

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customer driving techniques. The low levels of driver feedback in combination with unpleasant tonal sound components of EVs could lead to abnormal driving styles.

The prominent motor orders of the EVs are evident between 500 Hz and 10 kHz during vehicle run-up and run-down as seen in Figure 4.4. However, the spread is focused mainly between the 1 kHz and 5 kHz frequency band. This specific frequency band corresponds to the most sensitive interval of the human auditory system [16]. The combination of unsatisfactory sound and sensitive hearing interval can lead to the annoyance of consumers. Additionally the inverter switching frequency primal traces are found to be below 10 kHz, and thus audible to humans. These audible high pitched switching frequencies (>5 kHz) could significantly increase the perceived annoyance to the driver and passengers as suggested by Lennström *et al.* [8]. The increased amount of high frequency content in electric vehicles, motor orders and switching frequencies could deteriorate overall satisfaction, as found by a previous study Lennström *et al.* [6]. The high frequency content can further encourage the adaptive driving styles, to avoid the annoyance and thus pose a possible safety risk as well.

The specific Prominence Ratio (PR) for WOT motorbay noise of the test vehicles were calculated, to determine the extent of annoyance caused by the high frequency content as found by Lennström *et al.* [8]. Prominence ratio is an indication of the notability of tonal components within a sound stimulus. Figure 4.5 illustrates the specific PR with respect to time for each of the vehicle sound signatures during a complete run-up and run-down. The prominent motor orders are visible for all vehicles as well as the jagged motor orders of the Porsche. The artificial warning sound in the Renault is highly prominent during the start and end of the WOT run, however it appears to be insignificant in the Smart spectrogram. The inverter switching frequencies are also prominent for all vehicles, and especially vivid for the Citroën. Lennström *et al.* [8] found that prominence ratios in excess of 5 dB indicate highly audible sounds, and that annoyance increases with the order number in this region. The author suggested that tones exceeding 800 Hz, should be kept to a PR-level below 3 dB. The motor orders and switching

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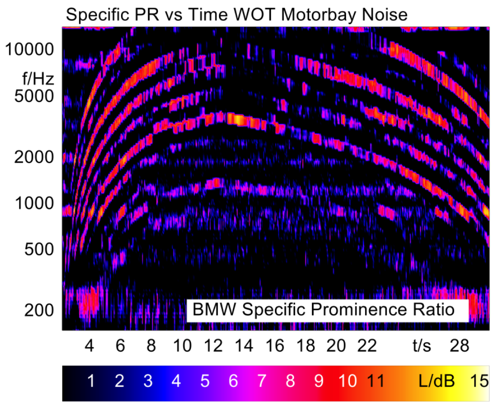
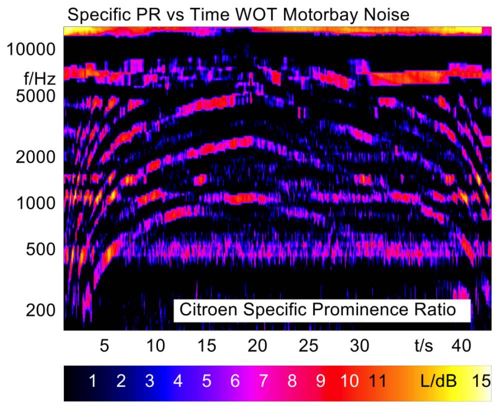
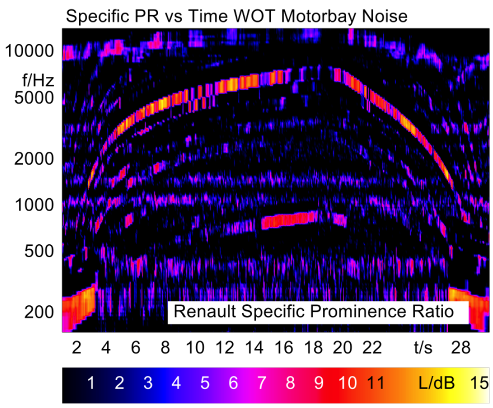


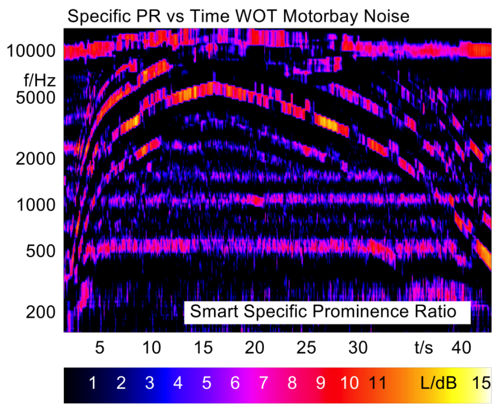
(a) BMW i3



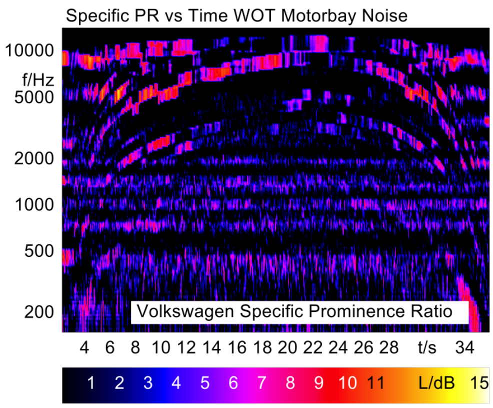
(b) Citroën C-Zero



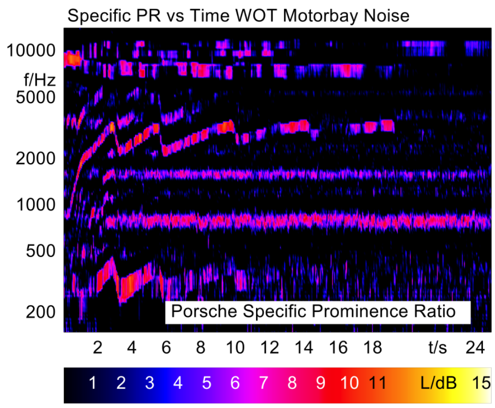
(c) Renault ZOE



(d) Smart Electric



(e) Volkswagen e-Up!



(f) Porsche Panamera Hybrid

Figure 4.5: Specific prominence ratio vs time analysis of electric vehicle motor-bay noise during run-up and run-down.

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frequencies exceed the 800 Hz band and the PR-level can be observed to reach values in excess of 10 dB, which suggest severe annoyance by these prominent high frequency components.

One possible solution to this problem was found during the investigation of the HEV, and more specifically the drive train setup of this vehicle. The vehicle in question has a multi-stage gearbox, compared to the direct drive setup of the other EVs. The multi-stage gearbox has several gear changes during a WOT run, which allows for a reduced maximum rpm of the electric motor. This in turn relates to smaller excitations in the electric motor and thus reduces the high frequency content by lowering the motor orders. Additional solutions such as high frequency shielding for the electric motor should also be considered. Increased roughness in the low to mid-frequency range should also be considered in an attempt to improve overall satisfaction. The increased roughness could potentially reduce the prominence of the high frequency content and function as a masker, similarly as the roughness from ICE firing orders masks other vehicle component noise [18].

4.5 Conclusion

The sound signatures of five standard production electric vehicles were analysed and compared in order to investigate the content and character of these sounds. Additionally a hybrid electric vehicle with a multi-stage gearbox (MSG) was also investigated. According to literature, we know that electric vehicles are extremely silent for low vehicle speeds and that legislation in several countries is motivating EV manufactures to produce EVs with appropriate warning sounds. However these warning sounds do not apply for higher vehicle speeds or the satisfaction based on driver feedback. Time- and frequency-based analyses were conducted to investigate the sound signatures of these vehicles according to the defined test protocol.

Results found the Smart Electric and Citroën C-Zero to have the highest recorded

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Sound Pressure Level for both interior and motorbay noise. These vehicles were also found to have substantially higher sound energy in the high frequency bands ranging from 10 to 20 kHz. The extremely high level that was measured for the Citroën in this specific range was later linked to the inverter switching frequency of the vehicle. However, in general, all the electric vehicles were found to have significant noise levels in the 1 to 5 kHz frequency band. This band is linked to the most sensitive human hearing interval and thus could lead to annoyance.

The Renault ZOE and Smart Electric were found to have artificial warning sounds at low vehicle speeds, with the Renault exhibiting it more prominently. All the electric vehicles were found to produce local minima with respect to SPL in the frequency range from 200 to 500 Hz. The lack of prominent orders and roughness in this frequency range, strengthens the argument of the 'bland' and 'dull' sound character of EV signature sound as found by [6; 50]. Additionally it was concluded that the high frequency content of EV signature sounds could cause drivers to adapt their driving style. The combination of high frequency noise and decreased sound quality satisfaction, due to increased annoyance, poses a problem for electric vehicle consumers.

The Hybrid Electric Vehicle with a MSG was found to have less high frequency content and could therefore reduce annoyance caused by the prominent high frequencies of EVs. The addition of roughness in the low to mid-frequency range could improve perceived sound quality and act as a masker for the high frequency content. However additional solutions need to be investigated in order to improve the customer satisfaction of electric vehicle sound signatures.

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Chapter 5

The Subjective Dimensions of Sound Quality of Standard Production Electric Vehicles

The exposition presented in this chapter is a collaboration effort with Dr. Annie Bekker of the Department of Mechanical and Mechatronic Engineering at Stellenbosch University, Stellenbosch, South Africa, and Prof. Jörg Bienert of the Department of Mechanical Engineering at the University of Applied Sciences, Ingolstadt, Germany. The work was published in the Applied Acoustics Journal in 2017. Dr. Bekker is the co-author of this paper as the supervisor of the PhD candidate, and Prof. Bienert acted as host supervisor during an exchange semester in Germany, and provided access to Head Acoustics ArtemiS and a half-anechoic chamber that was used for jury testing. A signed declaration to this effect is in the possession of both the candidate and supervisor. The paper investigates the psychoacoustic aspects of electric vehicles, and the principal components that govern the semantic space [13]. This paper achieves two of the main objectives of this dissertation. Firstly, by determining the perceived consumer satisfaction of the motorbay sound signature of electric vehicles, and the underlying sound dimensions that govern it. Furthermore, sound enhancements were found that can potential improve perceived consumer satisfaction. The subjective evaluations and the evaluated stimuli that were used, can be found in Appendices B.2.1, B.2.2 and C respectively.

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5.1 Introduction

The market acceptance of electric vehicles is determined to an extent by the inherent sound quality and the effect of these sound cues on vehicle occupants and the surrounding environment [10]. Existing literature focusses on three common aspects of electric vehicle (EV) sound. Firstly, electric and hybrid electric vehicles (HEVs) generate minimal sound when driving at low speeds [18]. This leads to very quiet environments in the interior as well as exterior of the vehicle. The low sound emissions are beneficial in reducing noise pollution levels in cities and creating a quieter soundscape. The diminished noise pollution levels are considered to be a great attribute of electric vehicles, especially as we move towards future cities. On the other hand, the quiet nature of these vehicles results in some negative aspects of the low noise levels. Literature portrays electric vehicles as being too quiet, so much so that electric vehicles actually pose a safety risk to pedestrians and cyclists [1]. The magnitude of concern is so great that legislation and guidelines in US, EU and Japan now suggest that electric vehicles should emit an additional warning sound at low speeds [45–47]. Furthermore, the inherent sound quality of electric vehicles are a subject of interest for consumers. Lennström *et al.* [6] suggests that electric vehicle sound is bland in character, and a study by Cocron *et al.* [35] investigated the concerns of inadequate acoustic driver feedback experienced whilst driving an electric vehicle. A study by Lennström *et al.* [8] investigated the high frequency content of electric vehicle sound, and shows that these high frequencies lead to perceived annoyance.

Taking these three aspects into consideration, one is left to ponder about the ways to develop an alternative sound signature or improve the sound signature of EVs currently in development, in order to satisfy both the safety and consumer requirements. Such a sound would be sufficiently quiet, yet have inherent warning characteristics and be associated with desirable EV sound quality. Could such a sound be created and how would one go about it? A study done by Cocron *et al.* [35] suggests that a warning sound should signify a change in speed. Thus warning sound concepts should correlate with vehicle speed, motor speed or motor load, which is indicative of the vehicle acceleration as well. One possible method could be to use the current electric motor noise or develop an artificial sound signature using motor rpm and motor orders. However, could

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these speed-dependent sound signatures improve the sound quality? And how would they compare to current production electric vehicle sounds? Do enhanced electric vehicles sounds improve or diminish juror satisfaction? To answer these questions, it was necessary to investigate the subjective dimensions that govern consumer perceptions of electric vehicle sound satisfaction.

To this end, several commercial EV sound signatures were measured during Wide Open Throttle (WOT) acceleration drives [12]. The test vehicles of BMW and Renault were selected for the jury evaluation process. One of the vehicle sound signatures was selected as a base stimulus and was adapted in several dimensions to provide enhanced speed-related sound concepts. Consumer satisfaction was evaluated through jury testing and the principal components of the EV signature sound were determined through statistical analysis.

5.2 Experimental Procedure

The WOT sound signatures of five standard production EV were measured in the motorbay of the vehicle as to obtain the unfiltered electric motor sound. The motorbay refers to the compartment where the electric motor and inverter is situated, either under the hood or in the rear of the vehicle. The Motorbay sound is inherent and authentic to the character of the electric vehicle and its components, which is necessary to avoid a false sound perception [7]. These standard production EV sound signatures were measured and compared in a study by Swart *et al.* [12] where the full experimental details are provided. A study by Sukowski *et al.* [59] reported that the highest jury response rate was provoked by acceleration conditions and thus the WOT stimuli were considered. It was found that there was very little variation in the five acoustic stimuli from the respective electric vehicles. As such, only two standard production stimuli, namely the BMW i3 and Renault ZOE, were selected for this study and evaluated against several enhanced sound signatures. The full details of these stimuli are discussed in Section 5.2.2

Two subjective evaluation tests were developed in order to evaluate electric vehicle sound signatures and the manipulation thereof. The evaluations were based

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on the methodologies recommended by Jennings *et al.* [4]. The first evaluation used forced choice comparison, whereas the second evaluation made use of bipolar semantic differential scales in order to evaluate the sounds. The evaluations were conducted by means of jury testing in a half anechoic chamber at the Technische Hochschule Ingolstadt, Germany.

5.2.1 Jury

Jury testing was performed on a group of 32 international students. The jury pool was divided into two groups, Group A consisted of 14 members and Group B of 18 members. Group A had no prior exposure to electric vehicle sound, whereas Group B was exposed to a physical electric vehicle pass-by experience before conducting the subjective evaluation. This was done in order to produce a balanced jury which represents the consumer market that typically consists of members that have prior exposure to EVs and members that don't. Furthermore the influence on the subjective responses due to the pre-test pass-by exposure of an electric vehicles was also investigated. Examination of the completed evaluation revealed one juror member with a slight hearing impairment which lead to his exclusion from the analysis, thus bringing the juror pool down to 31 members. The breakdown of the final jury considered for analysis is provided in Table 5.1 and shows that the pool was male-dominated and biased towards younger individuals.

Table 5.1: Jury composition.

Jury Attribute	Group A	Group B	Total
Male	12	14	26
Female	2	3	5
Average Age	22	24	23
Max Age	26	33	33
Min Age	20	20	20

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5.2.2 Test Stimuli

The BMW i3 (2014) was chosen as the reference sound upon which sound manipulations were performed. As the BMW i3 is an award winning vehicle and a amongst the leaders in the electric vehicle market, it was selected as the baseline stimulus [60; 61]. The Renault ZOE (2013) was also chosen from the study by Swart *et al.* [12], as it has an alternative exterior warning sound at low speeds [3] and thus provides some variation for the jury evaluations. Manipulation methods such as filters, reverberation and pitch modifiers were used to change the baseline sound. The full set of stimuli is presented in Table 5.2 and 5.3.

Stimuli for Forced Choice Comparison

The purpose of this evaluation was to achieve a ranking of stimuli according to juror preference. One reference stimulus and 8 modified stimuli were evaluated. The BMW i3 Motorbay WOT measurement (Sound A) was chosen as the reference stimulus. The influence of frequency content was investigated by adjusting the high (Sound B), middle (Sound C) and low (Sound D) frequency bands of the reference sound. Low motor orders were added (Sound E) to the existing reference sound in an attempt to improve powerfulness of the sound and reduce sharpness as found by Jennings *et al.* [4] and Fastl & Zwicker [16] respectively. Harmonies were added in an attempt to improve the musical satisfaction of the sound. A major 7th harmony was chosen such that the main motor order of the BMW i3 forms the 7th in the harmony. Reducing the level of the main motor order, in combination with the added harmonic orders, it is perceived as an overtone rather than the fundamental tone. The Major 7th harmony (Sound F) was added in order to increase pleasantness in the reference sound [62]. The high frequency content of the electric motor sound was reduced by a complete pitch modification of the measured stimulus (Sound G). Side bands (Sound H) were added to mimic effects of amplitude modulation and thereby induce roughness and rumbling sensations into the reference sound. These sensations have been linked with enhancing the sportiness and strength of the sound [4]. Reverberation (Sound I) was added in order to provide a fuller sound character and counteract the dullness [50] of EV sound. The reference sound was altered using Au-

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Table 5.2: Evaluation 1 modified sound stimuli.

Label	ID	Description
Sound A	Reference Sound (RS)	BMW i3 motorbay WOT measured sound
Sound B	RS-High-Freq-FX	High frequency band diminished
Sound C	RS-Mid-Freq-FX	Mid frequency band amplified
Sound D	RS-Low-Freq-FX	Low frequency band amplified
Sound E	RS-Low Orders	Low orders added
Sound F	RS-HarmEm7	E major 7th harmony added
Sound G	RS-Pitch-FX	Entire pitch transposed down
Sound H	RS-Side-Bands	Side bands added
Sound I	RS-Reverb	Reverberation added

dacity software in collaboration with Garage Band recording software produced by Apple. The addition of orders and side band effects were created using MATLAB R2011b. Lastly, linear amplitude envelopes were applied to the enhanced and computer generated sound signatures, in order to ensure linearity of sound stimuli [4]. A linear sound envelope allows the stimuli to have a rate of increase in magnitude that is proportional to the vehicle speed.

Stimuli for Bipolar Semantic Evaluation

Enhanced sound signature concepts were generated by combining some of the most promising sound modifiers from Evaluation 1 to alter the standard production EV sound. These enhanced sound signatures were evaluated against standard production EV sound signatures to determine their semantic attributes and relative juror satisfaction. Harmony, order and side band addition was selected as well as, frequency filtering, reverberation and descending pitch transposition to attempt to improve juror satisfaction with the generated concept sounds. The detailed composition of the concept sounds are shown in Table 5.3. The final concept sounds were also filtered with respect to amplitude as to improve the linearity of electric vehicle signature sound. Linearity of the sound envelope ensures a linear amplification of the sound with respect to the motor run up. The computerised alternative sound was created in MATLAB, by building up the prominent motor orders and adding some reverberation effects and frequency filtering, thus eliminating measured broadband noise such as wind and tyre noise.

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Table 5.3: Evaluation 2 enhanced sound signatures.

Label	ID	Description
Sound AA	BMWi3	Motorbay WOT measured sound
Sound BB	Concept 1	Pitch transposition with G major harmony added
Sound CC	Renault ZOE	Motorbay WOT measured sound
Sound DD	Concept 2	Low order, side band and E major 7th harmony addition
Sound EE	Computer	Computer generated sound using MATLAB

The remaining sounds AA and CC were measured from standard production electric vehicles, the BMW i3 and Renault ZOE respectively.

5.2.3 Test Setup

The jury tests were conducted in a half anechoic chamber with a ball speaker as evaluation medium. The speaker allows for multiple juror evaluations within a short time frame. Members of the jury were positioned in a circle around the speaker as shown in Figure 5.1. The jury was positioned around the speaker such that the same radial distance from the speaker was maintained. A Macbook Pro was used to generate the stimuli signals for playback. The laptop was connected to an amplifier to ensure an adequate Sound Pressure Level (SPL) without inducing clipping. The Sound Level Meter (SLM) was used to measure the playback level of all sounds and thus ensure that an equal SPL level was achieved. The SPL was verified throughout both evaluations to confirm that this level was maintained.

5.2.4 Test Protocol

A repeatable test protocol was developed to ensure a consistent experience for jury groups A and B. A detailed outline of this procedure is provided below:

Step 1: Test Briefing - A printed evaluation form was handed out to each member of the jury. Filling instructions were provided along with an explanation

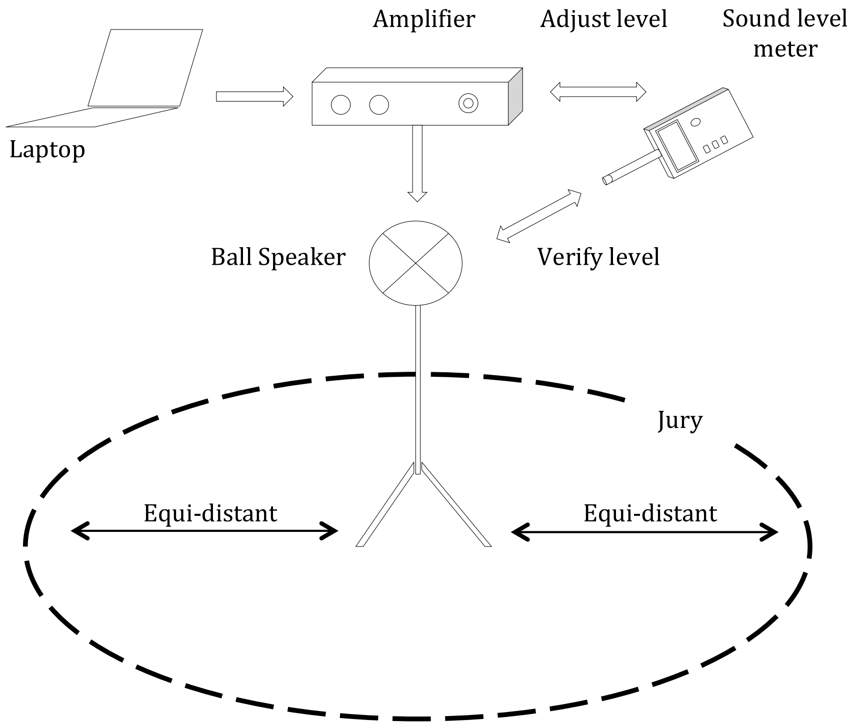

Figure 5.1: Test setup for subjective evaluation of electric vehicle sounds.

of the test protocol. Uncertainties were clarified in order to minimize the need for any explanations inside the anechoic chamber.

Step 2: Positioning - The jurors were entered the anechoic chamber and were seated equidistant from the ball speaker. The doors were sealed thereby indicating the start of the test.

Step 3: Evaluation 1 Part 1: Playback, Meditation and Feedback - Each sound stimulus was played to the jury. A meditation time of 10 seconds was allowed before the sound was repeated for a second time. Reflection and feedback time of 30 seconds was provided to complete the given subjective evaluation task. Completion of each question was checked after the specified time by an indication of raised hands. Additional time was provided as necessary. This process was repeated for each sound comparison.

Evaluation 1 Part 2: Playback, Meditation and Feedback - The modified sound stimuli Sound B to Sound I (see Table 5.2) were considered for the

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this part of the evaluation. Each modified sound was played to the jurors several times. The jury was required to rank the modified sound according to preference. The eight modified sounds were repeated for five cycles with five seconds resting time between each cycle. The resting time between individual sound tracks was kept to a minimum in order to reduce the length of a test cycle. One minute of additional reflection and feedback was provided at the end to complete the required ranking, which was sufficient since most jurors completed the ranking before the end of the last cycle.

Relaxation and Recovery - Members of the jury were escorted out of the anechoic chamber and out of the testing facility to a quiet area, upon completion of Evaluation 1. A recovery period of 15 minutes was provided as to allow the jury to relax. Water was provided to jury members during this period for rehydration. The jury returned to the anechoic chamber and Steps 1 and 2 were repeated before the commencement of Evaluation 2.

Evaluation 2: Playback, Meditation and Feedback - The sound stimuli listed in Table 5.3 were played to the jurors. Each sound was repeated up to 12 times to allow the jury sufficient time to mark each bipolar semantic pair. The test sound was repeated once more on completion of each bipolar semantic evaluation, as to allow jurors to provide a satisfaction rating for the sound. A meditation period of 30 seconds was provided in order to complete the satisfaction rating. This process was repeated for each bipolar semantic evaluation with a rest period of 30 seconds between evaluations.

Step 4: Collection - The completed subjective evaluation forms were collected after conclusion of the jury testing. The completed forms were then electronically captured to a computer. The extracted data was exported into Excel spreadsheets for further analysis.

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5.2.5 Subjective Evaluation

The first evaluation was designed to establish likes and dislikes of various sound manipulation techniques with regard to EV sound. Sound modifiers obtained from the first evaluation were used in order to create improved stimuli for the second evaluation.

Evaluation 1 Part 1: Forced Choice Comparison

The first evaluation comprised of two distinct parts: The first part required the jury to participate in a forced choice comparison between the original stimulus and potential sound enhancers whereas the second part involved the ranking of these enhancer stimuli. Forced choice comparison provides a clear winner, however no knowledge of the winning margin is provided e.g. Is Sound A preferred slightly to Sound B, or with a larger margin? A winning margin field was added in the evaluation, as suggested by Otto *et al.* [19], in order to gather information regarding the preference scale as portrayed in Figure 5.2. Additionally a 'reason' field was added to establish the rationale behind the like or dislike of the modified sound. The forced pair comparison was repeated eight times. The BMW i3 reference sound was compared to a different modified sound for each of the eight cases. The specific modified sound for each case is listed in Table 5.2, where Sound A denotes the reference sound.

Evaluation 1 Part 2: Sound Ranking

A basic sound ranking was performed on the modified sound stimuli, Sound B to Sound I, as listed in Table 5.2. The sound ranking was performed to identify the most preferred sound modifier. The sound ranking also provides an indication of the least preferred modifiers, which can then be used in order to produce variation in the stimulus pool.

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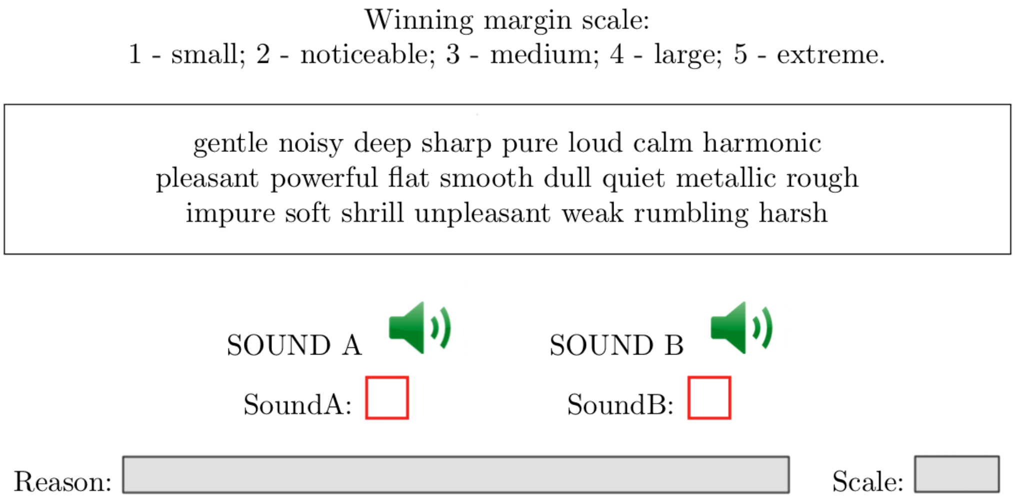

Figure 5.2: Subjective evaluation 1.

Evaluation 2: Bipolar Semantic Evaluation

The second evaluation was designed using 12 bi-polar semantic differential pairs as detailed by Swart & Bekker [11]. The study selected several semantics from similar sound sources, such as washing machines, trains and aircrafts. Suitable semantics for electric vehicles were chosen based on the results from this study. The five sound stimuli described in Table 5.3 were evaluated using the bi-polar semantics pairs in Figure 5.3. The bipolar semantics are separated by a seven point scale as proposed by Lennström *et al.* [6]. The bipolar semantic evaluation provides information regarding the subjective sound character of each sound as perceived by the jury. A satisfaction rating from 0 to 10 was also added in order to determine the correlation between the semantics and overall juror sound satisfaction.

5.3 Results

The exported results were analysed through various statistical methods in Excel and Statistica 12. The specific methods and results for each evaluation is documented below. The results were averaged across the different participation groups as well as the entire jury pool.

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SOUND AA

	-3	-2	-1	0	1	2	3	
Quiet	○	○	○	○	○	○	○	Loud
Calm	○	○	○	○	○	○	○	Shrill
Pleasant	○	○	○	○	○	○	○	Annoying
Deep	○	○	○	○	○	○	○	Metallic
Comfortable	○	○	○	○	○	○	○	Uncomfortable
Powerful	○	○	○	○	○	○	○	Weak
Sporty	○	○	○	○	○	○	○	Conservative
Rumbling	○	○	○	○	○	○	○	Flat
Exciting	○	○	○	○	○	○	○	Boring
Spirited	○	○	○	○	○	○	○	Dull
Effortless	○	○	○	○	○	○	○	Strained
Refined	○	○	○	○	○	○	○	Harsh

Please rate your satisfaction of the sound.

Satisfaction:

Figure 5.3: Subjective evaluation 2.

5.3.1 Subjective Evaluation 1

The results from the forced choice comparison test conducted in Evaluation 1 is depicted in Figure 5.4. The individual comparison results for the different evaluation groups (Figure 5.4a and 5.4b), as well as the combined results (Figure 5.4c) are illustrated. The preference boundary provides an indication to whether the standard or modified sound is preferred.

Results from Group A indicate that only sounds E and I were preferred above the standard production sound. Sound E and I represent the addition of low orders and reverberation respectively as indicated in Table 5.2. Sounds D and F resulted in a neutral decision and thus no clear preference was found. The juror preference for all remaining modified sounds were in favour of the standard production vehicle sound signature of the BMW i3.

The results from Group B differed from Group A in the sense that sound B, E and G were preferred above the standard sound, however sound I was not. The preferred sounds represented high frequency filtering, low order addition and pitch transposition respectively. Additionally it is showed that low frequency amplification produces a neutral preference yet again, and harmony addition revealed

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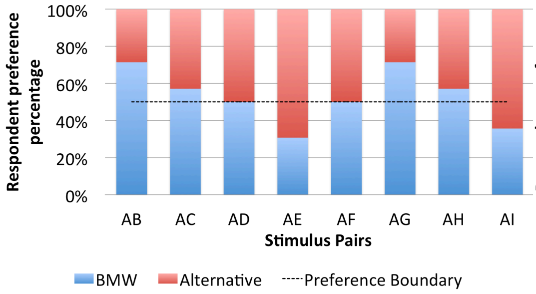
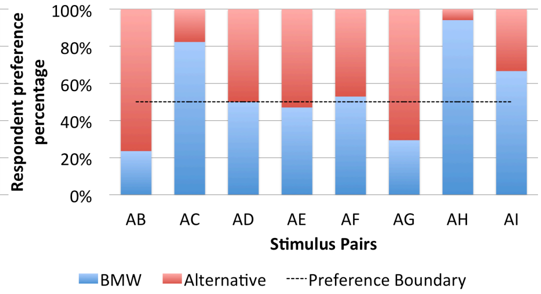
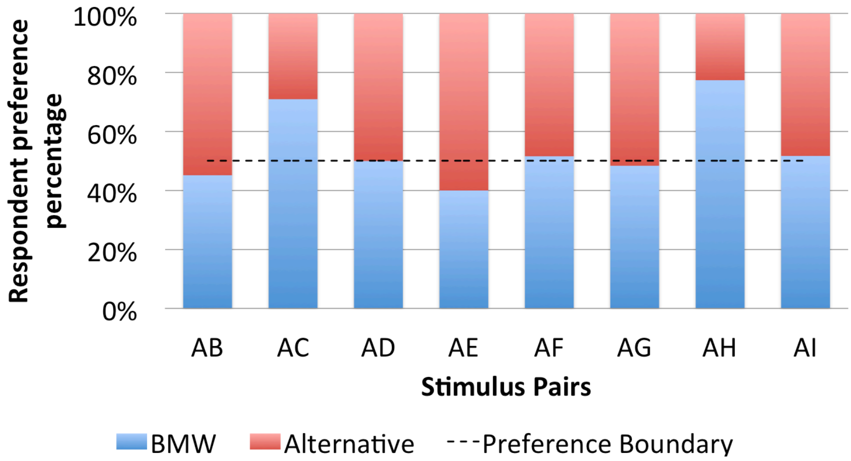


(a) Group A



(b) Group B



(c) Combined Results.

Figure 5.4: Standard and modified electric vehicle motorbay noise preference comparison.

similar results as with Group A. It should be noted that Group B was exposed to electric vehicle pass-by tests as mentioned in Section 5.2.1. This could provide a possible explanation for the difference in preferences, however additional comparison between the groups are needed.

The combined results showed sounds C and H to be disliked in comparison to the standard production EV sound signature. This result showed that mid frequency amplification and the addition of side bands decreases the sound preference for modified EV sounds. The combined results revealed that high frequency filtering and low order addition were preferred by the jury and could indicate a means as to improve sound satisfaction. Low frequency amplification, harmony addition, pitch transposition and reverberation showed fairly neutral results with respect to preference.

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Table 5.4: Modified sound stimuli rankings.

	Mean	Median	First Places
First	Sound B	Sound B	Sound G
Second	Sound G	Sound G & D	Sound B
Third	Sound D	Sound E	Sound D & E

The second part of Evaluation 1 required jurors to rank the modified sound signatures. Table 5.4 shows the mean, median and first places results for the ranking of modified sounds. The first places column indicates the sounds that were selected most frequently as the number 1 ranked modified sound. The overall mean and median for the rankings were also calculated and the top three sounds in each category is shown. The results revealed that Sounds B, D, E & G were most preferred as modified sounds. The results from the sound ranking thus coincides with the combined results for the forced choice comparison test. Thus indicating that high frequency filtering, low frequency amplification, low order addition and pitch transposition should be considered as potential focus areas for generating electric vehicle concept sound signatures. The results from Evaluation 1 shows that the preselected modifiers were among the top ranked modifiers, thus justifying their selection for further evaluation. Reverberation and harmonisation of the sound showed neutral results.

5.3.2 Subjective Evaluation 2

The jury satisfaction ratings for the different sound signatures in Evaluation 2 is tabulated in Table 5.5. Group A indicated that they were most satisfied with the sound signatures from the Renault ZOE and Concept 2 stimuli. This is true for both the median and mean satisfaction of the group jury pool. Group B differs in opinion from Group A and suggests that all enhanced EV sound stimuli is preferred above the standard production vehicle sound. The difference in opinion could be accounted for by the exposure to EVs that Group B experienced before the evaluation. An ANOVA and Mann-Whitney test was conducted to investigate if there is a significant difference between the groups. The results showed no significant difference between the 12 semantic pairs. However the juror satisfaction ratings showed a significant difference ($p > 0.05$) of 8.5% between the mean val-

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ues of the groups. The pre-test exposure to an EV pass-by thus promotes a higher mean satisfaction rating but does not influence the evaluation of the sound character. The most preferred sound for Group B, was that of the Concept 1 stimulus. The combined results show that the enhanced EV sounds are preferred above the standard production vehicle sounds with respect to the mean satisfaction. The combined median satisfaction of the jury indicates the same satisfaction rating for all vehicles, except the Renault. The median satisfaction provides no inter-vehicle variance with respect to the remainder of the vehicles, and therefore the mean satisfaction was chosen as the preferred analysis. Any future reference to satisfaction rating or juror satisfaction will be based on the mean satisfaction rating. The Concept 2 stimulus provided the highest juror satisfaction rating, with 60%, as perceived by the jury. The BMW has the most satisfactory sound for the standard EVs with a combined rating of 53%. The winning margin for the best enhanced sound over the standard EV sound is thus 7%. It should also be noted that the highest juror satisfaction rating is 60%, which in broader terms still signifies a relatively unsatisfactory sound.

The averaged subjective responses of the entire jury pool, the combined response of Group A and B, for Evaluation 2 are presented in Figure 5.5. Figure 5.5 displays three different polar plots. Polar plots are useful as they map out the sound character of each sound according to the semantic differential pairs. The outer ring displays the positive subjective semantic for the 12 pairs, and the center represents the corresponding opposite semantic pair [4]. The semantics on the outer ring are associated with positive connotations, whereas the paired counterparts are more negatively associated. Thus in theory, this should suggest that a sound character migration from the center towards the outskirts of the polar plot should improve satisfaction. However sound quality is a complex phenomenon and the validity of this statement will need to be tested. The polar plots were divided into three categories namely, Pure Electric, Enhanced Electric and All Sounds.

The Pure Electric category compares the sound character of the BMW i3 and Renault ZOE. The results show that the BMW is perceived to be more powerful and sporty than the Renault, and the BMW sound signature has a greater inherent rumbling character. The Renault on the other hand is perceived to be more effortless, comfortable, calm and quiet than the BMW i3.

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Table 5.5: Sound satisfaction for all vehicles.

	BMW i3	Concept 1	Renault ZOE	Concept 2	Computer
Group A					
Median	50.0%	40.0%	60.0%	60.0%	50.0%
Mean	48.5%	46.2%	56.2%	55.4%	47.7%
Group B					
Median	60.0%	70.0%	50.0%	65.0%	70.0%
Mean	56.5%	64.1%	49.4%	63.8%	63.1%
Total					
Median	60.0%	60.0%	50.0%	60.0%	60.0%
Mean	53.0%	56.3%	52.3%	60.0%	56.2%

The enhanced EV polar plot compares the two enhanced vehicle sounds (Concept 1 and 2) and one computer generated sound. The computer generated sound can be seen to have the highest ratings for semantics with positive connotations, except for the 'sporty' and 'powerful' semantics. The second concept sound was perceived to be the most sporty and powerful. Whereas Concept 1 appears to be the least exciting and spirited enhanced EV sound.

When all the stimuli are considered it can be seen that there is a significant difference in the sound character of the various sounds. The enhanced EV sounds can be observed to have a greater deepness in the sound character when compared to the standard production sound. The variation in the perceived deepness is also the greatest of all evaluated semantics. This can be attributed to the selection of pitch transposition and the addition of lower orders as sound modifier concepts. The BMW and the Concept 2 sound stimulus have the most sporty and powerful sounding signatures, whereas the computer generated sound has the least sporty sound. The Renault reveals the lowest perceived rumbling levels. The Concept 1 stimulus has the least exciting and spirited sound of all the evaluated stimuli.

5.3.3 Statistics

The extracted jury data was further analysed using various statistical methods, such as factor analysis, principal component analysis and cluster analysis. These methods were used in order to determine the semantics that provide the most

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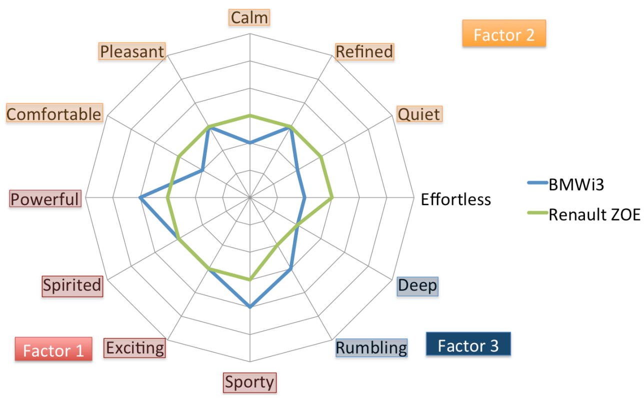
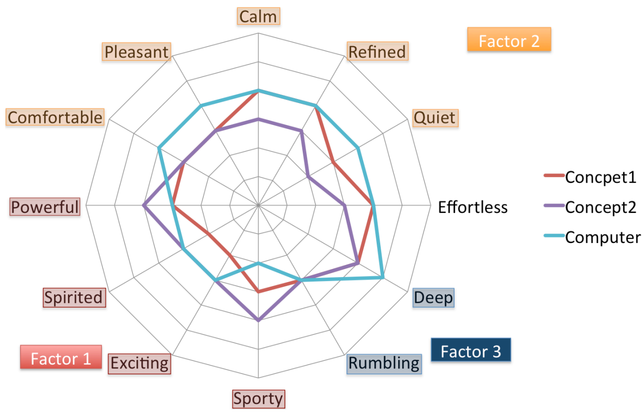
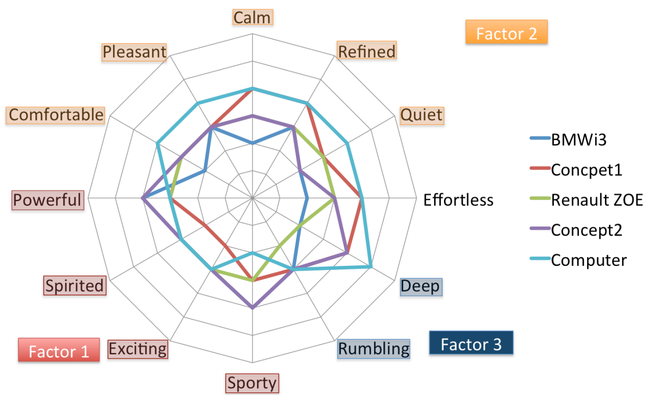


(a) Pure Electric



(b) Enhanced Electric



(c) All Sounds

Figure 5.5: Subjective semantic sound characteristics of electric vehicles.

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variance as well as establish a correlation between the subjective semantics and the juror satisfaction ratings.

Principal component analysis is used to determine the underlying dimensions in a set of data, such as determining the principal dimensions in vehicle sound quality [4]. The specific dimensions, or principal components, can be seen as a grouping variable for different semantics that possess similar qualities or character. The scree plot in Figure 5.6 illustrates the percentage variance in the data according to the number of principal components. The scree plot identifies three principal components that cause the largest variance in the data, as seen by the 'knee' in the plot. Furthermore, the factors were calculated in order to identify the components that cause the greatest variance based on a factor loading score of 0.55. The factor loadings in Figure 5.6 suggest the first component to be associated with the 'powerful', 'sporty', 'spirited' and 'exciting' semantics. The second component is highly correlated with the 'comfortable' and 'pleasant' semantics. The last component shows to correlated with the 'deep' and 'rumbling' semantic. It is of interest to note that components 1 and 2 have multiple correlation whereas component 3 is only correlated to two semantic. It can be seen that the 'effortless' semantic does not load with any of the principal components. The reason is that the 'effortless' semantic correlated with multiple factors, which resulted in a factor loading that was not significant (<0.55). The semantics with the highest loading for each factor is thus found to be 'sporty', 'comfortable' and 'rumbling'.

A second statistical analysis, namely Cluster analysis [63], was done in order to establish the grouping of the 12 semantics. Cluster analysis is a method that groups variables based on similarities or dissimilarities, and thus attempts to establish a natural order or structure within the variables [63]. A tree diagram of the resulting semantic cluster is displayed in Figure 5.7. The linkage distance resembles a measurement of similarity, thus the greater the linkage distance, the smaller the similarity between the semantics [63]. The diagram shows three distinct groupings. The first cluster indicates that the 'refined', 'effortless', 'quiet', 'calm', 'pleasant' and 'comfortable' semantics are associated. The cluster analysis considers the 'spirited', 'sport', 'powerful' and 'exciting' semantics to be linked. Lastly the 'deep' and 'rumble' semantics are shown to be coupled. The cluster

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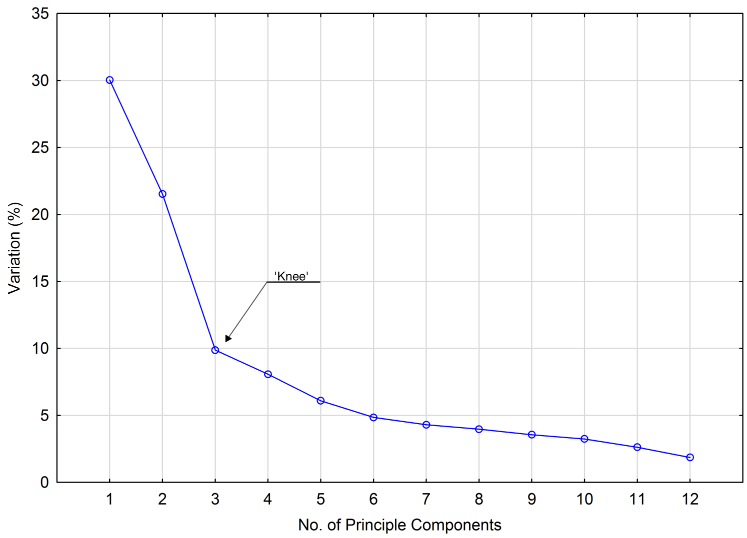

Semantics	Loading
Factor 1	
Sporty	0.81
Exciting	0.80
Spirited	0.78
Powerful	0.71
Factor 2	
Comfortable	0.83
Pleasant	0.80
Calm	0.70
Refined	0.60
Quiet	0.56
Factor 3	
Rumbling	0.74
Deep	0.71

Figure 5.6: Scree plot and factor loadings.

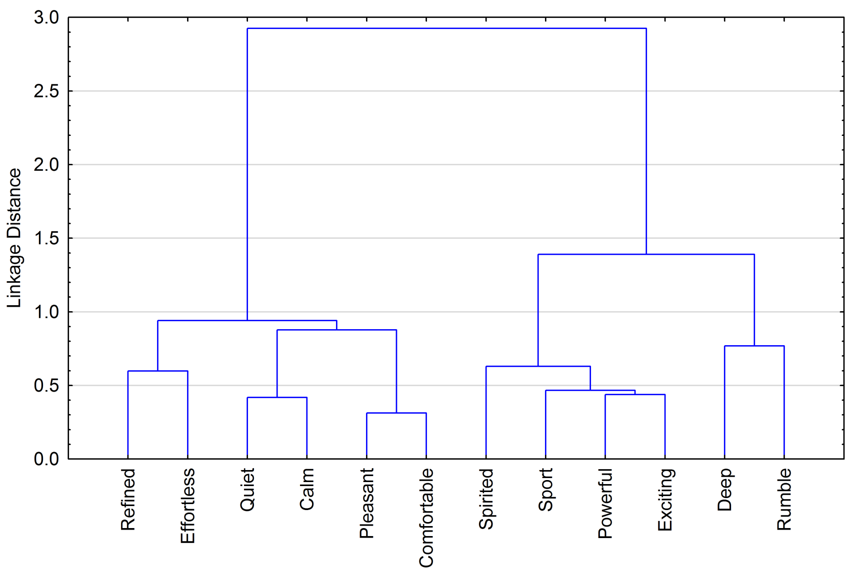

Figure 5.7: Tree diagram representation of the cluster analysis. (12 Variables, Ward's method, 1-Pearson r)

analysis agrees with the results from the factor loadings. Each cluster can be seen to be grouped around the three main factors namely, Powerful, Comfortable and Deep. Therefore, confirming the principal components to be a 'Power/Sporty Factor', a 'Comfort Factor' and a 'Deepness Factor' . A study by Giudice *et al.* [7] on EV interior sound quality found three similar factors, namely a Powerful factor, a Calm/Refined factor and a Futuristic Factor.

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A biplot [64] was generated for the different test sounds and the manner in which they group according to the first two principal components are displayed. Biplots are used to visually display the relationship between the semantics (variables) and the subjective responses (samples) according to specific dimensions (axes) such as the principle components [64]. The first two principal components were selected as the they provided most of the variance. The biplot was generated using ellipses and a scaling parameter (α) of 0.5 [65] as shown in Figure 5.8. The Figure indicates that the different vehicles are not distinctly grouped, but rather clustered around the origin. The data can be seen to be significantly scattered rather than contained by the ellipses, indicating a large variation in the subjective responses. The biplot reveals that the standard EV sound is less comfortable and pleasant than the enhanced sounds. It can also be seen that the BMW and Concept 2 sounds are more sporty and powerful than the remainder of the vehicles, as was found in Figure 5.5. The ellipses from the enhanced sounds are located lower with respect to the ordinate. The satisfaction ratings in Table 5.5 indicated that the enhanced sounds are most preferred, thus suggesting that sound quality migration, with respect to the ordinate, influences satisfaction. An ordinate descent will also provoke a significant increase in the ‘sporty’, ‘powerful’, ‘exciting’, ‘spirited’, ‘pleasant’ and ‘comfortable’ semantics, which resembles Factor 1 and 2 found through factor analysis.

A Spearman correlation test was computed on the different semantics with respect to juror satisfaction. Spearman correlation test provides a method to establish the strength of the relationship between variables, i.e. the correlation [66]. The Spearman correlation test was chosen, as the variable scales differ between the semantics (ordinal scale) and satisfaction rating (interval scale) [66]. Figure 5.9 shows the correlation for the different semantics. The ‘quiet’ and ‘rumble’ semantics were excluded as they produced insignificant correlations pertaining to satisfaction (i.e $p > 0.05$). The ‘pleasant’, ‘exciting’ and ‘comfortable’ semantics are shown to have the highest correlation with satisfaction, indicating that high ratings in these semantics should reflect high ratings in satisfaction. The lowest correlated semantics were found to be ‘sporty’ and ‘deep’. This indicates that large changes in sportiness and deepness in EVs will reflect small changes in satisfaction. It is of interest to note that all these semantics have positive correlations with satisfaction, and thus the increase in sound quality with respect to

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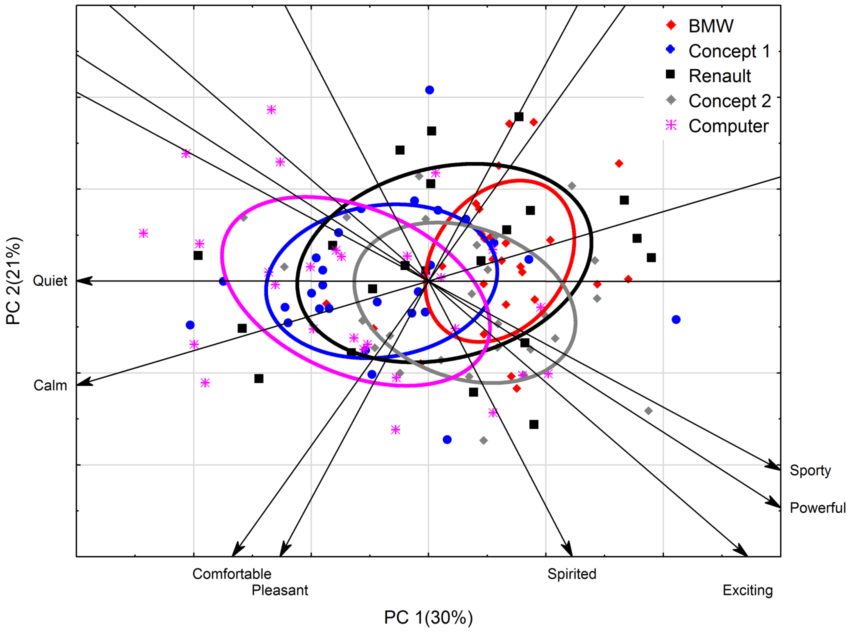

Figure 5.8: Power factor vs comfort factor for different sound signatures.

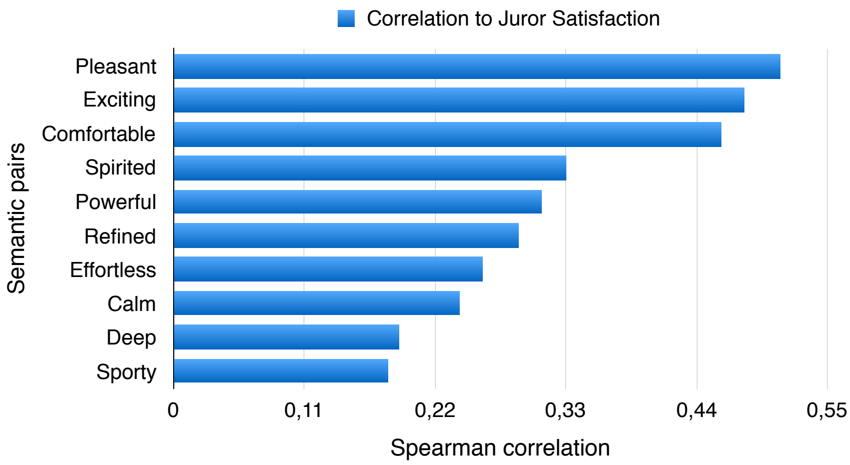

Figure 5.9: Spearman correlation of semantics with respect to juror satisfaction.

these different semantics should increase satisfaction.

Lastly, a conclusion can be drawn between the results from the bi-plot and juror satisfaction. The five semantics with the highest correlation with satisfaction is also located nearest to the ordinate of the bi-plot. The positive satisfaction correlation of these semantics shows that a decrease in the ordinate value of the bi-plot will indeed increase the perceived satisfaction.

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5.4 Discussion

An article by Jennings *et al.* [4] that investigated the sound quality of 72 luxury internal combustion engine (ICE) vehicles found two underlying principal components. A power factor and a refined factor provided 89% of the variance. This study on the electric and enhanced electric vehicle sound found three principal components that provided only about 60% of the variance, which is considerably lower than for the ICE vehicle counterparts. This could be due to the neutral sound character of EVs [6], which does not cause substantial variance in the sound character. In addition, only five stimuli was evaluated compared to the 72 of Jennings *et al.* [4], which could also contribute to the low variance.

The power and comfort factors found for EV sound corresponds to the ICE counterparts, however the third factor, Deepness, is a new dimension, and could be accounted for by the audible wind and tyre noise, due to the lack of engine noise masking found in EV. Jennings *et al.* [4] reported that several studies found a third factor, described as metallic/booming, which demonstrates similarities between the third factors for EV and ICE vehicles. The first two principal components showed to have good correlation with satisfaction. The Power factor revealed strong correlation through the 'exciting', 'spirited' and 'powerful' semantics. The second principal component associated with pleasantness and comfortableness, indicates a strong positive correlation with regard to satisfaction. The third principe component indicated a weaker positive correlation with satisfaction. An article by Lennström *et al.* [6] found high satisfaction correlations for EVs with the 'quiet' and 'pleasant' semantics, and similar correlation magnitude for the 'powerful' semantic. The pleasant and powerful correlations from this study agrees with the results from Lennström *et al.* [6], however contradicting to it, this study found low correlation for the 'quiet' semantic. The low correlation for the 'quiet' semantic with regard to satisfaction in this study, as compared to the study by Lennström *et al.* [6], could be due to the motorbay sound that was used in this study rather than the interior sound used by Lennström's study. The motorbay sound was used in order to capture EV drive-train sound character at the source, without damping or filtering from the transfer path towards the interior.

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All semantics showed to have positive correlations with respect to satisfaction but with varying degrees of magnitude. The results from the Spearman correlation test shows that semantics with positive connotations are linked to a positive change in satisfaction. Thus indicating, as previously mentioned in Section 5.3.2, that striving towards the outer ring of a sound characteristic polar plot should increase satisfaction. However this statement appears to be flawed when comparing the Spearman test with the polar plots. The highest correlated semantics, 'pleasant', 'exciting' and 'comfortable', indicate that the Computer generated sound in Figure 5.5c should represent the most satisfactory sound, but the results from the subjective evaluation indicates rather that Concept 2 is most preferred. This contradiction statement initiated a more in depth comparison and analysis.

The results from the Spearman correlation test were used to generate a new satisfaction weighted polar plot. The individual semantics were weighted according to the Spearman correlation with regard to satisfaction, and a new polar plot was generated and is shown in Figure 5.10. The BMW i3 sound and the Concept 2 sound is plotted against the computer generated sound. The radial axis represents the satisfaction and was limited to a maximum value of 70% as none of the vehicles had an overall satisfaction greater than 60%.The weighted plot illustrates the predicted satisfaction for the three vehicles, and thus the vehicle that represents the greatest surface area on the polar plot should also embody the highest satisfaction rating, which in this case is the computer generated sound. However, this is again in contradiction to the jury, who preferred the Concept 2 sound. The question arises as to why the highest predicted satisfactory sound does not coincide with the measured response. Factors such as a young, inexperienced jury could provide a possible explanation for this conflict. It could however also be argued that EVs have a neutral and bland sound character and minor variance exists between the sound signatures of the different vehicles, thus only some of the semantics are truly activated. The only significant winning margin for the Concept 2 sound is found through the 'powerful' and 'sporty' semantics, and could explain the increased satisfaction.

As mentioned previously, Jennings *et al.* [4] found that Powerful and Comfortable are the two principal components of ICE vehicles sound. An article by the BMW Group [67] suggests however that motor vehicle sound can be categorised

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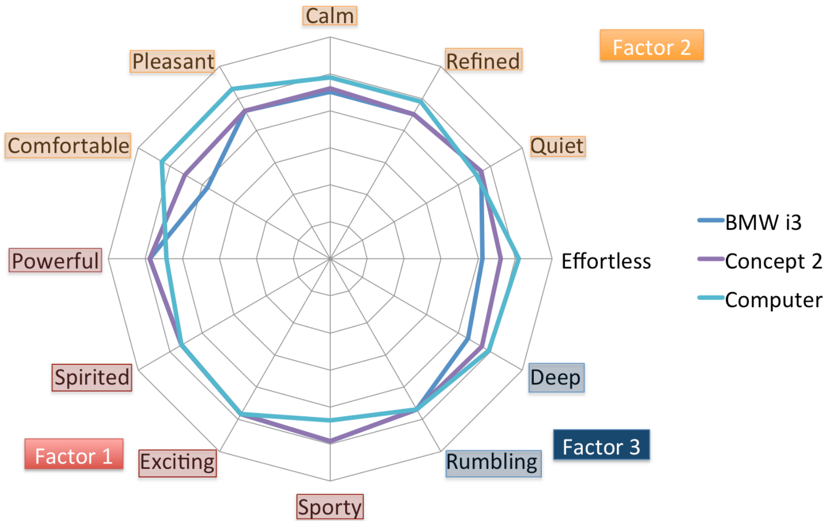

Figure 5.10: Satisfaction weighted polar plot.

by a Sporty and Comfortable factor. This leads to question of how well sportiness is represented in EV sound? The results from the polar plot indicate that the Concept 2 sound has the highest Sporty rating which could explain the jury preference. However on closer inspection one can see that the BWM has the same sporty rating, which contradicts this statement. In combination to this, it is observed that motorbay EV sound show an overall low correlation (≤ 60%) for all vehicles with regard to satisfaction. This suggest that EV sound does not have suitable or sufficient Sporty and Powerful sound character as stated by [11], and that the current production EVs do not provide enough variance within these semantic spaces. The small variance in sound character can be seen in Figure 5.5, where the 'sporty' semantic is observed to provide a larger variation within the different EV sounds than the Powerful semantic. It is also of interest to note that the largest variation within the semantic space is found for the 'deep' semantic. Sound quality is thus a complex concept and satisfaction cannot only be linked to specific semantics but rather the combination of them all.

The overall low satisfaction rating and low factor variation, in combination with the neutral sound character of EVs illustrates the need for sound modifications. These factors also potentially reveal that the correct semantic set to describe EV sound in full is still to be determined and could explain the weak principal components.

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5.5 Conclusion

The Drive-train noise from two different standard production EVs were evaluated subjectively and compared to three enhanced EV sound signatures. The motorbay signatures of the enhanced and original vehicle sounds were evaluated through jury testing. Forced choice comparison and bi-polar semantic differential evaluation techniques were used to measure the response of the jury. High frequency filtering, low frequency amplification, low order addition and pitch transposition was found to be preferred sound modifiers for generating EV concept sound signatures. The results indicated that the enhanced EV sounds were preferred above the standard production EV sounds with regard to perceived juror satisfaction. Various statistical analyses were conducted on the subjective evaluation results, such as factor analysis, principal component analysis and cluster analysis. The three main factors were found to be a Power factor, a Comfort factor and a Deepness factor. A Pearson correlation test revealed 'pleasant', 'exciting' and 'comfortable' to be the highest correlated semantics with respect to satisfaction. The first two principal components correlated well with satisfaction and agreed with literature. An additional analysis was performed where the semantic scores were weighted with the corresponding Pearson satisfaction correlation scores. The result indicated a discrepancy between the predicted satisfaction and the true measured satisfaction scores. The source of the conflict was argued to originate from the lack of variance within different standard production EV sound, as well as the bland and neutral sound character profile they possess. Lastly it was shown that the need for enhanced EV sound is supported by the low overall satisfaction ratings of the standard production vehicles. To conclude EV sound quality is a complex concept and cannot be based purely on the satisfaction scores of individual semantics but rather the complete sound space. It is recommended that additional sound concepts should be investigated that can provoke significant sound satisfaction improvements.

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5.6 Acknowledgements

I want to thank Prof D. Nel, a statistical consultant, at the University Stellenbosch for assisting me with the various statistical analyses required for this study. The support of the National Research Foundation under the Competitive Support for Unrated Researchers is gratefully acknowledged for project funding.

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Chapter 6

Interior and Motorbay Sound Quality Evaluation of Full Electric and Hybrid-Electric Vehicles Based on Psychoacoustics

The exposition presented in this chapter is a collaboration effort with Dr. Annie Bekker of the Department of Mechanical and Mechatronic Engineering at Stellenbosch University, Stellenbosch, South Africa. The work is presented as the final article that was submitted for the Internoise 2016 conference in Hamburg, Germany. Dr. Bekker is the co-author of this paper as the supervisor of the PhD candidate. A signed declaration to this effect is in the possession of both the candidate and supervisor. The paper investigates the psychoacoustic aspects of electric vehicles signature sound, for the interior and motorbay of the vehicle [14]. This paper contributes toward one of the main objectives of this dissertation by investigating several known psychoacoustic metrics and their ability to evaluate and distinguish between EV signature sounds. Furthermore, a contribution is made towards a framework that links the subjective semantics with known psychoacoustic metrics with respect to perceived consumer satisfaction.

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6.1 Introduction

In the automotive industry, sound sensations during wide-open-throttle (WOT) acceleration influence consumer impressions of vehicle character [6]. In this industry, the sound quality entails both the physical quality of a sound as well as the subjective attributes a person associates with that sound. Furthermore, it refers to the suitability of a sound for a specific product and the quality thereof, subconsciously conveyed to customers through the vehicle sound cues [5]. The study of internal combustion driven vehicles has shown that roughness or rumble, linearity, the dominance of the engine firing order, the sound pressure level of the low engine orders, the loudness level, the sharpness level, and the sound impulsiveness are the key acoustic features that influence customer perceptions. With alternative and electrically driven vehicles emerging on the market, the potential influences of electric drive-trains on the sound sensations of drivers and associated psychoacoustic metrics will become of greater interest to manufacturers. Jennings *et al.* [4] state that novel drive-trains for low-carbon vehicles introduce new sound quality drawbacks such as reduced masking from the absence of an internal combustion engine, and new sound sources, such as the motor and electronic switching devices. Information conveyed to the driver by these sound cues differs from that associated with a traditional automotive sound experience [6] and could therefore create new consumer impressions. Lennström *et al.* [6] found that the lower sound emissions from electric propulsion systems reduce the internal noise of electric vehicles and that some participants in consumer studies had labelled the sound experience as 'bland'. A study of consumer expectations [58] found that the owners of electric vehicles were viewed as people who “did not derive pleasure from driving" and were “lacking that sense of fun". In order to develop a pleasant, harmonious passenger cabin sound for electric vehicles, the relationship between subjective perception and psychoacoustic metrics needs to be understood.

Through the comprehensive study of 72 vehicles, Jennings *et al.* [4] proposed a framework for sound evaluation of internal combustion engine (ICE) vehicles. Von Gosler & Van Niekerk [5] evaluated the correlation between subjective responses and objective metrics for ICE vehicles. The combined framework of these studies entails the statistical correlation between objective metrics and

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subjective semantic differential tests to yield the subjective dimensions that govern consumer satisfaction in sound quality. It is the aim of the present work to contribute towards such a framework for electric vehicles.

6.2 Method

6.2.1 Test Vehicles

Five standard production electric vehicles were selected for testing along with one hybrid electric vehicle. The vehicles were tested in Germany in June and July in 2014 and were sourced from local vehicle showrooms. The test vehicles are listed in Table 6.1.

Table 6.1: Test vehicles used to evaluate the interior and motorbay sound quality.

Manufacturer	Model	Drive System
BMW	i3	Full Electric
Citroen	C-Zero	Full Electric
Porsche	Panamera	Hybrid Electric
Renault	ZOE	Full Electric
Smart	Electric	Full Electric
Volkswagen	e-Up!	Full Electric

The hybrid electric Porsche Panamera is equipped with an automatic multi-stage gearbox, compared to the direct drive system of all the other electric vehicles. The hybrid electric vehicle was selected as it has the ability to be driven in full electric mode and thus, considering the different gearbox, provides variability to the data. Unfortunately all vehicles could not be tested in the same location, due to availability limitations. However all vehicles were tested on secluded roads with similar road surfaces and gradients. All tests were conducted on dry road surfaces with negligible wind and temperature differences between test days.

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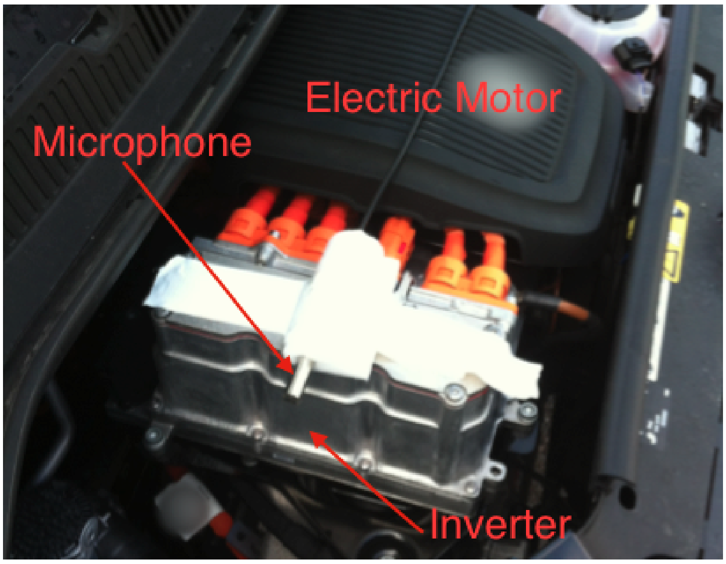

Figure 6.1: Motorbay microphone placement.

6.2.2 Test Setup

Motorbay[1] sound measurements were recorded with the use of a half-inch pre-polarized microphone. The microphone was secured underneath the hood of the vehicle and mounted in close proximity to the electric motor and inverter, as shown in Figure 6.1. Care was taken to position the microphone such that the exterior wind noise was minimized. Additionally, the motorbay microphone was wrapped in foam to isolate it from structure-borne vibration. The interior vehicle sound was measured using a binaural SQuadriga headset from Head Acoustics. The measurements were recorded on the SQuadriga portable data acquisition system.

Constant speed tests of 60 km/h and 80 km/h maintained for all vehicles. WOT drives were conducted on all full electric vehicles, therefore excluding the Hybrid Porsche Panamera, as the electric mode did not allow for the maximum acceleration of this vehicle.

[1]The Motorbay sound in this context refers to sound measured inside the motorbay compartment of the vehicle. The sound was measured in close proximity to the electric motor, either under the hood or towards the rear of the vehicle, depending on where the motor was positioned.

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6.2.3 Subjective Evaluation

A subjective evaluation was conducted by a jury of 31 members in a half anechoic chamber. The subjective responses of jury members were evaluated for two electric vehicle sound signatures (recorded in the motorbay) as well as three enhanced sound signatures. The study evaluated jury responses through twelve bi-polar semantic differential pairs as listed in Table 6.2. These bi-polar semantic pairs were subsequently correlated with the calculated objective metrics. The enhanced sound signatures were developed from the BMW motorbay sound stimulus by applying frequency filtering, order and harmony addition, and reverberation to the reference sound. The first concept sound, Concept 1, was altered with a downward pitch transposition and the addition of a G major harmony to the reference sound. An enhanced stimulus sound, Concept 2, was created by applying high frequency filtering and adding an E major 7th harmony, lower order and side band frequencies. The last concept sound enhancement, named the Computer stimulus, was constructed in Matlab using the main motor orders of the electric motor, and further enhanced with frequency and amplitude modulation. All the enhanced sounds were scaled in amplitude to match the same dB(A) level as that of the EV stimuli.

Table 6.2: Subjective semantic bi-polar pairs.

Quiet Loud	Calm Shrill	Pleasant Annoying	Deep Metallic	Comfortable Uncomfortable	Powerful Weak
Sporty Conservative	Rumbling Flat	Excited Boring	Spirited Dull	Effortless Strained	Refined Harsh

6.2.4 Objective Evaluation

Sound Pressure Level and Loudness analyses were performed on the measurements of the constant speed drives at 60 and 80 km/h. First, the SPL and Loudness were compared to establish if any changes or variation could be detected between the two methods. Additionally, the Specific Loudness was compared to third octave band analysis to determine if differences could be observed through

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the frequency spectra. Transient psychoacoustic metrics, such as Loudness, Sharpness and Roughness versus time, were calculated for the interior and motorbay sound signatures of the pure electric vehicles. The transient metrics of Fluctuation Strength and SIL were calculated in addition to the above mentioned metrics for the BMW and Renault motorbay sound signatures. Furthermore, three enhanced sound signatures were generated and subjected to the described analysis.

6.2.5 Correlation

The objective results from the BMW, Renault and the three enhanced sound signature concepts were used to determine a correlation between objective metric scores and subjective responses from the semantic bi-polar test. The Statistica 13 software package was used to perform a Spearman correlation test between the subjective and objective attributes of the stimuli. The subjective scores comprised averaged subjective semantic values, which were calculated for every semantic pair for the different stimuli. The averaged semantic values were correlated against several different single value methods that represented the transient objective metric results. These single values included the average, median, maximum, root mean square (RMS) and integration values.

6.3 Results

6.3.1 SPL vs Loudness

A comparison of the SPL and Loudness analyses is presented in Figure 6.2. It can be seen that the metrics concur as to the Loudness ranking of the electric vehicles, i.e. quiet to loud. At 60 km/h, the SPL metric predicts that the Porsche is less quiet than the BMW i3 whereas the Loudness metric results suggest the opposite. The motorbay SPL values for all vehicles vary between 85 and 100 dB(A), whereas the motorbay Loudness values vary between 60 and 140 Sone. The Loudness

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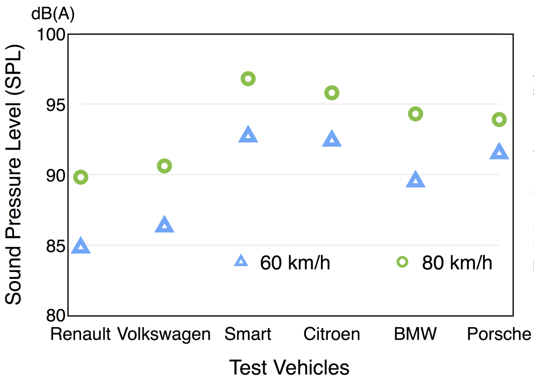
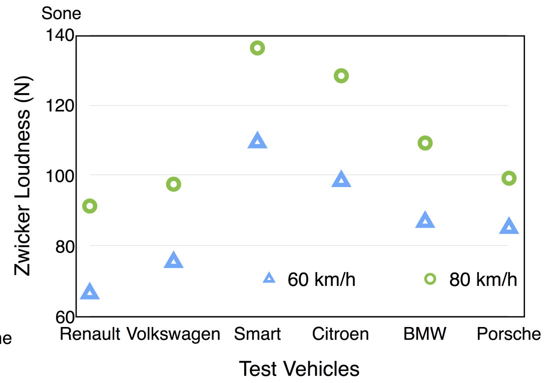
analysis allows the data to be spread over a wider range of values, thereby increasing the resolution through which differences in loudness can be detected.



(a) SPL



(b) Loudness

Figure 6.2: Motorbay SPL and Zwicker Loudness comparison at 60 km/h and 80 km/h.

The results in Table 6.3 confirm this, as the difference in magnitude can be observed more precisely. The table compares the interior cabin and motorbay values for the SPL and Loudness analyses for the 60 km/h constant speed drive test. The SPL analysis predicts that the best noise insulated vehicle is the Porsche which offers a 32.3 dB(A) reduction of sound between the vehicle cabin and the motorbay. However, the Zwicker Loudness analysis indicates that the insulation, from motorbay to interior, offered by the Smart (91.3 Sone), Citroën (81.4 Sone) and BMW (72.9 Sone) exceeds that of the Porsche (72.3 Sone). According to Fastl and Zwicker [16] a person is able to perceive a difference in SPL of 3 dB, thus any two sounds that do not vary by more than 3 dB appear to have the same "loudness" in terms of SPL. The question arises as to how this corresponds to subjective experiences of Loudness. When comparing the values from the Smart and Citroën vehicles, one can see that the SPL values are similar and fall within the 3 dB difference range for both interior and motorbay sounds, thus suggesting that there should be no perceivable level of difference between these vehicles. However, when the Loudness values are compared, a difference of 11 Sone is observed in the motorbay sound. Could this signify that a difference in loudness is still perceivable by automotive consumers?

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When comparing the BMW and Porsche, it can be seen that there is a difference of 2 dB(A) between the interior and motorbay SPL between these two vehicles. Based on the previous comparison, one would expect that the Loudness analysis would reveal a larger difference between the stimuli, but this is not the case. The difference in Loudness values of the BMW and Porsche is found to be less than 1 Sone for the interior and motorbay sound. As such, the SPL and Loudness analysis concur that the “loudness" of the BMW and Porsche would likely be perceived as similar. Results from the comparison suggest that the analytical psychoacoustic metrics Loudness and SPL do not concur on their predictions of the subjective experiences of the loudness. Care is advised in the selection of the correct objective metric that matches subjective perceptions, especially if these metrics are used in sound design to predict customer perceptions. Genuit [56] stated that the use of SPL is inadequate for identifying and evaluating sound sources with several noise components, such as the drive-train noise of a vehicle.

Table 6.3: Differences between vehicle Loudness and SPL at 60 km/h.

Manufacturer	Loudness [Sone]		SPL [dB(A)]	
	Interior	Motorbay	Interior	Motorbay
BMW	13.9	86.8	61.9	89.5
Citroen	17	98.4	63	92.4
Porsche	12.8	85.1	59.2	91.5
Renault	12.7	66.5	58.9	84.8
Smart	18.1	109.4	64	92.7
Volkswagen	16	75.4	62	86.3

6.3.2 Octave vs Specific Loudness

A third octave band analysis was conducted on constant speed drive tests at 80 km/h. A comparison of Specific Loudness and third octave band analyses is presented in Figure 6.3. Figure 6.3a presents the specific loudness levels on a Bark scale which is a psychoacoustic scale [68] where the perceptual doubling of frequency corresponds to a doubling in Bark units. A key difference between third octave band analysis and Specific Loudness is the cut-off frequency where the

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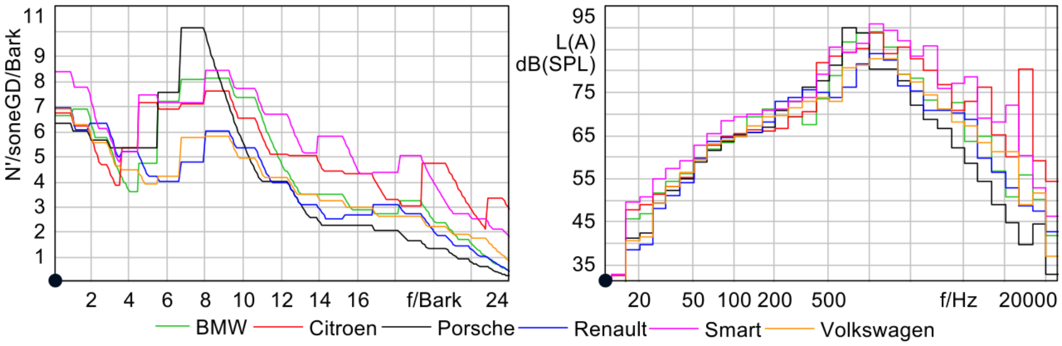
upper limit of 24 Bark is 15.5 kHz compared to 22.3 kHz for third octave band analysis.



(a) Specific Loudness (b) 3rd Octave

Figure 6.3: Comparison of motorbay Specific Loudness and third octave band analysis for test vehicles at 80km/h.

Electric vehicles produce tonal characteristics in the frequency range above 1 kHz, where human hearing is highly sensitive [8; 69]. Furthermore, the frequency range between 200 and 9000 Hz [6] has been shown to be influential in the perceived sound satisfaction of electric vehicles. The emphasis of Specific Loudness analysis on this frequency range enables a clearer differentiation between WOT acoustic stimuli. The Bark scale used for Specific Loudness provides a compressed frequency domain that highlights the areas that are of interest for perceived loudness. The sound energy difference in the extreme frequency range above 10 kHz (or 23 Bark) is accentuated in the third octave band analysis where human perception is not as sensitive.

6.3.3 Transient Loudness and Sharpness for WOT drives

The transient objective metrics of Loudness and Sharpness were calculated for all electric vehicles. The stimuli from motorbay and interior (driver side) WOT drives were used for the analyses, and performed with Artemis Suite from Head Acoustics. Figure 6.4 presents the transient Loudness analysis for the test vehicles for WOT acceleration tests. It was observed that the vehicles have similar

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WOT Loudness profiles, that increase with vehicle run-up time, in both the interior and motorbay. The difference in motorbay loudness is better differentiated between vehicles than that in the interior cabin. The Renault has the lowest Loudness trace, whereas the Smart, Citroën and Volkswagen tend towards higher Loudness values. The peaks in the Loudness curves represent intersections of the dominant motor orders and the switching harmonics [69] which negatively influence the linearity of the acceleration sound.

The interior and motorbay Sharpness values are shown in Figure 6.5, where several differences can be observed. The motorbay Sharpness increases with speed for the first four seconds of the vehicle acceleration, whereafter the Sharpness value fluctuates around a mean value. The Smart and Renault show large fluctuations in the Sharpness value, with the Smart exhibiting the maximum Sharpness of all the tested vehicles. The interior Sharpness analysis indicates a completely different envelope with respect to run-up time. The interior Sharpness increases as the vehicle starts accelerating, but subsequently decreases abruptly. This 'initial peak' can be accounted for by the audible prominent tonal character of the electric motor harmonics as the vehicle starts to accelerate. Electric vehicles are otherwise quiet at low speeds and thus the initial motor acceleration is audible, in the absence of idle noise and vibration. With a further increase in speed, the masking effects increase, causing the Sharpness value to decrease to a point where the tonal components dominate again. Thereafter the Sharpness value increases with speed. Again, the peaks in the interior Sharpness are likely attributed to the intersection of main motor orders with the switching harmonics, thus intensifying the Sharpness value at those instances.

6.3.4 Objective and Subjective Correlation

Acoustically speaking, very little variation was experienced when listening to the five electric vehicle WOT sound signatures in the vehicle interior. One of the potential concepts through which engineers plan to address the "bland" electric vehicle sound signature is through sound enhancement whereby acoustic cues are purposely played over the vehicles speaker system. In order to preserve the electric vehicle sound character, two motorbay sound signatures (BMW and Re-

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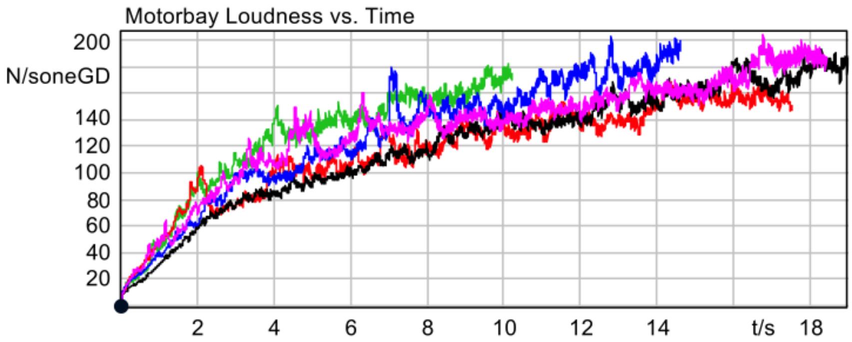
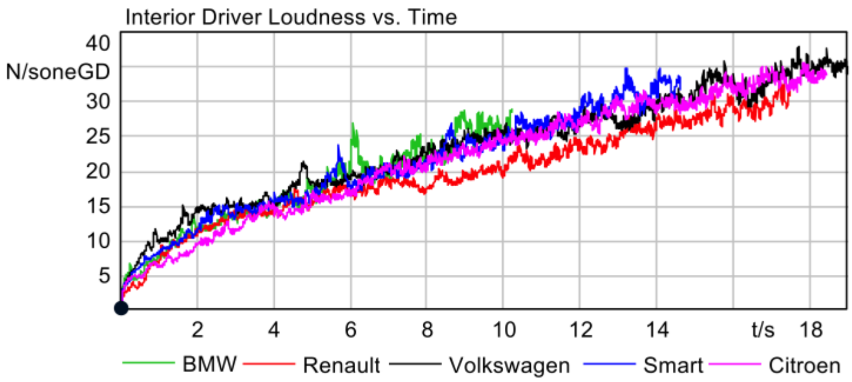


(a) Motorbay



(b) Interior (Driver side).

Figure 6.4: Motorbay and interior Loudness comparison of electric vehicles.

nault) were evaluated along with three enhanced sound signatures. The stimuli were evaluated objectively against the transient Loudness, Sharpness, Roughness, Fluctuation Strength, and Speech Intelligibility metrics.

Figure 6.6 illustrates a selection of the calculated objective metrics for the two electric vehicle recordings and concept sound stimuli. Despite the fact that the stimuli were normalized with respect to SPL, there is a difference in the Loudness value as shown in Figure 6.6a. Furthermore, the enhanced sounds are markedly less sharp and settle around 2 acum without much fluctuation in sharpness when compared to the original EV motorbay sounds, as seen in Figure 6.6b. The reduction in Sharpness is explained by the high frequency filters that were applied to the enhanced sounds. Figure 6.6c shows that Roughness was introduced to a varying extent in the initial portion of the enhanced signature sounds. The Computer generated stimulus is characterized by initial Roughness, attributed to the addition of frequency modulation. The Concept 2 stimulus is differentiated by

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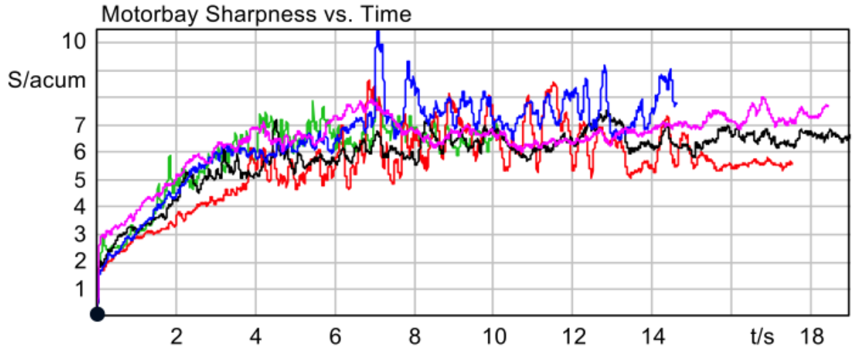
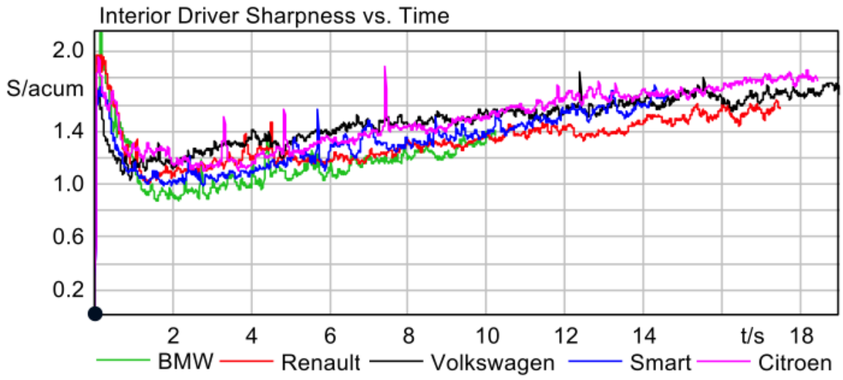


(a) Motorbay



(b) Interior (Driver side).

Figure 6.5: Motorbay and interior Sharpness comparison of electric vehicles.

inherent Roughness towards the end of the vehicle's run-up, which was induced through order and harmony addition.

The average, median, maximum, R.M.S and integration values of the objective metrics were considered for the statistical Spearman correlation. In addition to these values, a second local maximum value was also calculated, which considers a non-global maximum value towards the end of the vehicle's run-up, e.g. the increased Roughness of Concept 2 in Figure 6.6c. The integration value represented a single value for the area under the temporal envelopes.

The Spearman correlation was calculated using Statistica 13, and revealed several strong correlations between the subjective semantics and the objective metrics. The valid correlations ($\rho < 0.05$) are presented in Table 6.4. The Loudness metric is positively correlated with the 'Uncomfortable' semantic, thus indicating that an increase in Loudness will cause a decrease in perceived comfort. Interestingly,

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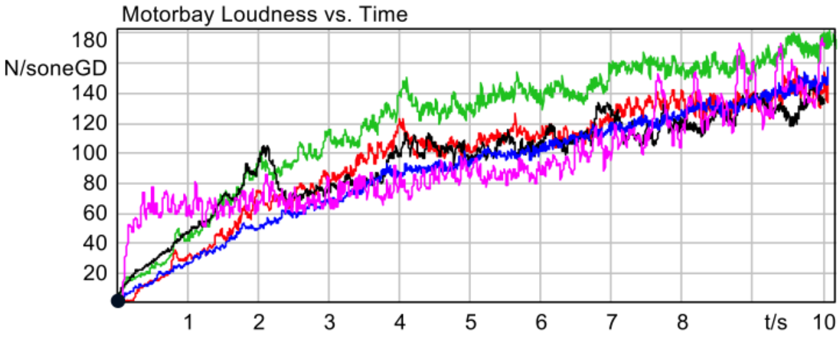
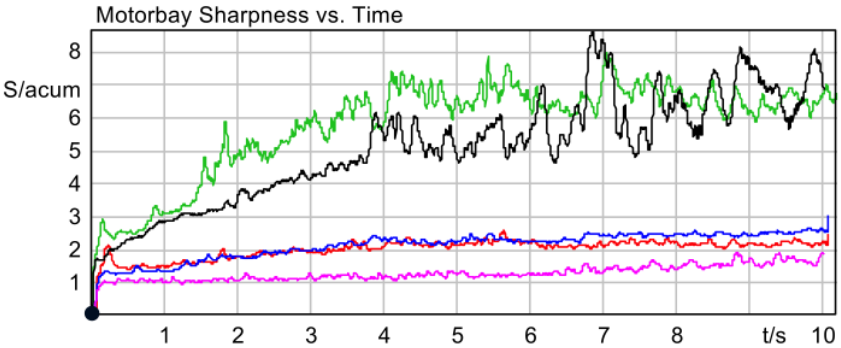
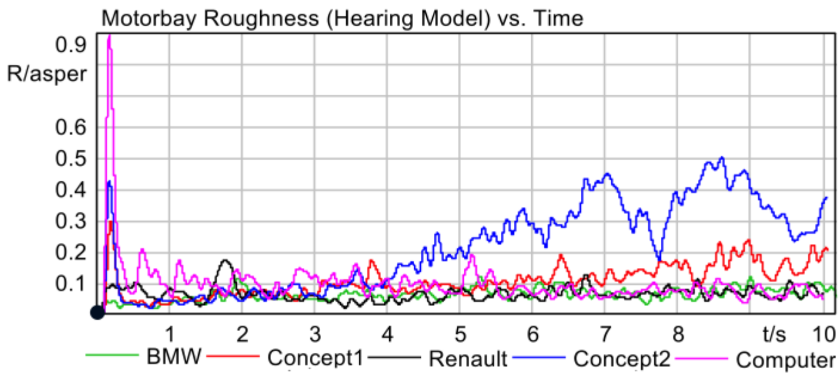


(a) Loudness



(b) Sharpness



(c) Roughness

Figure 6.6: Loudness, Sharpness and Roughness for electric and enhanced sound stimuli.

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Table 6.4: Spearman correlation between subjective and objective metrics.

Subjective Semantic	Type*	ρ	Correlation
Loudness			
Uncomfortable	2	0.04	0.89
Sharpness			
Shrill	AE-3,5	0.01	0.95
Strained	AE-3,5	0.01	0.95
Metallic	A	0.01	0.95
Uncomfortable	AE-3,5	0.04	0.89
Roughness			
Deep	3	0.01	0.95
Comfortable	3	0.04	0.89
Fluctuation Strength			
Quiet	AE-2	0.01	0.95
Conservative	AE-2	0.01	0.95
Comfortable	3	0.04	0.89
Speech Interference Level			
Shrill	3,5	0.01	0.95
Strained	3,5	0.01	0.95
Metallic	A 3,5	0.01	0.95
Uncomfortable	A	0.04	0.89

* Type is defined as follows: 1 - Average, 2 - Median, 3 - Global Maximum, 4 - R.M.S, 5 - Local Maximum, 6 - Integration, A - All, AE - All excluding

the correlation only existed for the median Loudness values of the stimuli.

Sharpness is highly correlated with several semantics that have negative connotations such as, ‘Shrill’, ‘Strained’, ‘Metallic’ and ‘Uncomfortable’. The ‘Shrill’ and ‘Metallic’ semantics describe the sound character as influenced by the high frequency content, whereas the ‘Strained’ and ‘Uncomfortable’ semantics rather describe the induced effects of the high frequency content as perceived by the customer. These findings support the potential of the Sharpness metric to predict problematic sound quality attributes in similar sounding vehicles. The Sharpness metric is highly correlated with all single value representations of the transient signal, except for the global and local maxima. This suggests that the perceived “sharpness” is not based on an instantaneous value, but rather the sound dose, or exposure over time.

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In contradiction to Sharpness, it is seen that Roughness correlates only with the global maximum values. Furthermore, the 'Deep' and 'Comfortable' semantics of Roughness are the bi-polar counterparts for the 'Metallic' and 'Uncomfortable' semantics of Sharpness. Thereby it appears that Roughness could possibly counteract Sharpness, as increased Roughness correlates with an increase in the 'Deep' and 'Comfortable' semantics. Fastl & Zwicker [16] states that the addition of lower frequency sound can decrease Sharpness, which can explain the counteraction of Sharpness and Roughness.

Fluctuation Strength correlates well with the semantics 'Quiet' and 'Conservative' for all single value reduction techniques of the transient signal, except the median values, and with the 'Comfortable' semantic for the global maximum only. Fluctuation strength is highly dependent on low modulation frequencies and the modulation depth, which can be decreased due to interference from broad band noises, such as wind and tyre noise. It is therefore understood that a vehicle sound signature could be seen as 'Quiet' or 'Comfortable', at the start of the acceleration when the sound signature and modulation depth is unaffected by external sources.

Lastly, it was observed that the SIL metric correlates with several semantics: the SIL metric correlates well with local and global maxima of the Shrill and Strained semantics, as well as all single value reductions for the Metallic and Uncomfortable semantics. The SIL metric provides an indication of the deterioration of speech within specific frequency bands and thus it is understood that an increase in SIL could result in a more uncomfortable and strained sound experience.

6.4 Conclusion

The functionality of Zwicker Loudness and Sound Pressure Level were investigated to determine the appropriate metric for an EV signature sound. It was found that the Loudness metric provides a larger measured difference scale, which improves the identification of underlying differences in similar-sounding vehicles. Octave analysis provides an adjustable width of the frequency bands, depending on the order, i.e. normal or 3^{rd} octaves, over a larger bandwidth, whereas

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the Bark scale for specific Loudness is fixed. However, the compressed scale of the Specific Loudness analyses are found to focus on specific frequency ranges that are of interest in vehicle acoustics, and is therefore suggested as a more appropriate Loudness or level metric. The transient Loudness metric correlated well with the 'Uncomfortable' semantic, and revealed minor distinctions between the original and enhanced sound characters. In contrast to transient Loudness, Sharpness illustrated significant differences between original and enhanced electric vehicle sound. The time varying Sharpness and SIL metric correlated well with 'Shrill', 'Strained', 'Metallic' and 'Uncomfortable' semantics. It was thus concluded that the Sharpness metric could be used as a possible identifier of unwanted sound character as perceived by consumers. The transient metric of Roughness was found to have an opposing semantic correlations with regard to Sharpness and SIL. The transient Fluctuation Strength metric correlated well with Quiet, Conservative and Comfortable semantics. It is concluded that the transient metrics of Loudness, Sharpness, Roughness, Fluctuation Strength and SIL could be used to visually distinguish between similar-sounding vehicles, as well as potentially offer insight to the vehicle sound character as perceived by consumers.

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Chapter 7

The Relationship Between Consumer Satisfaction and Psychoacoustics of Electric Vehicle Signature Sound.

The exposition presented in this chapter is a collaboration effort with Dr. Annie Bekker of the Department of Mechanical and Mechatronic Engineering at Stellenbosch University, Stellenbosch, South Africa. The work is presented as the final draft to be submitted, with the co-author, to the Journal of the Acoustic Society of America. Dr. Bekker is the co-author of this paper as the supervisor of the PhD candidate. A signed declaration to this effect is in the possession of both the candidate and supervisor. The paper attempts to reconcile the gap between the interpretations of subjective and objective approaches to determine sound quality, such that sound quality can be assessed in a fast and efficient manner which also relates to actual consumer experiences. In doing so, this work identifies the links between subjective sound experiences and objective metrics that govern and describe electric vehicle sound signatures and attempts to develop a benchmark consumer satisfaction metric for electric vehicle signature sound [15], which is a unique contribution to the field of EV acoustics. This paper contributes toward two of the main objectives of this dissertation. Firstly, by determining the perceived consumer satisfaction of the interior sound signature of electric vehicles, and the underlying sound dimensions that govern it. Furthermore, this paper de-

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termines the prediction capabilities of known psychoacoustic metrics with respect to perceived consumer satisfaction. The FFT vs Time analyses of all the evaluation stimuli are shown in Appendix A. The full subjective evaluation can be found in Appendix B.2.3 followed by the recorded stimuli in Appendix C

7.1 Introduction

The investigation of vehicle sound quality is usually governed by two approaches: a subjective evaluation and an objective evaluation. The subjective evaluation approach is where jurors evaluate sound quality through physical test drives or listening room evaluations. Some of the advantages of the subjective evaluation approach is that the researcher is presented with a relevant response with regards to true perception of the stimuli in question. Disadvantages include that it is time consuming, costly, requires a significant number of participants to ensure validity and reliability, and has natural limitations on the number of stimuli that can be evaluated, due to jury fatigue [70]. In contrast, the objective evaluation approach utilizes an analytical and calculated method to determine the quantification of sound quality through analytical models, objective sound metrics and computer software. The advantages of the objective evaluation is that it is fast, efficient, and has virtually no limitations in terms of sample size or iterations per evaluation. The disadvantages of the objective approach include that the interpretation of the analyses with respect to the true perceived experience can be complex or detached. For example, if the calculated Roughness for Car A is found to exceed Car B by $Xasper$, how does this value relate to the perceived difference in Roughness as experienced by a person? Furthermore, does the specific psychoacoustic metric, for example Zwicker Loudness, only explain the perceived sensation of loudness, or could other characteristics also influence the specific subjective sensation? These are typical questions that sound quality engineers face. It is therefore necessary to attempt to reconcile the gap between the interpretations of subjective and objective approaches, such that sound quality can be assessed in a fast and efficient manner which also relates to actual consumer experiences. This work investigates the sound experiences and identifies the links between subjective sound experiences and objective metrics that

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govern and describe electric vehicle sound signatures, by means of jury testing, psychoacoustic software and statistical analyses. Subjective experiences were evaluated through a bi-polar semantic evaluation in a listening room. Spearman rank correlations and factor analyses were exercised to evaluate and understand the subjective sound space. Similarly, various time-varying or transient psychoacoustic metrics were calculated using the Head Acoustics ArtemiS Suite. Finally, a multiple linear regression analysis was performed to establish a proposed consumer satisfaction model that links the calculated objective metrics to the subjective experiences.

7.2 Experimental Procedure

A subjective evaluation was conducted on 52 respondents at Stellenbosch University to determine the perceived consumer satisfaction of electric vehicle signature sounds. A broad range of WOT stimuli was selected to evaluate the interior sound quality of electric vehicles as well as potential enhancements thereof. The sound stimuli comprised of five standard production electric vehicle sound signatures, six enhanced sound signatures, one hybrid vehicle sound signature, and one internal combustion vehicle interior sound signature. The full list of sound stimuli and their descriptions is presented in Table 7.1.

7.2.1 Stimuli

The standard production Wide Open Throttle (WOT) sounds of electric vehicles (EVs) and a hybrid electric vehicles (HEV) were recorded in Germany in 2015 as part of a previous study by the authors [12]; wherein the full recording procedure is described. These sound signatures (Sounds A,C,F,G,H and M) were recorded in the driver seat of the vehicles, on secluded public roads, using a HEAD Acoustics SQuadriga II binaural measurement system. Similarly, sounds B, D and E were also taken from a previous study by Swart *et al.* [13] however the sound signatures were scaled in magnitude to represent those typically experienced in vehicle interiors. Sound B is an enhanced concept sound that utilizes downwards pitch transposition effects and additional harmonies. Sound D, also a concept sound,

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Table 7.1: The comprehensive list of sound stimuli used to evaluate EV interior sound quality.

Sound	Source	Description
A	BMW i3	WOT interior sound signature at driver position.[1]
B	Concept1	Enhanced sound signature concept. (Pitch Transposition + Harmonies) [1]
C	Renault ZOE	WOT interior sound signature at driver position.[1]
D	Concept2	Enhanced sound signature concept. (Lower Orders + Harmonies) [1]
E	Computer	Computer generated stimulus using motor orders.[1]
F	Citroën C-Zero	WOT interior sound signature at driver position.
G	Smart Electric	WOT interior sound signature at driver position.
H	Volkswagen e-Up!	WOT interior sound signature at driver position.
I	Renault ZOE Interior	The repeated measures stimulus (Sound C).
J	Shepard's Tones	Shepard-Risset Glissando tone with 110 Hz fundamental frequency.
K	Computer Enhanced	Sound E with the addition of pink noise.
L	BMW Modulated	Sound A with frequency modulated pink noise.
M	Porsche Panamera Hybrid	WOT interior sound signature at driver position.[1]
N	Ford Bantam (ICE)	WOT interior sound signature at driver position.

[1]Refer to author's previous work [13] for full details.

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was enhanced through the addition of lower orders (<500 Hz) and harmonies as well as side band frequencies. Sound E is a purely digital sound concept which was designed and created using computer software. All generated and enhanced sound stimuli were scaled such that the RMS dB(A) level of the run-up does not exceed a perceivable difference of 3 dB(A) [16] with regard to the standard production EV sounds. Sound stimulus E was also enhanced further by adding a linearly increasing level of pink noise to the sound (Sound K) to simulate the contribution of road and wind noise. In likeness yet contrasting to the continuously increasing frequencies of motor orders of the mentioned stimuli, a sound stimulus (Sound J) was created using a Shepard-Risset Glissando tone [71]. Shephard's tones create an auditory illusion that the frequency of a sound is continually increasing whereas in reality it remains within a fixed bandwidth [72]. Furthermore the interior sound signature of the Renault ZOE (Sound C) was repeated in the stimuli pool (Sound I) in order to investigate the consistency of the re-evaluation by the jury. Sound L was generated by adding a gradually increasing level of frequency modulated pink noise to Sound A. The concept of modulated pink noise was introduced by Genuit & Fiebig [73] as a potential exterior alert signal sound for EVs, due to its high detectability and localization. This stimulus was included in the evaluation to glean potential consumer responses should these sounds carry to the vehicle interior. The last stimulus Sound N is from a light commercial internal combustion engine vehicle. This two seater vehicle was specifically selected as it is a well-known vehicle in South Africa with lower levels of sound quality compared to luxury vehicles.

7.2.2 Subjective Evaluation

The subjective evaluations were conducted using a bi-polar semantic differential test completed on a fillable PDF form, as shown in Figure 7.1. A comments section was provided for participants to add further commentary if desired. The sound stimuli were imbedded into the test form for ease of use and such that the juror could listen to the stimulus repeatedly. Twelve bi-polar semantics were adapted from a previous study by the authors [13], although the semantic pairs of 'Spirited' and 'Effortless' were replaced with 'Futuristic' and 'Creative', in an attempt to improve the explained variance of the underlying factors. The new

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semantics were chosen from a study by Giudice *et al.* [7] on the descriptive semantics used for electric vehicles. The playback order of the stimuli was randomized to avoid the possible known effects of jury fatigue or practice effects, which are potentially introduced when presenting stimuli in a fixed sequence.

Sound A

	-3	-2	-1	0	1	2	3	
Quiet								Loud
Calm								Shrill
Pleasant								Annoying
Deep								Metallic
Comfortable								Uncomfortable
Powerful								Weak
Sporty								Conservative
Rumbling								Flat
Exciting								Boring
Futuristic								Old-fashioned
Creative								Uninspired
Refined								Harsh

Please rate your satisfaction of the sound.

Satisfaction:

Additional Comments:

Figure 7.1: Subjective evaluation form using bi-polar semantics.

The subjective evaluation was conducted in a full RF anechoic chamber at Stellenbosch University with an average RMS background noise level of 26.2 dB(A). The evaluation was performed using a laptop, headphone amplifier and headphones as shown in Figure 7.2. The amplification on the Xonar USB digital-to-analog converter (DAC) was adjusted and then fixed such that the playback level (dB(A)) matched the actual sound level of the recorded vehicle sound. A pre- and post-test calibration was performed on the complete system using a B&K Head and Torso Simulator (HATS), to ensure that the playback level remained constant. Furthermore, the B&K HATS was also calibrated before and after the

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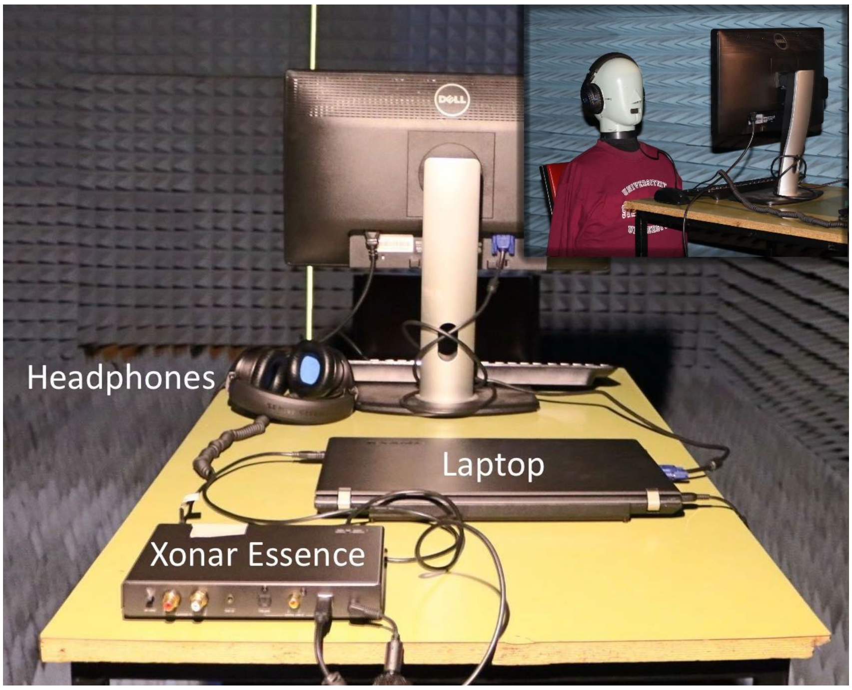

Figure 7.2: Jury evaluation equipment (main): Sennheiser HD6Mix monitoring headphones, Lenovo E51 laptop and ASUS Xonar Essence STU USB DAC and headphone amplifier. The B&K Binaural HATS used for level calibration (top right).

calibration measurements using a mobile sound calibrator. The average RMS background noise level during a one minute period with the headset was measured to be 23.4 dB(A).

The jury comprised of university staff, students and members of the surrounding community. The majority of the jury are untrained in the field of acoustics and the sound signatures of EVs are fairly new and unfamiliar to most South African consumers. The complete jury consisted of 52 members, 34 male and 18 female with an average age of 26 years (min:20 years and max:53 years). Each jury member performed the evaluation individually and was briefed before the evaluation regarding the evaluation form, bi-polar semantic scoring and the satisfaction rating. Furthermore, the participants were informed that each stimulus could be played multiple times at their convenience. The jury was briefed that the satisfaction rating should be based on how satisfactory the specific sound would be as an electric vehicle sound signature, 0 being unsatisfactory and 10 being satisfactory. Jurors were asked not to consider the test as a ranking of all the stimuli,

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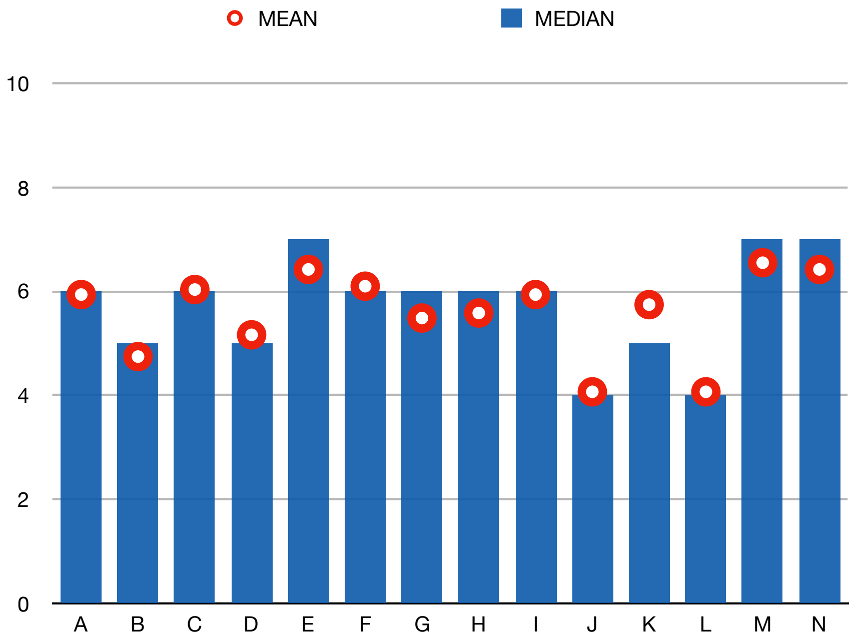

Figure 7.3: Mean and median satisfaction scores of all stimuli.

but rather to consider each stimulus and its attributes independently. The participants were unaware of the source of the stimuli or that there were repeated stimuli.

7.3 Results

The data from the 52 participants was analysed for test repeatability amongst the jury. No hearing loss or damage was reported amongst the jury members. It was found that 31 of the 52 participants were reliable with a significant correlation (r = 0.85) and were selected as the final jury for all analyses.

7.3.1 Basic Statistics

The mean and median satisfaction scores were calculated for all the stimuli listed in Table 7.1 and the results are shown in Figure 7.3.

It can be seen that sounds E, M and N are most preferred in both the mean and

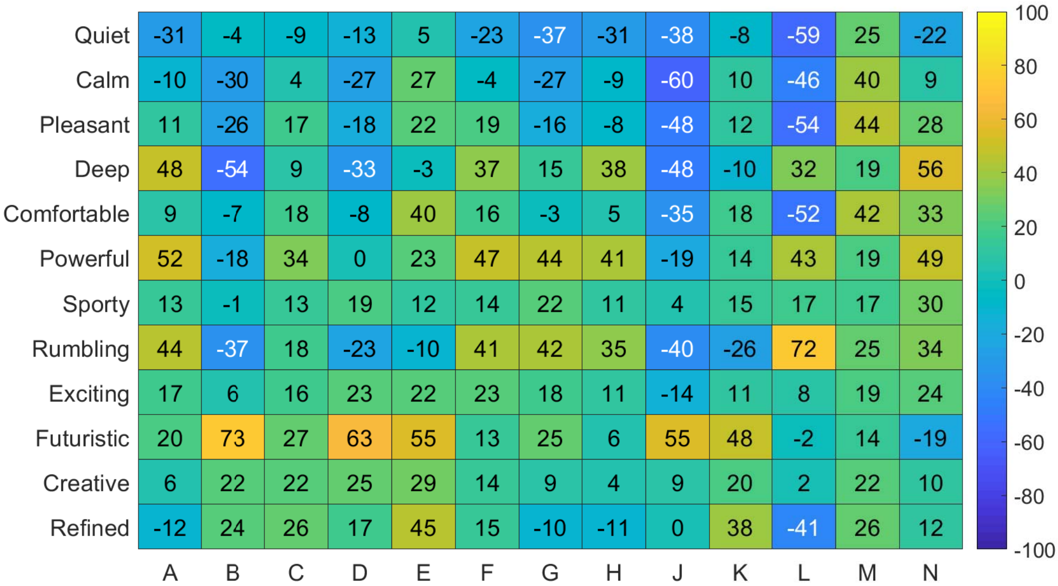

Figure 7.4: A heat map showing the mean semantic scores for each stimulus as a percentage value.

median ratings. SoundM, with the highest mean score and therefore the most preferred, was that of the hybrid Porsche Panamera. Jurors commented that the combination of the EV sound character with the familiarity of gear changes was attractive as an EV sound signature. Sound N was described as sounding old fashioned and like a regular car, however the deepness of the sound was preferred and in some cases even considered as sporty. Sound E was most preferred of the enhanced sound signatures, whereas the BMW and Citroën sounds were most preferred among the standard production EV sound signatures.

A Heatmap was generated to assist in visually grasping the distribution and variation of the mean subjective semantic scores for all the stimuli. The Heatmap in Figure 7.4 illustrates the average rating for each semantic as a percentage value for the specific semantic, i.e. 100% meaning a full score for that semantic and -100% a full score for the bi-polar counterpart. The Heatmap illustrates the differences in stimuli, for example the significant differences in semantic scores of Sound J and L compared to the other stimuli. For example Sound L is considered to have a significant 'Rumbling' sound character and to be considerably 'Uncomfortable' and 'Loud'. The stimuli B,D,E,J and K are considered to be very futuristic, and stimuli E and K are considered as more refined.

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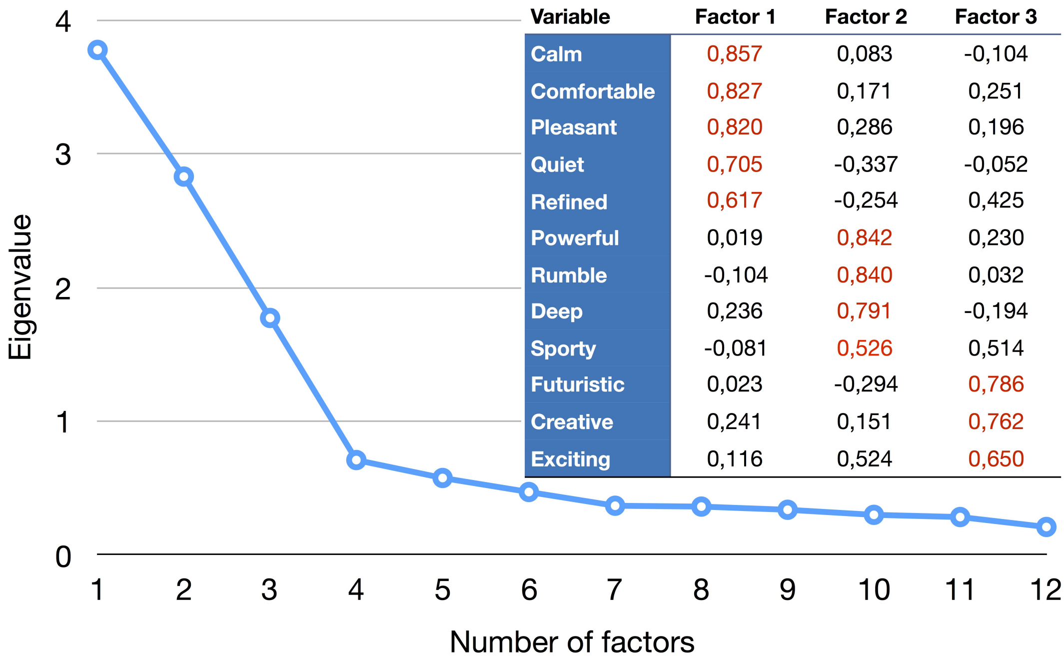

Variable	Factor 1	Factor 2	Factor 3
Calm	0,857	0,083	-0,104
Comfortable	0,827	0,171	0,251
Pleasant	0,820	0,286	0,196
Quiet	0,705	-0,337	-0,052
Refined	0,617	-0,254	0,425
Powerful	0,019	0,842	0,230
Rumble	-0,104	0,840	0,032
Deep	0,236	0,791	-0,194
Sporty	-0,081	0,526	0,514
Futuristic	0,023	-0,294	0,786
Creative	0,241	0,151	0,762
Exciting	0,116	0,524	0,650

Figure 7.5: Factor analysis of bipolar semantics.

7.3.2 Dimensions of EV Interior Sound

A factor analysis was performed on the semantic ratings of the jury in order to determine the underlying factors that govern the interior EV sound quality. To this end, the semantic scores for the ICE vehicle (Sound N) were excluded from this analysis. Three main factors were identified with a cumulative variance of 70% as shown in Figure 7.5. All semantics were found to load within these three factors in a significant manner (>0.52). The first factor is predominantly governed by the 'Calm', 'Comfortable' and 'Pleasant' semantics and coincides with a 'Comfort/Calm factor' found in several other studies for both EV and ICE vehicles [4; 7; 13]. The second factor is highly correlated with the 'Powerful', 'Rumble' and 'Deep' semantics. The 'Sporty' semantic is also found to partially load with the second factor and third factor, however a bigger contribution is weighted to the second factor. The third factor was found to be a 'Futuristic' factor, with strong contributions from the semantics of 'Creative' and 'Exciting' as well. The three main factors for electric vehicle interior sound are thus a 'Comfort' factor, a 'Power' factor and a 'Futuristic' factor.

In order to determine the influence of the semantics on consumer satisfaction

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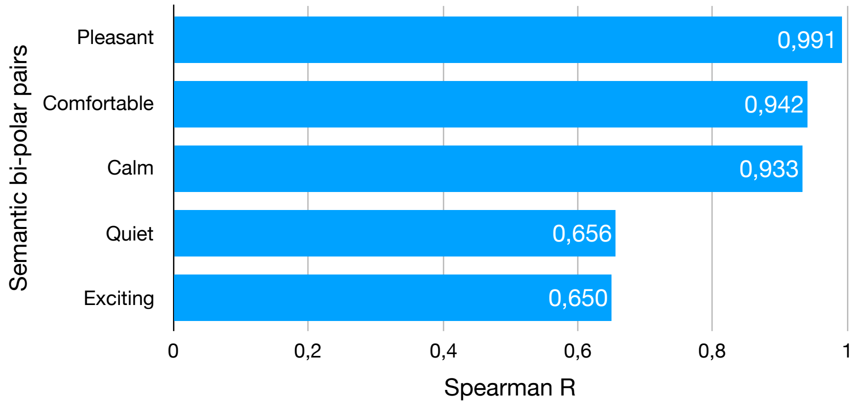

Figure 7.6: Spearman correlation between averaged semantics and mean satisfaction ratings.

ratings, a Spearman rank correlation was determined. The highest correlated semantics are presented in Figure 7.6. Significantly strong positive correlations were found between the 'Pleasant', 'Calm' and 'Comfortable' semantics. The semantics of 'Exciting' and 'Quiet' showed a weaker positive correlation with regard to consumer satisfaction, however still significant ($\rho < 0.05$). Remarkably it can be seen that four of the above mentioned semantics coincide with the 'Comfort/Calm' factor, thereby suggesting that this factor is highly influential on the perceived consumer satisfaction of electric vehicles.

7.4 Discussion

The underlying dimensions of 'Comfort/Calm', 'Power' and 'Futuristic' found for the interior EV sound coincide with the dimensions of a study done by Giudice *et al.* [7]. Their study found the underlying dimensions to be a 'Calmness/Refinement' dimension, a 'Futuristic/Science-Fiction' dimension and lastly a 'Powerful/Beefy' dimension. The addition of the 'Futuristic' and 'Creative' semantics as explained in Section 7.2.2 revealed an improvement in the explained variance from 60% in a previous study [13] to the 69.9% achieved in this study. The Spearman correlation revealed the 'Pleasant' semantic to be highly correlated with perceived satisfaction, which coincides with the previous study [13], however the degree of correlation is significantly stronger for the interior vehicle stimuli in this study.

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The factor analysis and Spearman correlations contribute a perspective of the semantic space of an electric vehicle signature sound and how the semantics relate to the perceived consumer satisfaction. To describe the EV sound space in a similar manner using psychoacoustics and analytical software, several metrics were selected and calculated for the stimuli. The transient or time-varying metrics of Sound Pressure Level (SPL), Zwicker Loudness, Sharpness, Roughness (Hearing Model), Fluctuation Strength, Impulsiveness(Hearing Model), Speech Interference Level (SIL) and Speech Intelligibility Index (SII) were calculated using Head Acoustics ArtemiS Suite [16; 26; 27]. These transient metrics calculate an analysis over time, which is required when a transient WOT signal needs to be quantified. One problem that NVH engineers face when comparing time-varying or transient psychoacoustic metrics to subjective jury responses, is the fundamental differences in the response outputs. The transient metrics provide continuous 'observations' with respect to time, whereas most subjective evaluations provide single value responses for the complete duration of the stimulus. Therefore, in order to compare these responses more accurately, it is necessary to reduce the transient metrics to a single value response. Several single value reduction (SVR) techniques, such as Global Maximum (Max), Root-Mean-Squared (RMS), Local Maxima (LMax), Mean and Integration value (IV), were investigated as possible representations of the measured psychoacoustic metrics [14]. Furthermore, the use of the 95^{th} percentile value (N_5) for Zwicker Loudness, that is the Zwicker Loudness value that is exceeded for 5% of the time signal, was also considered. This metric, also known as percentile Loudness (N_5) has been shown to correlate better with perceived Loudness values [74].

7.4.1 Comparison of Subjective Semantics vs Objective Metrics

The subjective semantics and objective metrics are both used to investigate the attributes of sound character and quality. However, literature regarding the relationship between the subjective semantics and objective metrics for electric vehicles is sparse. Lennström *et al.* [8] investigated the relationship between perceived annoyance and the psychoacoustic metric of Prominence Ratio. A study by Matuszewski & Parizet [9] investigated the relationship between unpleasantness and several psychoacoustic metrics. However, no studies have been found

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that illustrate the relationship between multiple subjective semantics and psychoacoustic metrics for electric vehicles. To this end, a Spearman correlation was determined between the subjective semantics and objective metrics, as presented in Table 7.2. The metric group indicates the psychoacoustic metric with the strongest positive(+) or negative(-) correlation with multiple SVRs as a whole. The column for Best SVR denotes the SVR technique of the metric group with the strongest correlation, followed by the Spearman rank correlation (R). The last column indicates an additional metric group which also correlated strongly. The psychoacoustic metrics that correlate best with the subjective semantics include Sharpness, Loudness and Impulsiveness. Furthermore it can be seen that maximum Sharpness and 95^{th} percentile Loudness (N_5) results in the strongest correlations for SVR techniques. Impulsiveness is best represented by either the maximum or RMS single values. Interestingly the 'Sporty' semantic did not correlate in a significant manner with any of the psychoacoustic metrics, and is likely attributed to the lack of noteworthy sportiness in the electric vehicle sound character. The 'Exciting' semantic correlated only with median values of SIL. The SVR techniques of LMax, Median and IV were found to correlate less frequently with the psychoacoustic metrics and were therefore excluded from further processing and analyses. Also significant are the semantics 'Calm', 'Comfortable' and 'Pleasant' that correlate inversely with the Sharpness psychoacoustic metric, or proportionally with the 'Shrill', 'Uncomfortable' and 'Annoying' bi-polar counterparts. The 'Calm', 'Comfortable' and 'Pleasant' semantics were previously found to have the strongest correlation with perceived satisfaction, thus signifying that a reduction in maximum Sharpness could lead to an increase in perceived satisfaction. In order to investigate and validate this claim, a set of multiple linear regression analyses was performed.

7.4.2 Investigation of Models and Predictors

The pool of stimuli described in Table 7.1 was reduced to twelve vehicle sound stimuli for the regression analyses. The repeated stimulus Sound I was excluded along with Sound N such that the reduced stimulus pool contained independent sounds only which are dissociated from any ICE contributions. The averaged responses (dependent variable) of the reduced stimulus pool and the Max and RMS

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Table 7.2: Correlations between subjective semantics and objective metrics for electric vehicles.

Semantic	Metric Group	Best SVR	R	Other Metrics
Calm	-Sharpness	Max	0.720	-SIL
Comfortable	-Sharpness	Max	0.709	+SIL
Pleasant	-Sharpness	Max	0.645	-SIL
Quiet	-Loudness	N_5	0.952	-Sharpness
Refined	-Loudness	N_5	0.855	-Impulsiveness
Powerful	+Impulsiveness	Max	0.900	-SII
Rumble	+Impulsiveness	Max	0.945	-SII
Deep	+Impulsiveness	RMS	0.855	+Loudness
Futuristic	-Impulsiveness	RMS	0.852	-Loudness
Creative	-Loudness	Mean	0.925	+Roughness
Exciting	-SIL	Median	0.662	none

values of the psychoacoustic metrics (predictors) were used to perform multiple linear regression analyses. A best subset regression was performed on the Max and RMS predictors and the twelve mean subjective satisfaction scores of the twelve vehicle stimuli. The best subset regression performs multiple regressions and the data using different linear combinations of the predictors to determine the dependent variable. The best 20 models are then analyzed to determine the predictors that occur most frequently across the different models. The results revealed that the predictors of Max and RMS Sharpness respectively occurred in 12/20 and 11/20 instances of the top 20 significant regression models respectively. This is significant as the best remaining predictors only occurred twice in the top 20 models. The psychoacoustic metric of Sharpness is thus the most distinguished predictor of perceived satisfaction for an electric vehicle interior sound signature, as confirmed by the Spearman correlation results in Section 7.4.1.

The Max and RMS Sharpness, along with 6 other promising predictors, were then selected to use in attempting to develop a consumer satisfaction metric, using multiple linear regression (MLR). The MLR is defined in Equation 7.1 as a linear combination of predictors/regressors ($X_{1...n}$) and their respective coefficients ($b_{1...n}$) [19]. Various linear regression models were calculated using the *fitlm* function in Matlab and the *step* function to determine optimized models with combinations of Sharpness and one additional metric. It was found that by ex-

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cluding Sound J and L, it was possible to fit a regression model using only a single predictor, the maximum Sharpness. A leave-one-out cross validation (LOOCV) was performed across the stimuli and the resulting consumer satisfaction model (CSM) as shown in Table 7.3 as CSM_1. The LOOCV was performed on all models before presenting the model in its final form. The proposed CSM possessed a good coefficient of determination (R^2) and predicted the perceived satisfaction scores with good accuracy. The standardized form of the model is shown as $|CSM_1|$. However, as previously stated, the regression model with a single predictor could not accurately predict Sounds J and L accurately. Upon further investigation, it was found that Sound J had significant high overall Sharpness levels (Max & RMS) due to the tonal components, and Sound L had high levels of sound fluctuation in the lower and upper frequency bands resulting in the unsuccessful estimation of these sounds.

$$y = b_0 + b_1 X_1 + b_2 X_2 + ... + b_n X_n + \epsilon \qquad (7.1)$$

A second MLR model was constructed using two predictors in an attempt to improve the coefficient of determination and the prediction of the problematic sounds. The second model CSM_2 was optimized using Max Sharpness and N_5 Loudness, with the coefficients as listed in Table 7.3. The standardized model $|CSM_2|$ is displayed directly underneath. The second model showed a higher coefficient of determination and was able to predict Sound J accurately as well. However, Sound L remained challenging to predict with good accuracy. A further scrutiny revealed that Sound L was perceived to be the loudest sound of all the stimuli, as seen in Figure 7.4, even though the metric of SPL and Loudness did not show a significant difference between the original stimulus Sound A and Sound J. A study by Sottek & Moll [74] stated that: "The existing loudness models cannot predict the loudness of all impulsive sounds reliably." The Sharpness metric proposed by Aure is by definition a type of weighted first moment of specific loudness N' divided by the total loudness N during a certain exposure time [16]. Thus the poor performance of Loudness prediction for fluctuating sounds could inherently also affect the Sharpness estimation of fluctuating sounds. Furthermore Fastl & Zwicker [16] also mention that the addition of lower frequencies decreases Sharpness, which could also account for the mis-prediction of models

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CSM_1 and CSM_2 of Sound L. For this reason, additional models were investigated in order to predict Sounds J and L with greater accurately.

Table 7.3: Proposed Consumer Satisfaction Metric (CSM) based on psychoacoustics.

Model	R^2	R^2_{Adj}	Intercept	Coefficients			
				b_1X_1	b_2X_2		
CSM₁	0.686	0.647	7.194	-0.843X_1			
|CSM₁|	0.686	0.647	5.833	-0.467X_1			
CSM₂	0.798	0.747	8.590	-0.968X_1	-0.066X_2		
|CSM₂|	0.798	0.747	5.676	-0.565X_1	-0.230X_2		
				b_3X_3	b_4X_4	b_5X_5	b_6X_6
CSMS₅	0.755	0.728	8.479	-2.105X_3			
|CSMS₅|	0.755	0.728	5.685	-0.642X_3			
CSMM	0.910	0.859	18.117	-7.563X_3	-3.458X_4	-231.1X_5	140.8X_6
|CSMM|	0.910	0.859	5.878	-1.147X_3	-0.403X_4	-0.417X_5	0.407X_6

Predictors

X_1 =Sharpness Max, X_2 =Loudness(N_5), X_3 =Sharpness (S_5)
X_4 =Impulsiveness RMS, X_5 =Fluctuation Strength RMS
X_6 =Fluctuation Strength RMS∗Sharpness (S_5)

7.4.3 Proposed Consumer Satisfaction Metric (CSM)

The N_5 Loudness is known to correlate better with perceived loudness. As such the 95^{th} percentile Sharpness (S_5) was investigated as a possible predictor. A third model $CSMS_5$ was found using the *fitlm* function and Sharpness (S_5) as the lone predictor. The $CSMS_5$ model showed improved performance on predicting the consumer satisfaction of all stimuli. The model could predict Sound J with greater accuracy using a single predictor, however could still not predict Sound L with great accuracy. The model performance can be seen in Figure 7.7.

A final effort was launched to find a model that could predict the consumer satisfaction of the fluctuating sound characteristics of Sound L. The pure linear combination of the *fitlm* function could not find an appropriate model with just two

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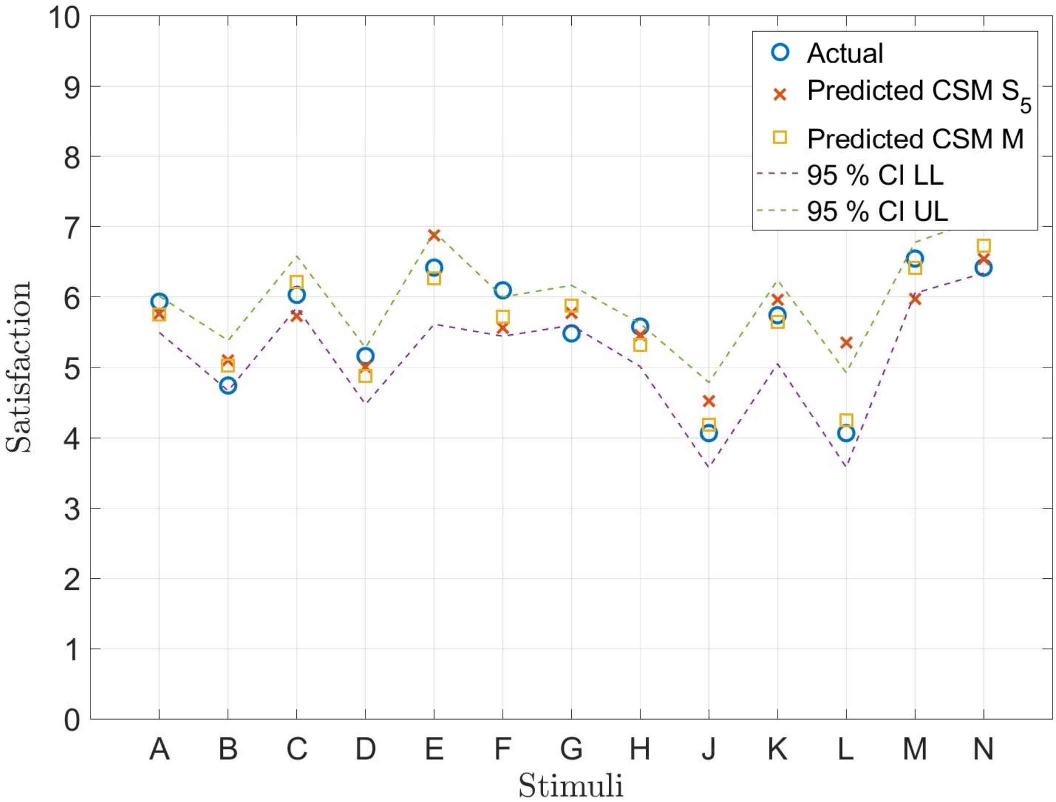

Figure 7.7: Comparison of the $CSMS_5$ and $CSMM$ model predictions to the measured interior responses.

or three terms, that could predict Sound L adequately. However the *step* function indicated that a pairwise interaction term combination of RMS Fluctuation Strength and Sharpness (S_5) was repeatedly selected. An optimized mixed model was found in the form of four predictors and the intercept as shown by model $CSMM$ in Table 7.3. The higher number of predictors as well as the pairwise interaction term lead to some concerns regarding the possibility of multicollinearity between predictor variables and thus the significance of the model was investigated. An analysis of variance (ANOVA) was conducted on the model and it was found that all predictors were uncorrelated and each term was significant ($\rho < 0.05$). Furthermore a Belsley collinearity diagnostic was computed to check for inter-variable collinearity [75; 76]. The Belsley diagnostic suggests that condition indices between 30 and 100 indicate moderate to strong multicollinearity, whereas lower values are indicative of weak correlations between variables. The highest condition indices for the $CSMM$ model were found to

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be 21.1, which suggests only low levels of variable collinearity. The performance of the $CSMM$ model and the prediction confidence interval are presented in Figure 7.7. The model has a high coefficient of determination and it outperforms the $CSMS_5$ model on most stimuli predictions, except stimuli B, C and G. The biggest improvement can be seen in the prediction of stimulus L, that has been problematic to predict with all other models. The addition of the Impulsiveness and Fluctuation Strength predictors allows for an improved estimation of consumer satisfaction of the fluctuating sound. On inspection of the standardized coefficients ($|CSMM|$), it can be seen that the most influential term on consumer satisfaction is X_3, the 95^{th} percentile Sharpness (S_5) by a substantial margin. Both these models suggest the influence and the necessity of including Sharpness as a predictor for electric vehicle sound quality and satisfaction. Sharpness is therefore recommended as an investigative tool, especially percentile Sharpness (S_5), to predict perceived consumer satisfaction.

7.4.4 CSM Validation and Recommendations

The proposed final models were used to predict perceived consumer satisfaction of a previous stimuli set recorded by the authors [13]. These previous stimuli were not recorded in the interior of the vehicle but rather in the Motorbay, which required the calculated psychoacoustic metric data to be standardized before proceeding to use it with the standardized version of the models. The performance of models $|CSMS_5|$ and $|CSMM|$ with regards to predicting perceived consumer satisfaction of Motorbay sound signatures is shown in Figure 7.8. The prediction confidence intervals of the best model, $|CSMS_5|$, is also illustrated. It can be seen that the $|CSMS_5|$ model outperforms the mixed model on most stimuli predictions, thus reiterating the necessity of Sharpness as a predictor for electric vehicle sound quality. The under-performance of the $|CSMM|$ could most likely be attributed to the combination of the complexity of the model (4 predictors) and the Motorbay sound character. The variance in the psychoacoustic metrics other than Sharpness could potentially cause the slight scaling factor that can be seen in the specific model predictions. However, additional training and validation of these models are needed to improve the prediction accuracy. The simplicity of the $|CSMS_5|$ model and the high prediction accuracy

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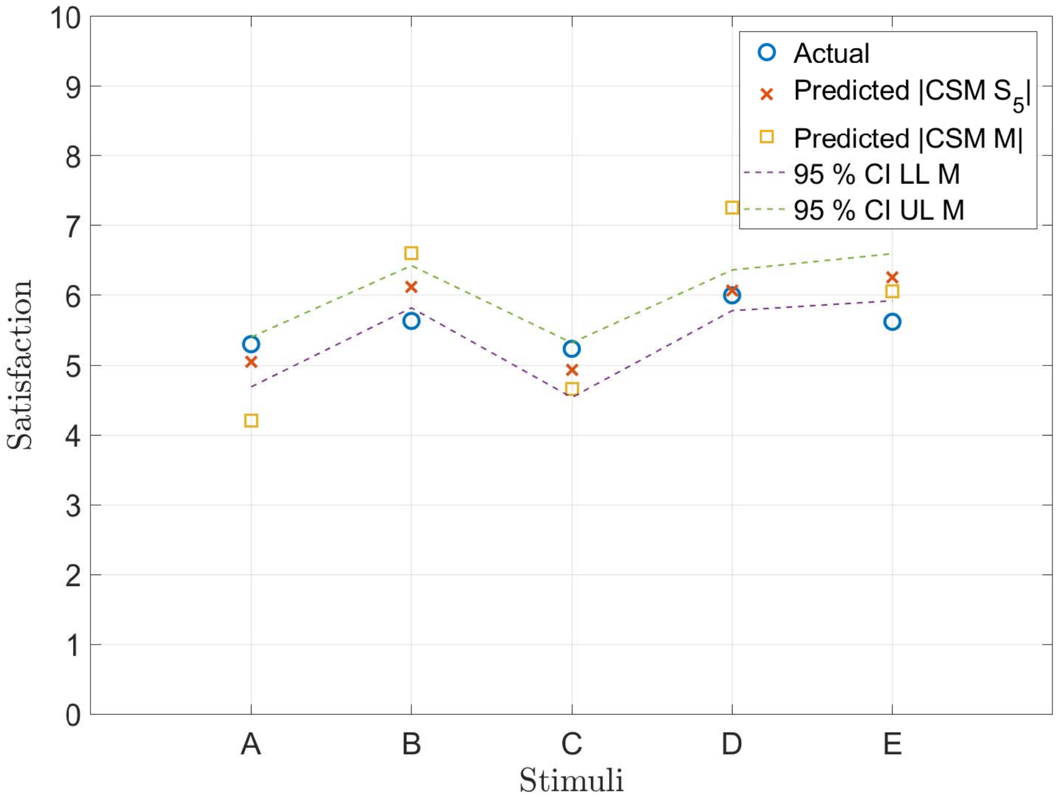

Figure 7.8: Comparison of the $CSMS_5$ and $CSMM$ model predictions to the measured motorbay responses.

for both interior and motorbay vehicle sound signatures are indicative of a robust model that can be used to predict perceived consumer satisfaction. To this end, the $|CSMS_5|$ model is proposed as a consumer satisfaction model for predictions of perceived satisfaction of the sound signatures of electric and hybrid electric vehicles. However, care should be taken when evaluating sound stimuli with fluctuating characteristics. It is recommended that this model should be validated further using additional datasets of interior and motorbay sound stimuli. Furthermore, potential improvements should be investigated using the combination of percentile Sharpness S_5 and new psychoacoustic metrics such as tonality or prominence ratio to improve the coefficient of determination. The percentile approximations (90^{th} or 95^{th}) of the Impulsiveness and Roughness metrics should also be investigated as potential predictors. The use of pairwise interaction terms is also encouraged in order to improve the model.

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7.5 Conclusion

The subjective and objective evaluation of electric vehicle sound quality was investigated through a jury evaluation and psychoacoustic metrics. A pool of 14 vehicle interior sound stimuli was investigated subjectively by a jury of 52 members. The sound stimuli included electric, hybrid electric and enhanced electric sound signatures as well as an internal combustion vehicle sound signature. The subjective semantic space revealed three underlying factors, namely a 'Comfort' factor, a 'Power' factor and a 'Futuristic' factor, that explained approximately 70% of the variance and coincides with similar literature [7]. The semantics of 'Pleasant', 'Comfortable' and 'Calm' were highly correlated ($R > 0.93$) with perceived satisfaction. The objective sound quality of the stimuli was mapped using several psychoacoustic metrics such as Loudness, Sharpness, Roughness, Impulsiveness and several others. The correlation between the subjective semantics and objective metrics was determined through a Spearman Rank correlation. Results revealed multiple significant correlations between the semantics and the psychoacoustic metrics of Sharpness, Loudness and Impulsiveness. The single value reductions of the objective metric correlations were used to model perceived consumer satisfaction through multiple linear regression. Two initial models were found, one using maximum Sharpness and the other, the linear combination of maximum Sharpness and N_5 Loudness. These models were surpassed by two final models $CSMS_5$ and $CSMM$ that utilized S_5 Sharpness and a combination of S_5 Sharpness, RMS Impulsiveness and RMS Fluctuation Strength as predictors respectively. The $CSMS_5$ model showed good prediction capabilities, apart from highly fluctuating sounds, where the $CSMM$ model performed significantly better. Both models were validated against an external dataset, where it was found that the simplistic $CSMS_5$ model performed best.

The proposed models, as well as the correlation results of this paper, indicate the significance of Sharpness in electric vehicle sound signatures. What does this suggest about the road ahead for electric vehicle sounds and future research with regards to consumer satisfaction? First and foremost, the model and the results suggest that perceived consumer satisfaction is predominantly affected by Sharpness of the sound character. Secondly, the reduction of overall Sharpness combined with improving the Pleasantness and Comfort of the sound character

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should be the main focus in developing improved sound signatures for electric vehicles. Lastly, it was shown that the gap between the subjective and objective approaches can be bridged using single value approximations of psychoacoustic metrics to accurately predict the perceived consumer satisfaction of electric vehicle sound signatures.

7.6 Acknowledgments

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Chapter 8

Conclusion

The sound signatures of electric vehicles (EVs) has long been a topic of discussion for automotive manufacturers and consumers, especially the sound aspects relating to pedestrian safety, sound quality, and the market uptake and acceptance of these vehicles. This study focused specifically on the sound character and quality of EVs, as perceived by the consumer. At the start of this dissertation, a comprehensive background was presented, established from relevant literature, that details vehicle acoustics, psychoacoustics and technical and perceptual evaluation procedures. The available tools and techniques to evaluate and asses the vehicle sound signatures in the spectral and temporal domains were explored. However, in order to evaluate EV sound signatures, the first questions must be: what does an EV sound like? How can one describe the sound signature of EVs? To this end, appropriate semantics that could describe EV signature sound were investigated in Chapter 3, through jury testing and a word list from literature used to describe machinery noise. It was found that the words 'powerful', 'rumble' and 'deep' are commonly used to describe the signature sound of these vehicles. However, the EV sound signatures were perceived as less powerful and sporty than conventional internal combustion engine (ICE) vehicles.

Once the semantic space that can describe an EV sound signature is understood, the next logical question was to determine whether all EVs sound the same? Are there distinct technical differences in the sound characters of different electric vehicles? As such, the sound signatures of five standard production EVs and one

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hybrid electric vehicle (HEV) were analysed objectively in Chapter 4, to determine the underlying differences between standard production EVs as well as to identify sound characteristics that are unique to EV signature sounds. It was found that EVs have a significant proportion of high frequency content, especially in the 1 to 5 kHz range, which is linked to the most sensitive frequency range of human hearing. Furthermore, it was found that EVs have low SPLs in the 200 to 500 Hz range. This frequency range is linked to powerfulness and sportiness in ICE vehicles.

The technical analysis of the different EVs showed distinct differences between the vehicles. However, are these differences perceivable to a consumer? The perceptual or subjective differences in the vehicle sound signatures were thus investigated. Two individual jury evaluations were conducted, one on the motorbay sound signatures, detailed in Chapter 5, and another on the interior sound signatures, given in Chapter 7. The underlying perceptual sound dimensions that describe the motorbay and interior sound signatures were investigated through principal component and factor analysis. Furthermore, the relationship between the subjective semantics and the perceived consumer satisfaction was determined for both environments. It was found that perceptual variation for both the interior and motorbay sound environments can be explained by three underlying perceptual dimensions. These dimensions include a 'Powerful', a 'Comfort' dimension for both environments, and a 'Deep' dimension for the motorbay sound signature compared to a 'Futuristic' dimension for the interior sound signature. Fundamental to the underlying 'Comfort' dimension are the semantics of 'Pleasant', 'Comfortable' and 'Calm', which were also shown to be highly correlated with perceived consumer satisfaction.

The technical and perceptual studies revealed different aspects of the sound character of current standard production EVs, which raised whether these aspects can be enhanced or changed to improve the perceived satisfaction. The study investigated eight sound enhancement techniques for the motorbay sound signatures in Chapter 5. Three enhanced sound stimuli were created from the combination of the most preferred enhancement techniques. A second study in Chapter 7 investigated the perceived sound quality of three additional enhanced sound signatures in the vehicle interior, against five standard production EVs, one HEV

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and one ICE vehicle sound signature. It was found that high frequency filtering and low order addition are the most preferred enhancement techniques. Furthermore, jurors preferred all enhanced sound signatures above standard production EV sound signatures for the motorbay evaluation. However, only the artificially generated computer stimulus was preferred for the interior evaluation.

The study was expanded by investigating the psychoacoustic characteristics of EVs in an attempt to understand the interaction of the subjective and objective dimensions of EV sound quality. As such, a technical investigation into EV and enhanced sound signatures with respect to several known psychoacoustic metrics was performed. The motorbay and interior sound signatures of standard production EVs, at constant speed and and wide-open throttle (WOT) test drives, were evaluated and compared using several psychoacoustic metrics, as described in Chapter 6. A more in-depth analysis of the EV interior psychoacoustics was performed in Chapter 7, taking into consideration additional psychoacoustic metrics and the influence of enhanced sound signatures. It was found that the psychoacoustic Loudness is more appropriate to evaluate EV sound signatures than the conventional SPL metric. Additionally, the psychoacoustic metric of Sharpness was found to assist in differentiating the similar sounding EV sound signatures and to identify unpleasant sound characteristics.

Lastly, the relationship between the subjective semantic responses and the calculated psychoacoustics was investigated. The relationship between the motorbay semantic scores in Chapter 5 and the corresponding psychoacoustic metrics was initially investigated in Chapter 6, through several single value reduction (SVR) techniques and a Spearman correlation. The relationship between the interior semantic scores and additional psychoacoustic metrics was investigated in Chapter 7. Furthermore, the relationship between the perceived consumer satisfaction and the calculated psychoacoustics was evaluated to establish a consumer satisfaction metric for EV sound signatures. It was found that the psychoacoustic Sharpness is highly correlated with the 'Shrill', 'Uncomfortable' and 'Annoying' semantics, also represented by their bi-polar counterparts 'Calm', 'Comfortable' and 'Pleasant'. These semantics were found to be highly correlated with a decrease in perceived consumer satisfaction. Finally, it was found that the psychoacoustic Sharpness, in particular the 95^{th} percentile Sharpness, can be

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used to effectively predict consumer satisfaction for EV sound signatures, both in the interior and motorbay environments.

The main conclusion from this study is that EV sound quality is governed by the high frequency content in the WOT sound signatures and this leads to the deterioration of the perceived consumer satisfaction. The high frequency content was shown to be a recurring concern in all the objective (technical) and subjective (perceptual) studies, both in the motorbay and interior sound environments. This is further substantiated by the proposed consumer satisfaction metric $CSMS_5$ in Equation 8.1, which was shown to effectively predict the perceived consumer satisfaction of EVs using the 95^{th} percentile Sharpness (S_5).

$$CSMS_5 = 8.479 - 2.105S_5 \tag{8.1}$$

Secondly, it is concluded that EV sound quality is complex when compared to conventional ICE vehicles and poses a challenge for NVH engineers. It was found that EV sound character can be described by three underlying perceptual dimensions: a 'Power' dimension, a 'Comfort' dimension and a 'Futuristic' dimension. These three dimensions could account for 70% of the explained variation in the interior sound signature of EVs, whereas comparative studies for ICE vehicles [4] could explain a greater variation with only two perceptual dimensions. The additional third dimension found in this study is indicative of the complex and challenging nature of EV sound quality, which coincides with a study by Giudice *et al.* [7]. Furthermore, the tonal motor orders, the inverter switching frequency traces, and the lack of prominent lower orders and masking offered by conventional ICEs all contribute to the unique challenge posed by EV sound signatures. A holistic approach is needed when evaluating EV sound quality, considering both the perceptual and technical dimensions and the interaction between these two approaches.

Finally, this study concludes that the comfort-related aspects of EV sound signatures should be enhanced to improve the perceived consumer satisfaction. The 'Comfort' dimension, represented by the 'Pleasant', 'Comfortable' and 'Calm' semantics, were found to be highly correlated ($R > 0.93$) with an increase in the perceived consumer satisfaction of EV sound signatures. Furthermore, the com-

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bination of the overall low perceived consumer satisfaction scores, the significant amount of high frequency content in EV sound signatures, and the preference of an enhanced sound signature all motivate the need to enhance EV sound signatures not only for legislation purposes, but also for the improved comfort and satisfaction of the consumer.

This study also concluded the following:

- The sound signature of the measured HEV is preferred due to the reduced frequency content and familiarity of the audible gear changes.
- Existing ICE bi-polar semantic evaluations can be adapted by adding suitable semantics to evaluate EV sound character.
- Known psychoacoustic metrics can be used to evaluate and predict perceived consumer satisfaction.

Reflecting on the work done in these studies, one also needs to identify and deliberate the limitations of the work. Firstly, the proposed consumer satisfaction metric was shown to over-estimate the perceived consumer satisfaction for highly fluctuating and impulsive sounds. An attempt was made to improve the performance of the metric for these sounds, however this was at the cost of metric robustness and simplicity. Secondly, the use of semantic terms to evaluate EV sound character can be dependent on the participants understanding and connotation to these words. Asking a farmer and a businessman how they would each describe the word 'powerful' might reveal completely different interpretations. However, likewise, potential EV consumers do not only consist of a group of automotive experts or students, but rather of people from different industries and with different cultural backgrounds. As such, in an attempt to diversify the group of people in this study, jury evaluations were conducted in South Africa and Germany, considering a broad range of nationalities, age groups and industries. Thirdly, the term 'satisfaction' which is used in this study can have several interpretations. Participants in the different studies were informed that the term 'satisfaction' should reflect the following: "If you would own and drive an electric vehicle, does this sound signature reflect what you want your vehicle to sound like? How satisfied would you be with this sound signature?". Different interpretations of this term could lead to a different result and a clear distinction and

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definition of the term should be made in future evaluations. Lastly, this study has shown that reducing the high frequency content in EV sound signatures leads to improved consumer satisfaction, however these tonal components form part of the authentic and inherent character of the motor. The challenge for NVH engineers is to develop an EV sound signature that reduces the high frequency components, whilst maintaining the unique and authentic sound character of these vehicles.

8.1 Future Work and Recommendations

It is recommended that the proposed consumer satisfaction model be evaluated against additional datasets. These datasets should include EVs from different vehicle classes and manufacturers, compared to the test vehicles in this study. Furthermore, the model should be evaluated against different driving conditions, such as constant speed tests and part throttle test, to see how the model performs under these conditions and whether adjustments can be made to account for the different driving conditions. The assessment of alternative drive conditions could improve the contextual validity of the model, with respect to daily driving scenarios. Additionally, the proposed model can be compared to a neural network approach to see if other potential predictor combinations can be found. It is also recommended that other psychoacoustic metrics, such as tonality or prominence ratio, should be investigated as potential predictors of consumer satisfaction in EV sound signatures. Lastly, the $CSMS_5$ should be evaluated against additional enhanced sound signatures and potentially also HEV sound signatures. The model adequately predicted the interior perceived satisfaction of the HEV sound signature in full electric drive for the training dataset. However the validation dataset did not include a HEV sound signature and thus additional WOT full electric drive HEV stimuli are required to assess the extended use of this metric for HEVs.

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Appendix A

Stimuli Graphs

A.1 FFT versus Time

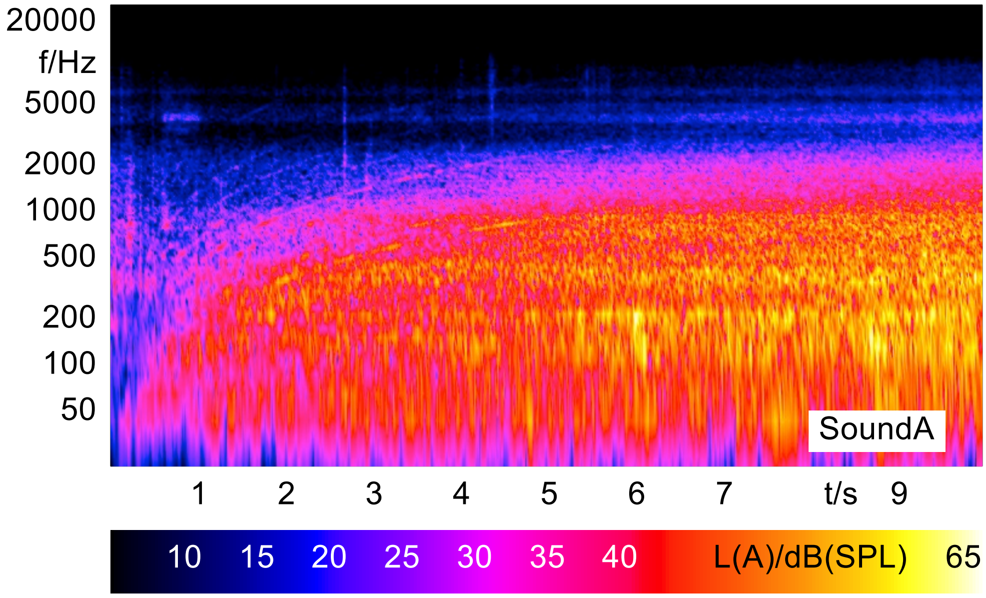

Figure A.1: The FFT vs Time spectrogram for Sound A during WOT acceleration.

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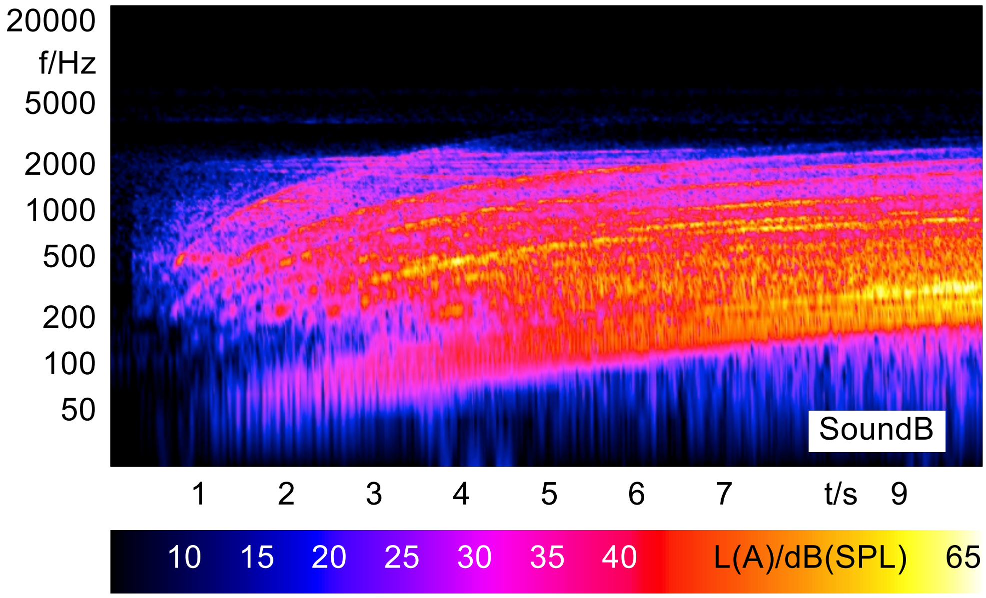

Figure A.2: The FFT vs Time spectrogram for Sound B during WOT acceleration.

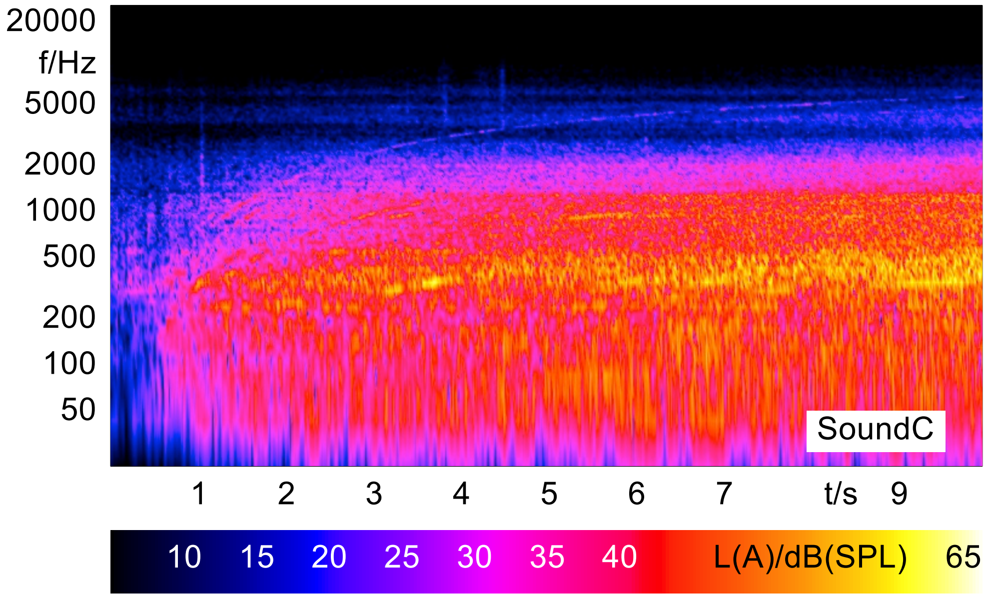

Figure A.3: The FFT vs Time spectrogram for Sound C during WOT acceleration.

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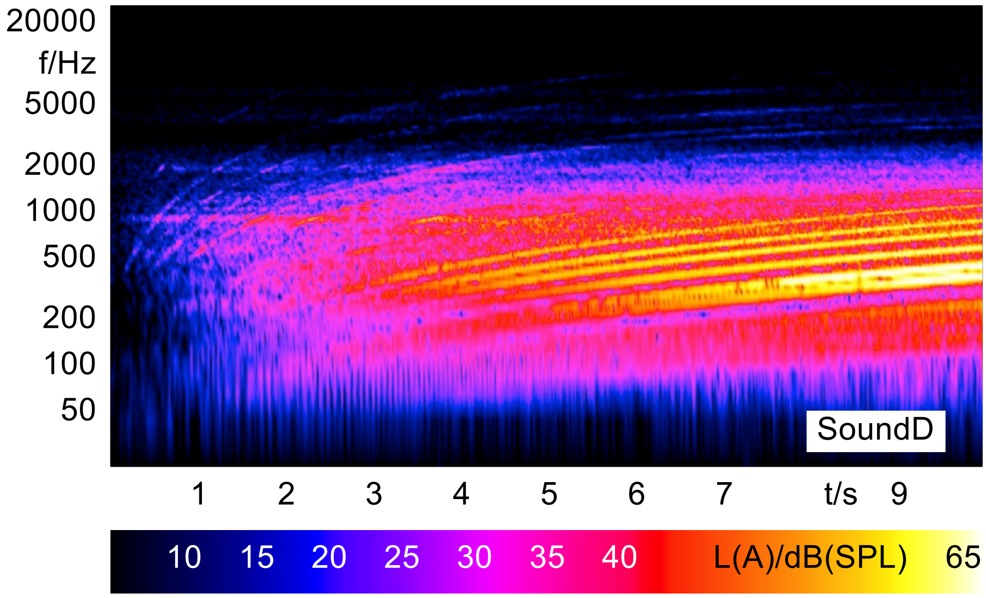

Figure A.4: The FFT vs Time spectrogram for Sound D during WOT acceleration.

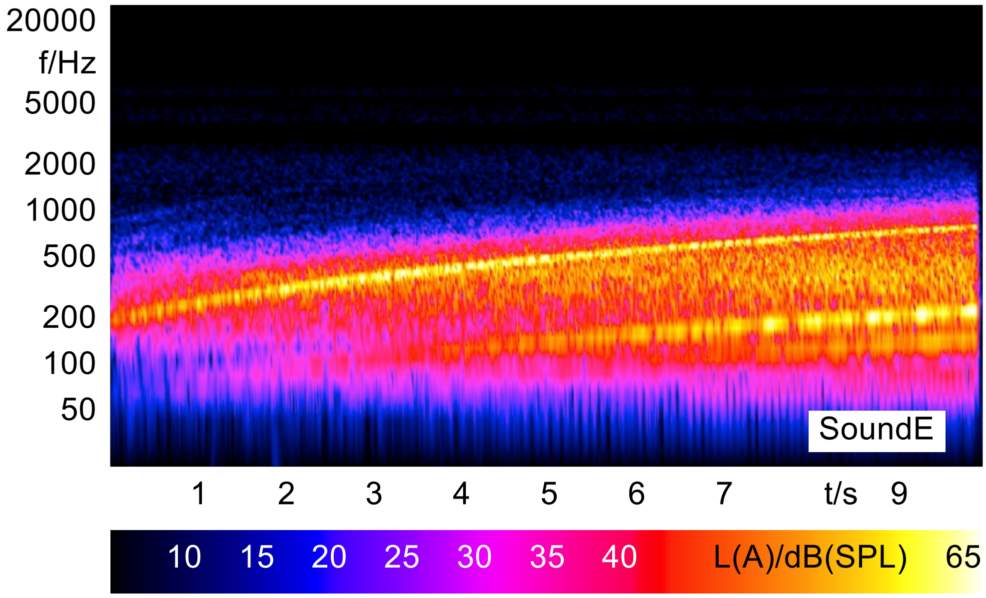

Figure A.5: The FFT vs Time spectrogram for Sound E during WOT acceleration.

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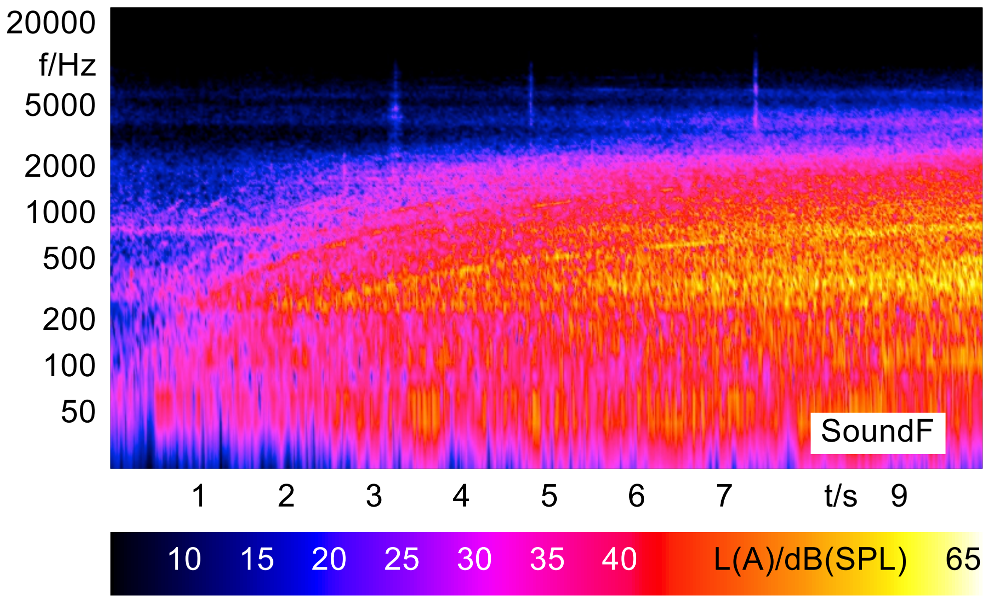

Figure A.6: The FFT vs Time spectrogram for Sound F during WOT acceleration.

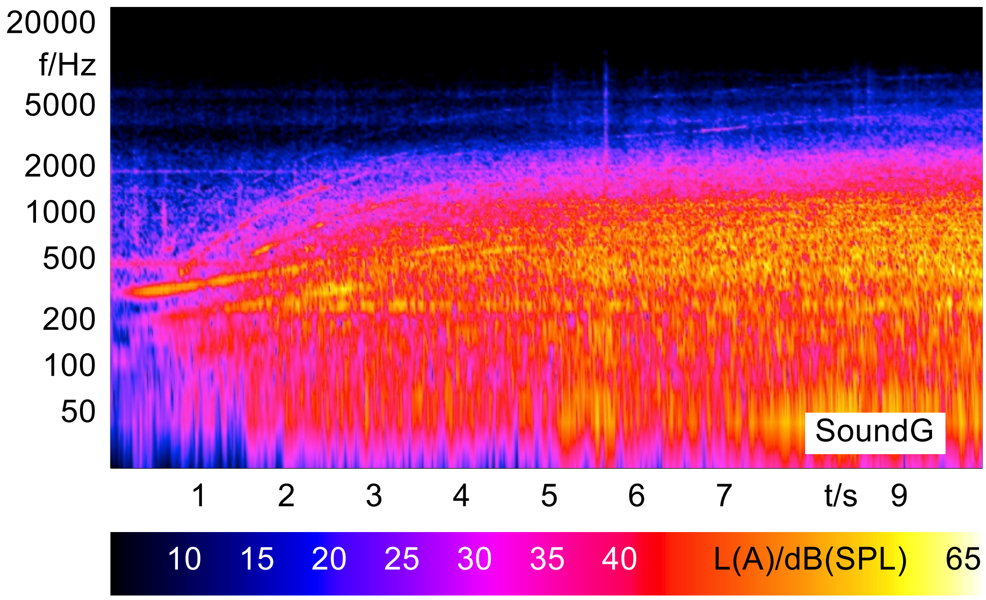

Figure A.7: The FFT vs Time spectrogram for Sound G during WOT acceleration.

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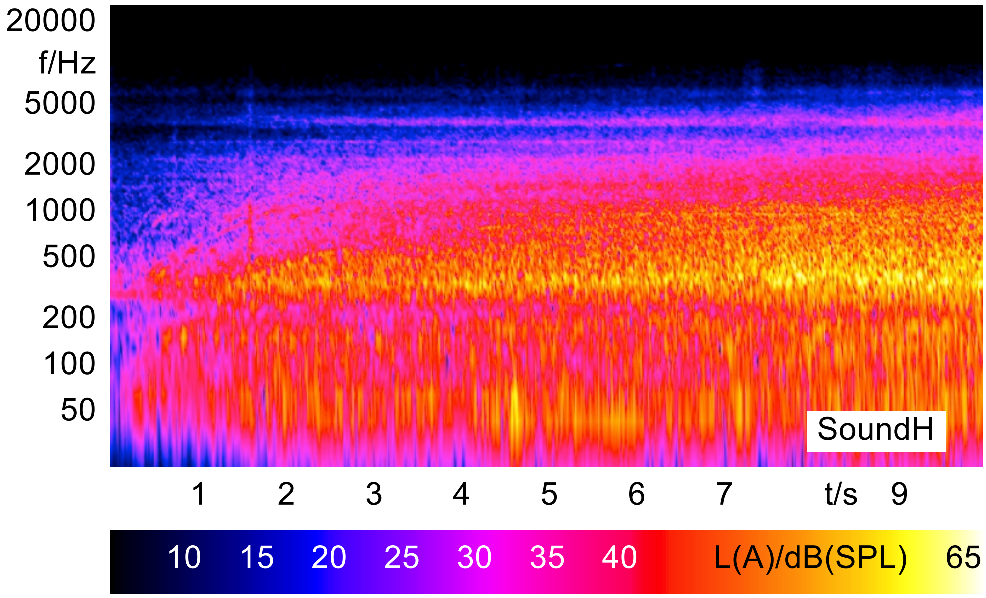

Figure A.8: The FFT vs Time spectrogram for Sound H during WOT acceleration.

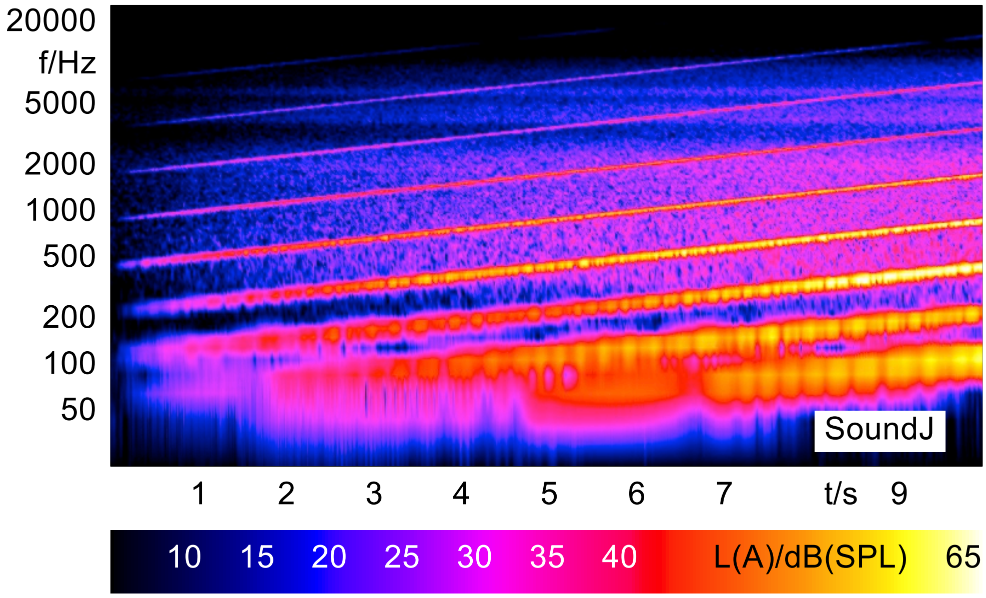

Figure A.9: The FFT vs Time spectrogram for Sound J during WOT acceleration.

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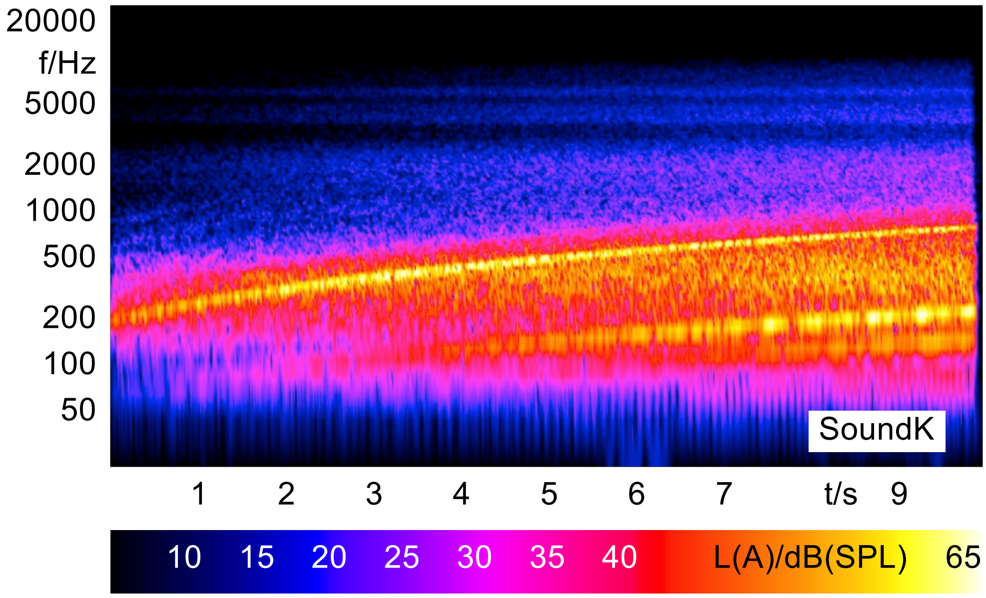

Figure A.10: The FFT vs Time spectrogram for Sound K during WOT acceleration.

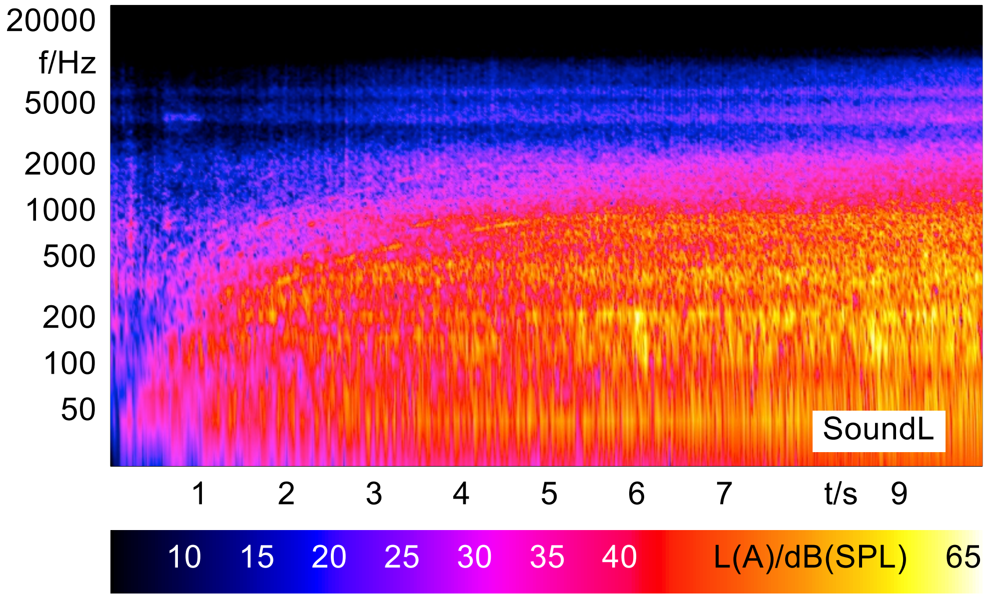

Figure A.11: The FFT vs Time spectrogram for Sound L during WOT acceleration.

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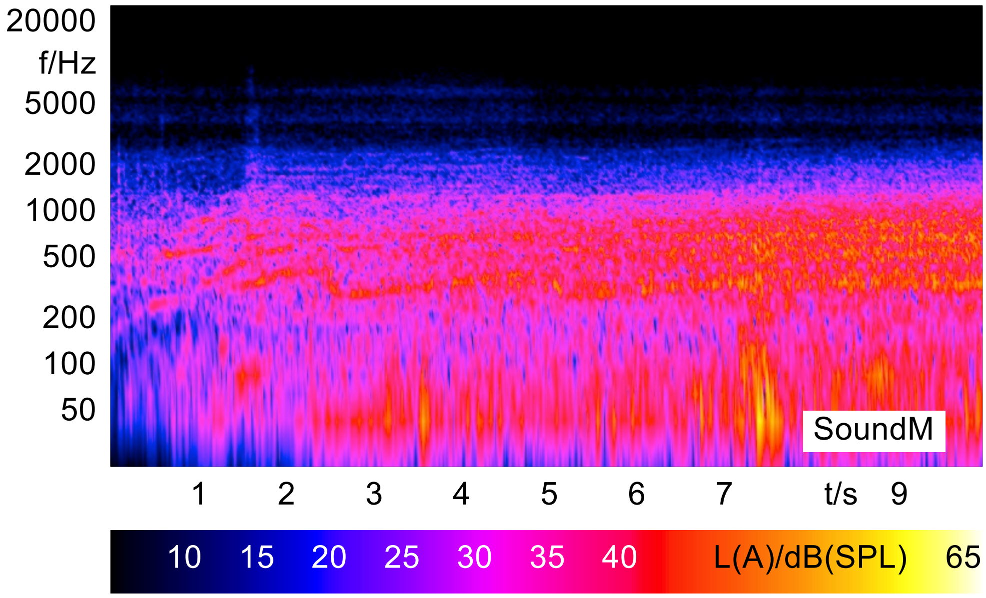

Figure A.12: The FFT vs Time spectrogram for Sound M during WOT acceleration.

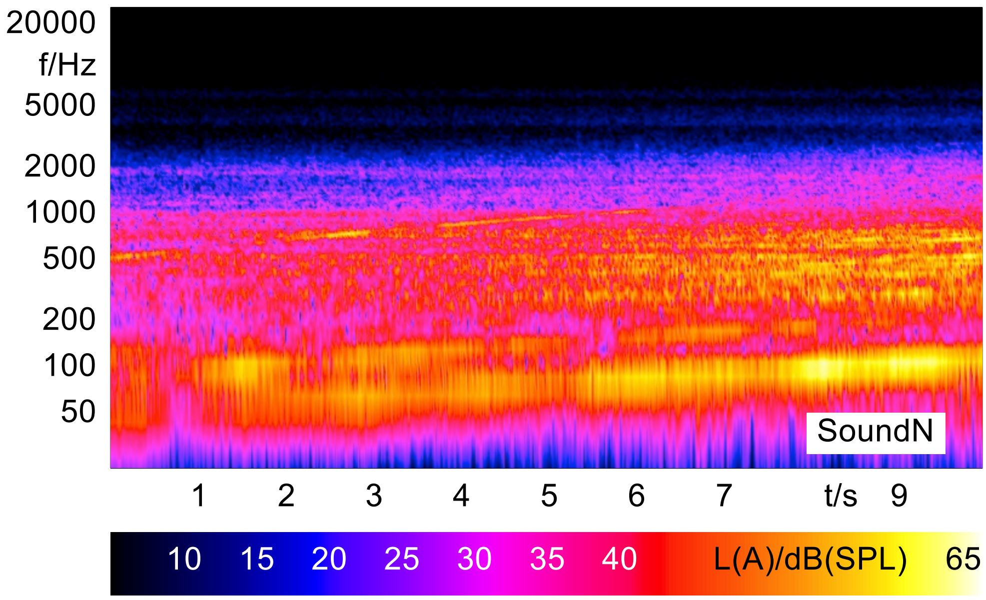

Figure A.13: The FFT vs Time spectrogram for Sound N during WOT acceleration.

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A.2 Psychoacoustic Metrics

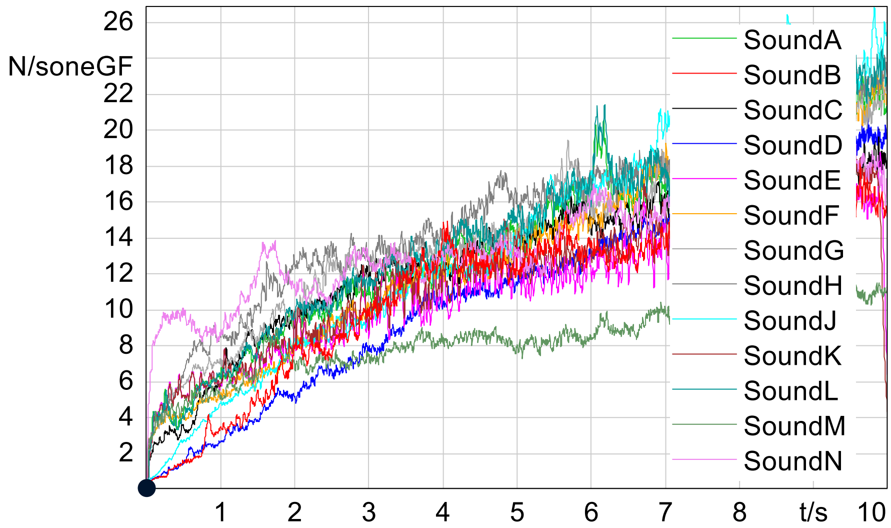

Figure A.14: Zwicker Loudness for all stimuli.

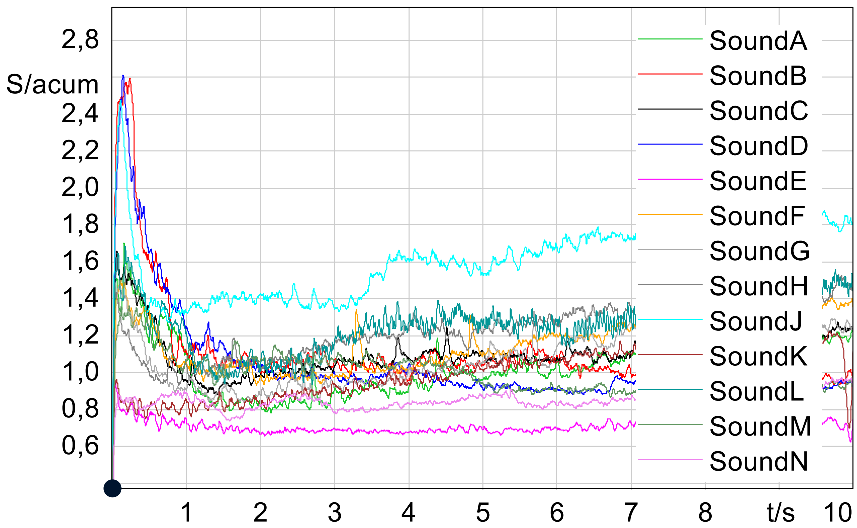

Figure A.15: Aure's Sharpness for all stimuli.

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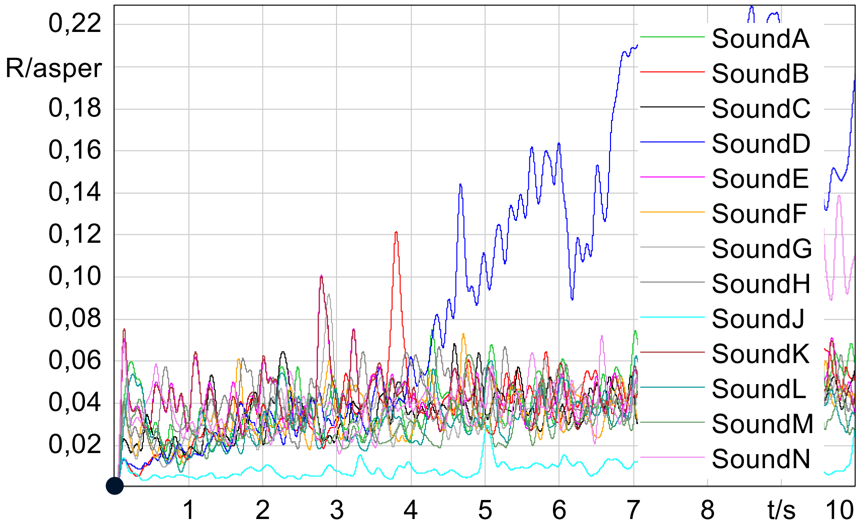

Figure A.16: Roughness (Hearing Model) for all stimuli.

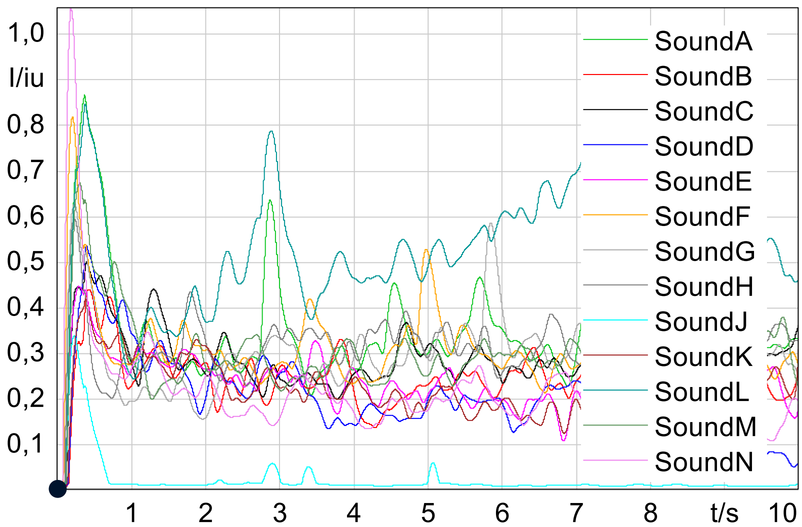

Figure A.17: Impulsiveness (Hearing Model) for all stimuli.

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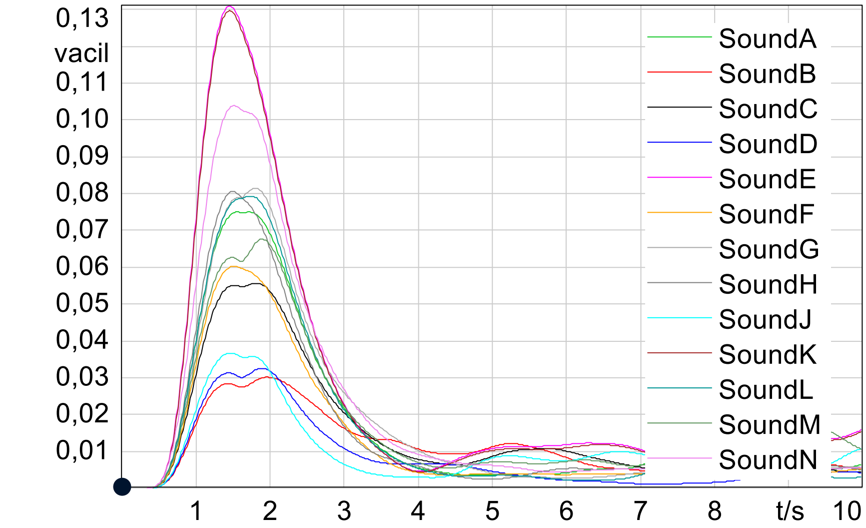

Figure A.18: Fluctuation Strength for all stimuli.

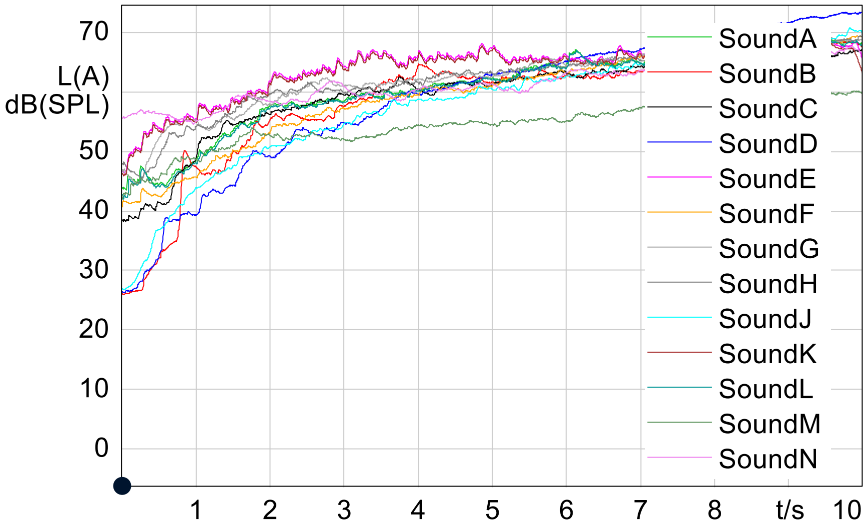

Figure A.19: Sound Pressure Level for all stimuli.

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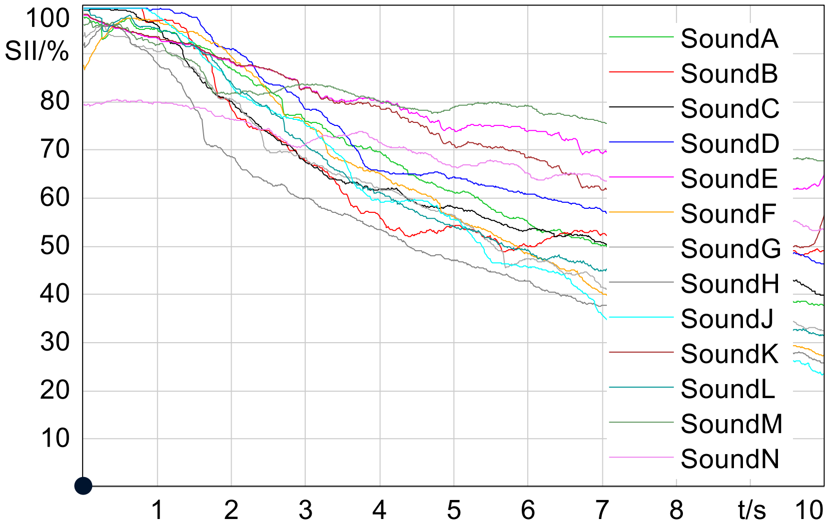

Figure A.20: Speech Intelligibility Index for all stimuli.

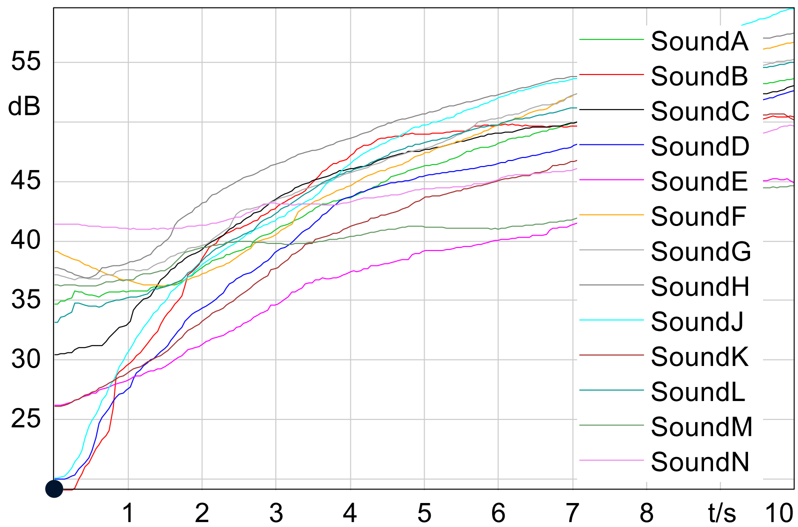

Figure A.21: Speech Interference Level for all stimuli.

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Appendix B

Subjective Evaluations

B.1 Subjective Evaluation for Electric Vehicles

Subjective Evaluation

October 24, 2013

Name: ______ Surname: ______

Gender: male ◯ female ◯

Age: ______

Home Language: ______

E-mail: ______

Nationality: ______

Ethic Group: ______

Occupation: ______

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1 Word Association

Please select 3 words from the box that best describes the sound clips A-E.

Pleasant Rumbling Shrill Light Aggressive Beautiful Bright High Loud Heavy Agitating Rough Impure Harsh Sharp Fast Strong Exciting Steady Hard Unpleasant Flat Muffled Dark Peaceful Ugly Sad Low Soft Light Calming Soothing Pure Gentle Dull Slow Weak Boring Unsteady Soft

SOUND A

Sound Clip A:

SOUND B

Sound Clip B:

SOUND C

Sound Clip C:

SOUND D

Sound Clip D:

SOUND E

Sound Clip E:

Please select the sound clip you preferred most and provide two additional adjectives that you would use to described the sound.

Preferred Sound: Sound A

Additional Words:

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2 Bi-polar Semantic Pairs

Listen to each of the given sound clips and rate each sound according to the bi-polar semantic differential scale provided.

SOUND AA

	-3	-2	-1	0	1	2	3	
Quiet	○	○	○	○	○	○	○	Loud
Fun	○	○	○	○	○	○	○	Laborious
Pleasant	○	○	○	○	○	○	○	Annoying
Luxurious	○	○	○	○	○	○	○	Bland
Comfortable	○	○	○	○	○	○	○	Uncomfortable
Powerful	○	○	○	○	○	○	○	Weak
Sporty	○	○	○	○	○	○	○	Conservative
Aggressive	○	○	○	○	○	○	○	Subdued
Exciting	○	○	○	○	○	○	○	Boring
Spirited	○	○	○	○	○	○	○	Dull
Effortless	○	○	○	○	○	○	○	Strained
Refined	○	○	○	○	○	○	○	Harsh

Please rate your satisfaction of the sound.

Satisfaction:

Stellenbosch University https://scholar.sun.ac.za

SOUND BB

	-3	-2	-1	0	1	2	3	
Quiet	○	○	○	○	○	○	○	Loud
Fun	○	○	○	○	○	○	○	Laborious
Pleasant	○	○	○	○	○	○	○	Annoying
Luxurious	○	○	○	○	○	○	○	Bland
Comfortable	○	○	○	○	○	○	○	Uncomfortable
Powerful	○	○	○	○	○	○	○	Weak
Sporty	○	○	○	○	○	○	○	Conservative
Aggressive	○	○	○	○	○	○	○	Subdued
Exciting	○	○	○	○	○	○	○	Boring
Spirited	○	○	○	○	○	○	○	Dull
Effortless	○	○	○	○	○	○	○	Strained
Refined	○	○	○	○	○	○	○	Harsh

Please rate your satisfaction of the sound.

Satisfaction:

Stellenbosch University https://scholar.sun.ac.za

SOUND CC

	-3	-2	-1	0	1	2	3	
Quiet	○	○	○	○	○	○	○	Loud
Fun	○	○	○	○	○	○	○	Laborious
Pleasant	○	○	○	○	○	○	○	Annoying
Luxurious	○	○	○	○	○	○	○	Bland
Comfortable	○	○	○	○	○	○	○	Uncomfortable
Powerful	○	○	○	○	○	○	○	Weak
Sporty	○	○	○	○	○	○	○	Conservative
Aggressive	○	○	○	○	○	○	○	Subdued
Exciting	○	○	○	○	○	○	○	Boring
Spirited	○	○	○	○	○	○	○	Dull
Effortless	○	○	○	○	○	○	○	Strained
Refined	○	○	○	○	○	○	○	Harsh

Please rate your satisfaction of the sound.

Satisfaction:

Stellenbosch University https://scholar.sun.ac.za

SOUND DD

	-3	-2	-1	0	1	2	3	
Quiet								Loud
Fun								Laborious
Pleasant								Annoying
Luxurious								Bland
Comfortable								Uncomfortable
Powerful								Weak
Sporty								Conservative
Aggressive								Subdued
Exciting								Boring
Spirited								Dull
Effortless								Strained
Refined								Harsh

Please rate your satisfaction of the sound.

Satisfaction:

Stellenbosch University https://scholar.sun.ac.za

SOUND EE

	-3	-2	-1	0	1	2	3	
Quiet	○	○	○	○	○	○	○	Loud
Fun	○	○	○	○	○	○	○	Laborious
Pleasant	○	○	○	○	○	○	○	Annoying
Luxurious	○	○	○	○	○	○	○	Bland
Comfortable	○	○	○	○	○	○	○	Uncomfortable
Powerful	○	○	○	○	○	○	○	Weak
Sporty	○	○	○	○	○	○	○	Conservative
Aggressive	○	○	○	○	○	○	○	Subdued
Exciting	○	○	○	○	○	○	○	Boring
Spirited	○	○	○	○	○	○	○	Dull
Effortless	○	○	○	○	○	○	○	Strained
Refined	○	○	○	○	○	○	○	Harsh

Please rate your satisfaction of the sound.

Satisfaction:

Thank you for taking part in this subjective evaluation, please Submit the form or Print as PDF and use your initials followed by your surname as the filename. (e.g. DJ Swart.pdf)

Reset Submit Print

Stellenbosch University https://scholar.sun.ac.za

B.2 Subjective Evaluation for Modified Sound Stimuli

B.2.1 Forced Choice Paired Comparison

Subjective Evaluation
of
Electric Vehicles

July 28, 2014

Gender: male ◯ female ◯

Age:

Home Language:

E-mail:

Nationality:

Hearing Ability:

Occupation:

Stellenbosch University https://scholar.sun.ac.za

1 Forced Choice Comparison

Two individual sounds will be played consecutively to the participant for each of the 10 sound pairs below. The participant is then required to choose one of the sounds from the pair, that sounds best. Please also provide a short description regarding the reason for your selection as well as a scale of the winning margin. A word box can be found below to assist you with the description, but please feel free to use your own words too. For example: *Sound X is Louder. Scale: 3.*

Winning margin scale:
1 - small; 2 - noticeable; 3 - medium; 4 - large; 5 - extreme.

gentle noisy deep sharp pure loud calm harmonic
pleasant powerful flat smooth dull quiet metallic rough
impure soft shrill unpleasant weak rumbling harsh

SOUND A SOUND B

SoundA: ☐ SoundB: ☐

Reason: Scale:

SOUND C SOUND D

SoundC: ☐ SoundD: ☐

Reason: Scale:

SOUND E SOUND F

SoundE: ☐ SoundF: ☐

Reason: Scale:

SOUND G SOUND H

SoundG: ☐ SoundH: ☐

Reason: Scale:

Stellenbosch University https://scholar.sun.ac.za

SOUND I SOUND J

SoundI: ☐ SoundJ: ☐

Reason: Scale:

SOUND K SOUND L

SoundK: ☐ SoundL: ☐

Reason: Scale:

SOUND M SOUND N

SoundM: ☐ SoundN: ☐

Reason: Scale:

SOUND O SOUND P

SoundO: ☐ SoundP: ☐

Reason: Scale:

2 Stimulus Ranking

Eight sound clips will be played to you several times. Please rank them from 1 to 8, according to your preference, where 1 is the best and 8 the worst.

SOUND 1	SOUND 2	SOUND 3	SOUND 4
Rank:	Rank:	Rank:	Rank:
SOUND 5	SOUND 6	SOUND 7	SOUND 8
Rank:	Rank:	Rank:	Rank:

Thank you for participating in this test. Any feedback or further comments are welcome. This test was designed by DJ Swart, University Stellenbosch.

Stellenbosch University https://scholar.sun.ac.za

B.2.2 Bi-polar Semantic Evaluation

Subjective Evaluation

August 23, 2014

Gender: male ◯ female ◯

Age:

Home Language:

E-mail:

Nationality:

Hearing Ability:

Occupation:

Stellenbosch University https://scholar.sun.ac.za

1 Bi-polar Semantic Pairs

Each of the given sound clips below will be played to you. Please rate each sound according to the bi-polar semantic differential scale provided. Finally also provide a satisfaction rating for each of the individual stimulus.

SOUND AA

	-3	-2	-1	0	1	2	3	
Quiet	○	○	○	○	○	○	○	Loud
Calm	○	○	○	○	○	○	○	Shrill
Pleasant	○	○	○	○	○	○	○	Annoying
Deep	○	○	○	○	○	○	○	Metallic
Comfortable	○	○	○	○	○	○	○	Uncomfortable
Powerful	○	○	○	○	○	○	○	Weak
Sporty	○	○	○	○	○	○	○	Conservative
Rumbling	○	○	○	○	○	○	○	Flat
Exciting	○	○	○	○	○	○	○	Boring
Spirited	○	○	○	○	○	○	○	Dull
Effortless	○	○	○	○	○	○	○	Strained
Refined	○	○	○	○	○	○	○	Harsh

Please rate your satisfaction of the sound.

Satisfaction:

Additional Comments:

Stellenbosch University https://scholar.sun.ac.za

SOUND BB

	-3	-2	-1	0	1	2	3	
Quiet	○	○	○	○	○	○	○	Loud
Calm	○	○	○	○	○	○	○	Shrill
Pleasant	○	○	○	○	○	○	○	Annoying
Deep	○	○	○	○	○	○	○	Metallic
Comfortable	○	○	○	○	○	○	○	Uncomfortable
Powerful	○	○	○	○	○	○	○	Weak
Sporty	○	○	○	○	○	○	○	Conservative
Rumbling	○	○	○	○	○	○	○	Flat
Exciting	○	○	○	○	○	○	○	Boring
Spirited	○	○	○	○	○	○	○	Dull
Effortless	○	○	○	○	○	○	○	Strained
Refined	○	○	○	○	○	○	○	Harsh

Please rate your satisfaction of the sound.

Satisfaction:

Additional Comments:

Stellenbosch University https://scholar.sun.ac.za

SOUND CC

	-3	-2	-1	0	1	2	3	
Quiet	○	○	○	○	○	○	○	Loud
Calm	○	○	○	○	○	○	○	Shrill
Pleasant	○	○	○	○	○	○	○	Annoying
Deep	○	○	○	○	○	○	○	Metallic
Comfortable	○	○	○	○	○	○	○	Uncomfortable
Powerful	○	○	○	○	○	○	○	Weak
Sporty	○	○	○	○	○	○	○	Conservative
Rumbling	○	○	○	○	○	○	○	Flat
Exciting	○	○	○	○	○	○	○	Boring
Spirited	○	○	○	○	○	○	○	Dull
Effortless	○	○	○	○	○	○	○	Strained
Refined	○	○	○	○	○	○	○	Harsh

Please rate your satisfaction of the sound.

Satisfaction:

Additional Comments:

Stellenbosch University https://scholar.sun.ac.za

SOUND DD

	-3	-2	-1	0	1	2	3	
Quiet	○	○	○	○	○	○	○	Loud
Calm	○	○	○	○	○	○	○	Shrill
Pleasant	○	○	○	○	○	○	○	Annoying
Deep	○	○	○	○	○	○	○	Metallic
Comfortable	○	○	○	○	○	○	○	Uncomfortable
Powerful	○	○	○	○	○	○	○	Weak
Sporty	○	○	○	○	○	○	○	Conservative
Rumbling	○	○	○	○	○	○	○	Flat
Exciting	○	○	○	○	○	○	○	Boring
Spirited	○	○	○	○	○	○	○	Dull
Effortless	○	○	○	○	○	○	○	Strained
Refined	○	○	○	○	○	○	○	Harsh

Please rate your satisfaction of the sound.

Satisfaction:

Additional Comments:

Stellenbosch University https://scholar.sun.ac.za

SOUND EE

	-3	-2	-1	0	1	2	3	
Quiet								Loud
Calm								Shrill
Pleasant								Annoying
Deep								Metallic
Comfortable								Uncomfortable
Powerful								Weak
Sporty								Conservative
Rumbling								Flat
Exciting								Boring
Spirited								Dull
Effortless								Strained
Refined								Harsh

Please rate your satisfaction of the sound.

Satisfaction:

Additional Comments:

Thank you for taking part in this subjective evaluation. This test was created and setup by DJ Swart, University Stellenbosch. For further questions please email him at 15729923@sun.ac.za.

Reset Submit Print

Stellenbosch University https://scholar.sun.ac.za

B.2.3 Bi-polar Semantic Evaluation 2

Subjective Evaluation

October 12, 2017

Gender: male ☐ female ☐

Age:

Home Language:

SU Number:

Hearing Ability:

Occupation:

Stellenbosch University https://scholar.sun.ac.za

1 Bi-polar Semantic Pairs

Each of the given sound clips below will be played to you. Please rate each sound according to the bi-polar semantic differential scale provided. Finally also provide a satisfaction rating for each of the individual stimulus.

Sound A

	-3	-2	-1	0	1	2	3	
Quiet								Loud
Calm								Shrill
Pleasant								Annoying
Deep								Metallic
Comfortable								Uncomfortable
Powerful								Weak
Sporty								Conservative
Rumbling								Flat
Exciting								Boring
Futuristic								Old-fashioned
Creative								Uninspired
Refined								Harsh

Please rate your satisfaction of the sound.

Satisfaction:

Additional Comments:

Stellenbosch University https://scholar.sun.ac.za

Sound B

	-3	-2	-1	0	1	2	3	
Quiet								Loud
Calm								Shrill
Pleasant								Annoying
Deep								Metallic
Comfortable								Uncomfortable
Powerful								Weak
Sporty								Conservative
Rumbling								Flat
Exciting								Boring
Futuristic								Old-fashioned
Creative								Uninspired
Refined								Harsh

Please rate your satisfaction of the sound.

Satisfaction:

Additional Comments:

Stellenbosch University https://scholar.sun.ac.za

Sound C

	-3	-2	-1	0	1	2	3	
Quiet	☐	☐	☐	☐	☐	☐	☐	Loud
Calm	☐	☐	☐	☐	☐	☐	☐	Shrill
Pleasant	☐	☐	☐	☐	☐	☐	☐	Annoying
Deep	☐	☐	☐	☐	☐	☐	☐	Metallic
Comfortable	☐	☐	☐	☐	☐	☐	☐	Uncomfortable
Powerful	☐	☐	☐	☐	☐	☐	☐	Weak
Sporty	☐	☐	☐	☐	☐	☐	☐	Conservative
Rumbling	☐	☐	☐	☐	☐	☐	☐	Flat
Exciting	☐	☐	☐	☐	☐	☐	☐	Boring
Futuristic	☐	☐	☐	☐	☐	☐	☐	Old-fashioned
Creative	☐	☐	☐	☐	☐	☐	☐	Uninspired
Refined	☐	☐	☐	☐	☐	☐	☐	Harsh

Please rate your satisfaction of the sound.

Satisfaction: ☐

Additional Comments:

Stellenbosch University https://scholar.sun.ac.za

Sound D

	-3	-2	-1	0	1	2	3	
Quiet	☐	☐	☐	☐	☐	☐	☐	Loud
Calm	☐	☐	☐	☐	☐	☐	☐	Shrill
Pleasant	☐	☐	☐	☐	☐	☐	☐	Annoying
Deep	☐	☐	☐	☐	☐	☐	☐	Metallic
Comfortable	☐	☐	☐	☐	☐	☐	☐	Uncomfortable
Powerful	☐	☐	☐	☐	☐	☐	☐	Weak
Sporty	☐	☐	☐	☐	☐	☐	☐	Conservative
Rumbling	☐	☐	☐	☐	☐	☐	☐	Flat
Exciting	☐	☐	☐	☐	☐	☐	☐	Boring
Futuristic	☐	☐	☐	☐	☐	☐	☐	Old-fashioned
Creative	☐	☐	☐	☐	☐	☐	☐	Uninspired
Refined	☐	☐	☐	☐	☐	☐	☐	Harsh

Please rate your satisfaction of the sound.

Satisfaction: ☐

Additional Comments:

Stellenbosch University https://scholar.sun.ac.za

Sound E

	-3	-2	-1	0	1	2	3	
Quiet	☐	☐	☐	☐	☐	☐	☐	Loud
Calm	☐	☐	☐	☐	☐	☐	☐	Shrill
Pleasant	☐	☐	☐	☐	☐	☐	☐	Annoying
Deep	☐	☐	☐	☐	☐	☐	☐	Metallic
Comfortable	☐	☐	☐	☐	☐	☐	☐	Uncomfortable
Powerful	☐	☐	☐	☐	☐	☐	☐	Weak
Sporty	☐	☐	☐	☐	☐	☐	☐	Conservative
Rumbling	☐	☐	☐	☐	☐	☐	☐	Flat
Exciting	☐	☐	☐	☐	☐	☐	☐	Boring
Futuristic	☐	☐	☐	☐	☐	☐	☐	Old-fashioned
Creative	☐	☐	☐	☐	☐	☐	☐	Uninspired
Refined	☐	☐	☐	☐	☐	☐	☐	Harsh

Please rate your satisfaction of the sound.

Satisfaction: ☐

Additional Comments:

Stellenbosch University https://scholar.sun.ac.za

Sound F

	-3	-2	-1	0	1	2	3	
Quiet	☐	☐	☐	☐	☐	☐	☐	Loud
Calm	☐	☐	☐	☐	☐	☐	☐	Shrill
Pleasant	☐	☐	☐	☐	☐	☐	☐	Annoying
Deep	☐	☐	☐	☐	☐	☐	☐	Metallic
Comfortable	☐	☐	☐	☐	☐	☐	☐	Uncomfortable
Powerful	☐	☐	☐	☐	☐	☐	☐	Weak
Sporty	☐	☐	☐	☐	☐	☐	☐	Conservative
Rumbling	☐	☐	☐	☐	☐	☐	☐	Flat
Exciting	☐	☐	☐	☐	☐	☐	☐	Boring
Futuristic	☐	☐	☐	☐	☐	☐	☐	Old-fashioned
Creative	☐	☐	☐	☐	☐	☐	☐	Uninspired
Refined	☐	☐	☐	☐	☐	☐	☐	Harsh

Please rate your satisfaction of the sound.

Satisfaction: ☐

Additional Comments:

Stellenbosch University https://scholar.sun.ac.za

Sound G

	-3	-2	-1	0	1	2	3	
Quiet								Loud
Calm								Shrill
Pleasant								Annoying
Deep								Metallic
Comfortable								Uncomfortable
Powerful								Weak
Sporty								Conservative
Rumbling								Flat
Exciting								Boring
Futuristic								Old-fashioned
Creative								Uninspired
Refined								Harsh

Please rate your satisfaction of the sound.

Satisfaction:

Additional Comments:

Stellenbosch University https://scholar.sun.ac.za

Sound H

	-3	-2	-1	0	1	2	3	
Quiet	☐	☐	☐	☐	☐	☐	☐	Loud
Calm	☐	☐	☐	☐	☐	☐	☐	Shrill
Pleasant	☐	☐	☐	☐	☐	☐	☐	Annoying
Deep	☐	☐	☐	☐	☐	☐	☐	Metallic
Comfortable	☐	☐	☐	☐	☐	☐	☐	Uncomfortable
Powerful	☐	☐	☐	☐	☐	☐	☐	Weak
Sporty	☐	☐	☐	☐	☐	☐	☐	Conservative
Rumbling	☐	☐	☐	☐	☐	☐	☐	Flat
Exciting	☐	☐	☐	☐	☐	☐	☐	Boring
Futuristic	☐	☐	☐	☐	☐	☐	☐	Old-fashioned
Creative	☐	☐	☐	☐	☐	☐	☐	Uninspired
Refined	☐	☐	☐	☐	☐	☐	☐	Harsh

Please rate your satisfaction of the sound.

Satisfaction: ☐

Additional Comments:

Stellenbosch University https://scholar.sun.ac.za

Sound I

	-3	-2	-1	0	1	2	3	
Quiet								Loud
Calm								Shrill
Pleasant								Annoying
Deep								Metallic
Comfortable								Uncomfortable
Powerful								Weak
Sporty								Conservative
Rumbling								Flat
Exciting								Boring
Futuristic								Old-fashioned
Creative								Uninspired
Refined								Harsh

Please rate your satisfaction of the sound.

Satisfaction:

Additional Comments:

Stellenbosch University https://scholar.sun.ac.za

Sound J

	-3	-2	-1	0	1	2	3	
Quiet	☐	☐	☐	☐	☐	☐	☐	Loud
Calm	☐	☐	☐	☐	☐	☐	☐	Shrill
Pleasant	☐	☐	☐	☐	☐	☐	☐	Annoying
Deep	☐	☐	☐	☐	☐	☐	☐	Metallic
Comfortable	☐	☐	☐	☐	☐	☐	☐	Uncomfortable
Powerful	☐	☐	☐	☐	☐	☐	☐	Weak
Sporty	☐	☐	☐	☐	☐	☐	☐	Conservative
Rumbling	☐	☐	☐	☐	☐	☐	☐	Flat
Exciting	☐	☐	☐	☐	☐	☐	☐	Boring
Futuristic	☐	☐	☐	☐	☐	☐	☐	Old-fashioned
Creative	☐	☐	☐	☐	☐	☐	☐	Uninspired
Refined	☐	☐	☐	☐	☐	☐	☐	Harsh

Please rate your satisfaction of the sound.

Satisfaction: ☐

Additional Comments:

Stellenbosch University https://scholar.sun.ac.za

Sound K

	-3	-2	-1	0	1	2	3	
Quiet								Loud
Calm								Shrill
Pleasant								Annoying
Deep								Metallic
Comfortable								Uncomfortable
Powerful								Weak
Sporty								Conservative
Rumbling								Flat
Exciting								Boring
Futuristic								Old-fashioned
Creative								Uninspired
Refined								Harsh

Please rate your satisfaction of the sound.

Satisfaction:

Additional Comments:

Stellenbosch University https://scholar.sun.ac.za

Sound L

	-3	-2	-1	0	1	2	3	
Quiet	☐	☐	☐	☐	☐	☐	☐	Loud
Calm	☐	☐	☐	☐	☐	☐	☐	Shrill
Pleasant	☐	☐	☐	☐	☐	☐	☐	Annoying
Deep	☐	☐	☐	☐	☐	☐	☐	Metallic
Comfortable	☐	☐	☐	☐	☐	☐	☐	Uncomfortable
Powerful	☐	☐	☐	☐	☐	☐	☐	Weak
Sporty	☐	☐	☐	☐	☐	☐	☐	Conservative
Rumbling	☐	☐	☐	☐	☐	☐	☐	Flat
Exciting	☐	☐	☐	☐	☐	☐	☐	Boring
Futuristic	☐	☐	☐	☐	☐	☐	☐	Old-fashioned
Creative	☐	☐	☐	☐	☐	☐	☐	Uninspired
Refined	☐	☐	☐	☐	☐	☐	☐	Harsh

Please rate your satisfaction of the sound.

Satisfaction: ☐

Additional Comments:

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Sound M

	-3	-2	-1	0	1	2	3	
Quiet	☐	☐	☐	☐	☐	☐	☐	Loud
Calm	☐	☐	☐	☐	☐	☐	☐	Shrill
Pleasant	☐	☐	☐	☐	☐	☐	☐	Annoying
Deep	☐	☐	☐	☐	☐	☐	☐	Metallic
Comfortable	☐	☐	☐	☐	☐	☐	☐	Uncomfortable
Powerful	☐	☐	☐	☐	☐	☐	☐	Weak
Sporty	☐	☐	☐	☐	☐	☐	☐	Conservative
Rumbling	☐	☐	☐	☐	☐	☐	☐	Flat
Exciting	☐	☐	☐	☐	☐	☐	☐	Boring
Futuristic	☐	☐	☐	☐	☐	☐	☐	Old-fashioned
Creative	☐	☐	☐	☐	☐	☐	☐	Uninspired
Refined	☐	☐	☐	☐	☐	☐	☐	Harsh

Please rate your satisfaction of the sound.

Satisfaction: ☐

Additional Comments:

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Sound N

	-3	-2	-1	0	1	2	3	
Quiet								Loud
Calm								Shrill
Pleasant								Annoying
Deep								Metallic
Comfortable								Uncomfortable
Powerful								Weak
Sporty								Conservative
Rumbling								Flat
Exciting								Boring
Futuristic								Old-fashioned
Creative								Uninspired
Refined								Harsh

Please rate your satisfaction of the sound.

Satisfaction:

Additional Comments:

Thank you for taking part in this subjective evaluation.
Please click on **Save** button to store your results.
For further questions please send an email to djswart@sun.ac.za.

Reset Save Exit

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Appendix C

Sound Stimuli

The various sound stimuli that were used for jury testing in this thesis is described in Table C.1 and is provided in digital format on a CD-ROM.

Table C.1: Complete set of sound stimuli used for subjective evaluations

	Track	Sound Label	Source
Chapter 3			
	1	Sound A	Motor Vibration
	2	Sound B	LEAF Interior
	3	Sound C	F14 Startup
	4	Sound D	LEAF Underhood
	5	Sound E	Washing Maschine
	6	Sound AA	LEAF Interior
	7	Sound BB	LEAF Underhood
	8	Sound CC	Concept Sound
	9	Sound DD	Mercedes Interior
	10	Sound EE	Porsche Interior
Chapter 5			
	11	Sound A	BMW i3 motorbay WOT
	12	Sound B	BMW i3 with high frequency filter
	13	Sound C	BMW i3 with mid frequency filter

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	14	Sound D	BMW i3 with low frequency filter
	15	Sound E	BMW i3 with low order addition
	16	Sound F	BMW i3 with E major 7th harmony addition
	17	Sound G	BMW i3 with pitch trasposition
	18	Sound H	BMW i3 with side band additions
	19	Sound I	BMW i3 with reverberation addition
	20	Sound AA	BMW i3 motorbay WOT
	21	Sound BB	BMW i3 with pitch transposition and G major harmony addition
	22	Sound CC	Renault ZOE motorbay WOT
	23	Sound DD	BMW i3 with low order, side band and E major 7th harmony addition
	24	Sound EE	Computer generated sound from prominent EV orders
Chapter 7			
	25	Sound A	BMW i3 interior WOT
	26	Sound B	Concept 1 with pitch transposition and G major harmony addition
	27	Sound C	Renault ZOE interior WOT
	28	Sound D	Concept 2 with low order, side band and E major 7th harmony addition
	29	Sound E	Computer generated sound from prominent EV orders
	30	Sound F	Citröen C-Zero interior WOT
	31	Sound G	Smart Electric interior WOT
	32	Sound H	Volkswagen e-Up! interior WOT
	33	Sound I	Renault ZOE interior repeater
	34	Sound J	Shepard's Tones stimulus
	35	Sound K	Sound E with additional pink noise
	36	Sound L	Sound A with frequency modulated pink noise
	37	Sound M	Porsche Panamera Hybrid interior WOT
	38	Sound N	Ford Bantam ICE interior WOT